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VOLUME 1

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Contributions to Astrophysics

VOLUME 1, NUMBER 1

NEW HORIZONS IN ASTRONOMY

edited by FRED L. WHIPPLE

DIRECTOR, ASTROPHYSICAL OBSERVATORY
SMITHSONIAN INSTITUTION

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Smithsonian Contributions to Astrophysics

The Smithsonian Institution's Astrophysical Observatory is passing through a period of reorganization. The scientific headquarters have been moved to Cambridge, Mass., where a close working association with the Harvard College Observatory is being developed. These changes, as well as the many advances in science and technology, force us to reevaluate the basic scientific policies and goals of the Astrophysical Observatory.

With the present rapid progress in basic science and its application to technology, research in the fundamental astrophysical processes of the sun, earth, planets, and interplanetary medium is going forward at a rapid pace. Concurrently, our mushrooming technology has become more and more sensitive to these phenomena of the solar system, heretofore thought to be of only academic interest.

In keeping with these developments, the Astrophysical Observatory must broaden the scope of its activities while continuing its long-established tradition of research—a tradition that began with the pioneering studies on aerodynamics by the observatory's founder, Samuel P. Langley, and continued during years of active investigations under Dr. C. G. Abbot in solar and terrestrial phenomena and their interrelationships. Thus, our future program will include not only radiation, its variations, and its effects on our planet, but also other phenomena that affect the earth and its atmosphere. We find, for example, that corpuscular radiation from the sun is associated with solar activity as well as with such geophysical phenomena as the aurorae, night air glow, terrestrial magnetism, the ionosphere, radio transmission, and other observed phenomena. Meteoric bodies, dissipated from comets or chipped from asteroidal sources, not only produce meteors in our atmosphere and provide samples of cosmic material for our museums but also ionize the high atmosphere and contribute to its chemical composition, scatter sunlight in the zodiacal light, and provide us with a cosmic ballistics laboratory of ultravelocity projectiles.

The Astrophysical Observatory, therefore, faces widening horizons. It will broaden the scope of its studies of solar phenomena and atmospheric effects to include related phenomena within the solar system such as meteorites, hypervelocity ballistics, and the zodiacal light. It will cooperate in exploiting new methods of research and technology such as nuclear processes and artificial satellites. To strengthen its effort the Astrophysical Observatory will not carry out its research in isolation; it will coordinate its work closely with that of other astrophysicists and geophysicists who are studying similar problems.

Although research in astrophysics continues to expand, no corresponding growth has occurred in the avenues of publication. Observational results are often so compressed in print that they cannot be analyzed in detail by independent investigators; and advances in technical procedures or instrumentations are often presented with such brevity that their value to the potential user is small.

In an effort to affect these trends and to provide a proper communication for the results of research conducted at the Astrophysical Observatory, we are inaugurating this new publication, *Smithsonian Contributions to Astrophysics*. Its purpose is the "increase and diffusion of knowledge" in the field of astrophysics, with particular emphasis on problems of the sun, the earth, and the solar system. Its pages will be open to a limited number of papers by other investigators with whom we have common interests.

We earnestly hope that *Smithsonian Contributions to Astrophysics* will serve to promote a greater understanding, appreciation, and enjoyment of that part of the universe in which we are privileged to live.

FRED L. WHIPPLE, *Director*
Astrophysical Observatory
Smithsonian Institution

Cambridge, Massachusetts
November 14, 1956

A grant from the National Science Foundation toward the publication of *New Horizons in Astronomy* is gratefully acknowledged.

New Horizons in Astronomy

Preface

The project of collecting a series of papers oriented toward new horizons in astronomy began in the 1954–55 Panel of Astronomy to the National Science Foundation. The initial impetus came largely from the enthusiasm of Dr. Otto Struve, who has presented some of his thoughts in a paper entitled "The General Needs of Astronomy" (Publ. Astron. Soc. Pacific, vol. 67, p. 214, 1955). The resulting deliberations led to the establishment of an *ad hoc* committee on the "Needs of Astronomy," of which I was made chairman. I felt that some of the goals of this committee could be attained by publishing a collection of papers by leaders in the various fields of astronomy who would present their concepts of research projects most likely to advance the science of astronomy during the next decade.

The purpose is at least fourfold:

To provide material that might assist the National Science Foundation, in its allocation of funds, to support the astronomical research most likely to be productive.

To help younger astronomers choose the most fertile fields for active research.

To encourage established astronomers to pause for a moment and reflect on the most advantageous planning in their own fields of research, and to supply them with a broader insight into the activities in other fields of astronomy, possibly related to their own.

To encourage research in new or neglected fields of astronomy, particularly those that border on other areas of physical science such as geophysics, electronics, chemistry, fluid dynamics, and the like.

The publication of *New Horizons in Astronomy* has been supported jointly by the Smithsonian Institution and the National Science Foundation. The Astrophysical Observatory shares with the National Science Foundation the hope that these papers may promote intensified efforts and increasingly significant results in astronomical research.

The hearty cooperation of the many busy scientists who took time from their other duties to write these papers should establish a debt of gratitude in the minds of all those who will profit by these contributions.

I am deeply indebted to Mr. Paul H. Oehser, Mr. Ernest Biebighauser, and Mr. John S. Lea, of the Editorial and Publications Division of the Smithsonian Institution, and to Mrs. Lyle Boyd, of the Harvard College Observatory, for their great interest and effort in this project; otherwise these papers would not now rest in your hands.

FRED H. WHIPPLE

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Techniques and Instrumentation

Optics

By I. S. Bowen[1]

Geometrical optics is one of the oldest of sciences. Most of the basic laws have been known for centuries, yet in the past two or three decades advances in optical designs have revolutionized astronomical techniques. An outstanding example of this is the Schmidt camera. Until the discovery of the principle of this instrument in 1931, camera optics providing critical definition over a field greater than two or three degrees in diameter were limited to focal ratios of $d/f=1/5$ or less. With the Schmidt camera critical definition can be achieved over wide fields at focal ratios as fast as $d/f=1$. This 10- to 100-fold gain in speed has opened up many new fields in astronomy.

Furthermore it has been possible to design, for special purposes, many modifications of the Schmidt cameras, some of which achieve even greater gains in speed and field. These include the Baker Super-Schmidt for meteor photography and the solid-block and thick-mirror Schmidts, the Schmidt-aplanatic sphere combination, and the twice-through corrector plates for spectroscopic applications. There are undoubtedly many additional modifications that should be explored. For example, the focal surfaces of most of these Schmidt systems are curved with a radius approximately equal to the focal length. Thin glass plates can be bent to radii greater than 18 inches and simple field flatteners yield satisfactory results in cameras with focal ratios up to about $d/f=1$. However, to exploit fully the still higher speeds in the shorter focal lengths it will be necessary to develop either field flatteners that are effective at the higher focal ratios or to find a flexible emulsion base that is stable against changes in temperature and humidity.

Another urgently needed development is an optical system that will provide a wide field of critical definition for telescopes of very large aperture. Schmidt telescopes have been successfully made with apertures up to 48 inches with a focal length of 120 inches. However, in order to avoid chromatic aberrations the focal length must increase as the 3/2 power of the aperture. Thus the minimum focus of a 200-inch Schmidt is 1,000 inches. The length of the tube would have to be twice this, or 2,000 inches; i. e., three times that of the present Hale telescope. This would make the cost of the telescope tube and the dome to house it prohibitive.

Unfortunately the field of good definition of a high-speed paraboloid is very small; less than ½ inch in diameter for the Hale telescope in which $d/f=1/3.3$. Corrector lenses designed by Dr. F. E. Ross and placed in front of the plate have successfully increased this area of good definition to a diameter of 3 or 4 inches. This still falls far short of the 14 × 14-inch area of critical definition attained with the 48-inch Schmidt, which operates at the even higher speed of $d/f=1/2.5$. Because of this small field, the use of large telescopes such as the 200-inch is impractical for most survey purposes.

Another important need at the present time is an objective prism or similar device that may be used for the wholesale classification of spectra of stars of magnitude fainter than can now be reached. Thus, because of the deterioration of the definition of the spectra by "seeing," it is not feasible to use an objective prism on telescopes of appreciably more than 10-foot focal length. Furthermore, the limit on the exposure time set by the sky background is essentially the same with an objective prism as for direct photography. If the usual dispersion of 200–300 A/mm is used and the spectra are widened to 0.2 or 0.3 mm, the starlight is spread over an area 1,500 to 4,000 times that of a star image,

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[1] Director of Mount Wilson and Palomar Observatories.

with the result that the limiting magnitude for the spectra is 8 or 9 magnitudes below the limit for direct photography. For a 10-foot focal length the limiting magnitude for direct photography is $M_{ph}=21$ and therefore for spectroscopy $M_{ph}=12$ or 13. This falls far short of the magnitudes that may be reached with slit spectra. Thus with the 200-inch telescope a 1-night exposure enables one to reach the 15th magnitude at 38 A/mm and the 18th magnitude at 170 A/mm. At the present time there is no equipment available for picking up unusual faint objects for detailed study at these higher dispersions with a slit spectrograph. The anticipated development of the image tube, discussed below, will render this problem even more serious by pushing the limit of the slit spectrograph from 2 to 5 magnitudes still fainter.

One suggested solution of this problem is the use, as a multislit, of a high-contrast positive print of a given star field taken with the same telescope. With a wide-angle telescope and a spectrograph having wide-angle collimator and camera optics, a large number of spectra could be obtained simultaneously without interference from the sky background. Unfortunately, if Schmidt optics are used throughout, the field flatteners necessary to bring the curved fields of the telescope and collimator into coincidence destroy the off-axis collimation. Some other wide-angle system must be devised for the purpose.

The efficiency of slit spectrographs would be substantially increased if larger gratings could be made or if gratings could be ruled which provide higher angular dispersion and still retain a high concentration of light in one order. In order to avoid interference between collimator and camera optics, this grating should preferably be of the transmission type. The so-called "venetian-blind type" described in "Astronomical Spectrographs: Past, Present, and Future," in "Vistas in Astronomy," is one possible solution if the necessary ruling techniques can be developed.

Another problem that needs investigation is that of seeing. Presumably very little can be done to reduce turbulence in the upper atmosphere. However, in solar instruments much of the disturbance is caused by the heating of the optical parts and their surroundings by the sunlight which is incident on them. Undoubtedly the local air turbulence due to this could be substantially reduced by proper light shields and by artificial cooling of parts that cannot be shielded. Useful studies could also be made to determine the most effective method for thermostating an optical instrument such as a spectrograph without setting up internal air currents and turbulence that often cause serious deterioration of the image.

Every large telescope is essentially a collector of light which is focused on some type of receiver. The properties of this receiver play a very large role in the proper design of the telescope. Thus up until the present century practically all astronomical observations were made visually; i. e., the human eye was the receiver. The range of wavelengths to which the eye has appreciable sensitivity is very small (1,000–1,500 A) and the field of view of critical definition is also very limited. Furthermore, the lens of the eye is a part of the optical system and sets an upper limit to the size of the cone of light that can be concentrated on the sensitive surface. For this type of receiver the simple two-lens refractor operating at focal ratios of $d/f=1/15$ to 1/20 was ideal. As a result nearly all large telescopes constructed in the last half of the 19th century were of this type.

By 1900 photographic procedures were rapidly replacing visual observations. The silver-halide grains, however, are sensitive in the ultraviolet to beyond the limit of transmission of the atmosphere while the more recent development of dyes has produced plates that are sensitive well out into the infrared range. Also, in order that an image be recorded on a photographic plate it is necessary that a certain minimum number of quanta fall on a unit area of the plate. This limit is such that in order to photograph faint galaxies and nebulosities in a feasible exposure time it is necessary to use a light collector with a focal ratio of at least $d/f=1/5$. This fact resulted in a sudden shift early in the present century to the use of the reflector, which provides the complete achromatism and greater speed necessary for the efficient use of the new type of receiver.

Not only were the properties of the photographic plate major factors in causing the shift from refractors to reflectors, but they have played an important role in fixing many of the design criteria for both the reflector itself and the auxiliary equipment, such as spectrographs, to be used with it. One of these properties is the linear resolving power of the plate. This resolving power sets the minimum focal length of the main telescope or of the spectrograph camera if a given angular resolving power or wavelength resolution, $\Delta\lambda$, is to be achieved. Furthermore, in all of these instruments this plate resolving power is the primary factor considered in setting up optical design and construction tolerances. Another property of the plate, namely, that it can record a very wide field at one time, led to the development of various wide-field optics culminating in the Schmidt camera. Similarly the necessity of concentrating a certain minimum of light per unit area in order to obtain an image has been the chief cause of the design and construction of optical systems of extreme speed ($d/f=1$ or greater) for spectrograph cameras.

It is now becoming apparent that another change in the receiver for astronomical observations is in the offing. Thus photoelectric surfaces have been developed, and are in use for television and other purposes, that have a quantum efficiency from 10 to 100 times as high as that of the best photographic plates. The electrical circuits used in some of these receivers permit the reduction or elimination of a uniform background of the type caused by scattered starlight and the permanent aurora, which sets the present limit in direct photography of the sky. Indeed it now appears that in the foreseeable future the limit of detectability of a faint star image will approach the theoretical limit. This limit is set by the necessity of collecting a larger number of quanta from the star than the probable random fluctuation in the number of quanta received from the sky background in the area of the sky covered by the object.

These developments are still in such an early stage that it is too soon to predict their possible effect on telescope design. Thus the linear resolving power will depend on the final type of receiver adopted. It is also quite probable that the new receiver will not require, like the photographic plate, a minimum concentration of quanta per unit area for a satisfactory record. One criterion for this will depend on the possibility of eliminating spurious thermal electrons by refrigeration or other means. In any case the much greater efficiency of the photoelectric process will permit the record of a given object to be obtained in very much less time than that required by the photographic process. The shift in these two properties will probably eliminate the necessity for optics of extreme focal ratio such as the types recently developed for both direct and spectroscopic observations. Regardless of the properties of the photoelectric receiver as finally developed, substantial changes in telescope and spectrograph design may be expected, if for no other reason than the elimination of many of the present restrictions set by the properties of the photographic plate.

Solar Instrumentation

By J. W. Evans[1] and R. B. Dunn[1]

The technical problems of solar observation are decidedly different from those in any other field of astronomy because of the abundance of light and the large apparent diameter of the sun. The latitude for the exercise of ingenuity in securing more and more refined information is practically unlimited, and affords a kind of satisfaction rarely found in any other field. The next 25 years promise to be the most exciting and the most productive since the formulation of the laws of spectrum analysis by Kirchhoff. Since 1945, the conception and construction of new instruments and techniques have accelerated markedly, as have the theoretical advances which designate the critical observations we need to determine the physical character of the sun. We have barely begun to get acquainted with the new tools and to exploit their possibilities, but the results are already impressive.

Most of the new developments are projections of older devices and methods, with refinements that greatly increase their power. Two of them, however, introduce entirely new methods that are sure to be exceedingly fruitful: the observation of the far ultraviolet spectrum of the sun from rockets, and the recording of solar radio emission.

The rocket observations are a fine example of cooperative effort in several fields to solve a very difficult technical problem. The recording instrument is either a spectrograph designed to work in the 900- to 3,000-angstrom range or an X-ray ionization chamber for the 1- to 5-angstrom region. The recorder must be mounted in the rocket with a device which keeps it pointed at the sun with an accuracy of a few minutes of arc, in spite of lively gyrations in its supporting platform. Finally, the rocket itself must be capable of carrying its load to an altitude of 100 km or more in order to rise above the regions of the earth's atmosphere that absorb the solar radiations in these wavelength regions and prevent their observation from the ground.

This brief description can give no concept of the difficulties encountered in the work, nor of the years of patience and imagination that were required to overcome them; but the results so far have more than justified the effort. The expected spectroscopic features duly appeared, but some very unexpected emission lines were also recorded. The expected lines strengthen our confidence in the broad features of existing solar theory, and the new lines present new conditions which any valid theory must satisfy. The rocket observations have unveiled a hitherto inaccessible part of the solar spectrum, but the quick glance we have been allowed sharpens the appetite for more details, more quantitative measurements, and a further extension to still shorter waves. Rockets can still do a great deal, but there can now be little doubt that a man-made satellite eventually will be our platform for solar research above the absorption of the terrestrial atmosphere. New difficulties will appear and be overcome, and new data on the solar spectrum will further delineate the structure of the sun. Such advances, inevitably, will raise new questions in place of the old ones solved, but they will concern questions of details which we cannot ask at present because we do not know enough.

It was discovered during World War II that the sun was the source of occasional radio noise strong enough to interfere with radar operations. This discovery has led to a new branch of solar astronomy which we have just begun to explore in its general outlines. Instead of the 2-to-1 range in wavelength of the visible spectrum, the observable radio emission from the sun covers a range of at

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[1] Sacramento Peak Observatory, Sunspot, N. Mex.

least 1,000 to 1. This provides a tool for analysis in depth. Shortwaves in the centimeter range originate near the visible surface of the sun. As we go to longer waves, the point of origin rises through the corona to heights of some hundreds of thousands of kilometers for the longest waves of 10 meters or so. Like the light spectrum, the nature of the radio spectrum depends on physical conditions at its point of origin and in the higher layers traversed by the radiation in leaving the sun. The interpretation of much that has been observed is not yet clear, but there can be no doubt that solar radio astronomy will occupy an extremely important place in future research.

The design and construction of new solar instruments at observatories all over the world continues at an ever-increasing pace. Some of them, like the Babcocks' magnetograph, are the response to a particular need. Others are new versions of tried-and-true devices, like spectrographs, for which there are sure to be many uses not necessarily specified in advance. In a field where we have still so much to learn, we should plan our new equipment with care in order to avoid unprofitable duplication.

In considering solar instrumentation, both present and future, we should always keep in mind our real object: to find out something about the sun. Specifically, we want the statistics, photometry, and physics of the solar atmosphere, and a good theoretical model that explains all the observations. We must approach the problem from every possible direction. Routine daily survey programs, detailed studies of active regions, critical observations designated by theoretical models, new types of observations—all should be used to solve the problem.

Each new instrument acquired should fill a specific need. A careful investigation is often required to determine whether the planned observation is already being carried out elsewhere. Especially in planning a survey program, the observer should ask himself: Should I make an effort to take a few prominence movies, when other observatories have collected such gross quantities of film that they defy any sort of reduction? Will my daily survey of sunspots contribute significantly to the daily coverage obtained elsewhere? Can the solar activity be adequately described from present solar surveys? In other words, the observer should have a specific problem in mind when building the instrument and when taking the observations.

In instrumental development there is room for every type of genius. To get an ingenious idea and show that it works is not enough. The inventor, or someone else, must still develop the instrument to the point where any capable observer can use it routinely to obtain reliable data. A typical example of instrument development is the coronagraph. Lyot showed that the coronagraph could be built, and he proceeded to build one. He used it with the utmost skill to solve several important coronal problems, and, incidentally, demonstrated its capabilities. Since then a great deal of work has resulted in developing the instrument, as a coronagraph, and in making it more convenient to operate. It is hoped that due to additional scale, resolution, photometry, and systematic use, Lyot's ideas will tell us even more about the sun than did his first observations. In some cases the conveniences themselves make the difference between taking or not taking the critical observation.

The development of the completed instrument is very often the result of a team effort. We need new gadgets and new ideas, but in the solar field we also need people who take existing ideas and instruments and add such vital factors as photometric standards, direct photoelectric photometry, differential photometry, seeing cancellation devices, and conveniences that speed the operation.

As elsewhere, solar instrumentation is getting so complex that we need specialists in the optical, electronic, and mechanical aspects and in data reduction, who will cooperate with the solar physicist to produce the final result. It is no longer feasible for a person to be skilled in all fields necessary to the solution of a problem. He must work with a group, and the group members must have mutual confidence in each other. A great deal of intercommunication is essential. Finally, the group must be competently directed and coordinated.

The value of some very simple solar observational device in an educational institution should never be underestimated. An example is a prominence birefringent filter. The direct contribution to research on the sun may be small or none, but the stimuli provided by such facilities may be decisive in attracting capable students to solar research, which greatly needs skilled workers.

Until a few years ago solar research was mainly concerned with broad average characteristics. One studied the spectrum without regard for small variations from point to point on the sun. The chromosphere was treated as a homogeneous atmosphere of uniform temperature. More recently the importance of the local differences has been recognized and the tendency has been toward a finer grained analysis, in which many small areas of the solar surface must be studied separately. The result is an enormous increase in the volume of information required, since we now have to consider many small areas instead of a single large one. Gathering data, reducing them to useful numerical quantities, and analyzing the greatly increased volume of such numerical quantities are already acute problems, and will become more serious as time goes on.

In gathering data, the unaccustomed pinch of the basic limitation of information contained in the available light from the sun is already being felt. A telescope receives light from a given area on the sun in the form of discrete quanta at an average rate of n per second, in a purely random fashion. This means that the number of quanta collected by the telescope in a given second differs from n in a random fashion, with a mean percentage error of $\frac{100}{\sqrt{N}}$. Hence a 1-second observation can at best determine the brightness of the area with this percentage accuracy, and the larger n is, the more accurate the observation. When we try to observe smaller and smaller areas of the sun we are, in effect, reducing n in proportion, and the fundamental errors of observation increase. Unfortunately we cannot make up for this by simply observing for a longer time. Seeing is never good enough to yield an undistorted and unsmeared image of the sun for more than a fraction of a second, and the longer our observation the more our small area becomes confused with light from neighboring areas. The idea of a scarcity of sunlight is perhaps a novel one, but may not seem so surprising when we consider that we would like right now to take the light from an area of 0.01 square millimeter in a 300-mm solar image, spread it out into a visible spectrum nearly a hundred yards long, and then determine the intensity in an area of 0.01 square mm of this spectrum. The one thing we can do is to increase efficiency in the use of the quanta we receive. The photographic plate utilizes only one in a hundred of the incident quanta. Modern photoelectric surfaces are about 10 times as efficient, and we have already begun to take advantage of this improvement. The problem of the future is to find still more efficient photoelectric surfaces, and to develop accurate and convenient methods for recording continuously the photoelectrons emitted from each point of the surface.

Once the observational data are secured, the problem of reducing them to numerical quantities must be faced. This has always been a laborious process, and the vastly greater volume of data now required demands a radically new method of automatic reduction. The magnificent spectra coming from the new vacuum spectrograph at the McMath-Hulbert Observatory emphasize the problem decisively, and I take them as a clear-cut example. The McMath-Hulbert observers find that both the Fraunhofer lines and the solar continuum show marked variations in the direction perpendicular to the dispersion. These variations are due to spectroscopic differences in the small regions imaged on the slit of the spectrograph. They consist in wiggles and changes of width in the lines, and changes in the brightness of the continuum. Thus the spectrograms have variations which must be measured in two directions instead of one, along the spectrum and across the spectrum. Now suppose we want to exhaust the information contained on such a plate over a wavelength range of only 5 angstroms. Let us say that the slit was 1 cm long, that the resolving power of the telescope was 0.2 mm along the slit, and the resolving power of the spectrograph was 0.01 A. Complete information, therefore, calls for the determination of the light intensity at 500 points along the spectrum for each of 50 points along the slit. In other words, we have to make 25,000 intensity determinations for a complete analysis, instead of the 500 that would suffice if there were no appreciable variations along the slit. In this instance the new dimension has multiplied the labor of analysis by a factor of 50. The information is there in the plate, but the labor of extracting it has become prohibitive.

The case of the wiggly lines is only one example of the trend toward the study of finer details on the solar disk, in the chromosphere, and in the corona. The result is an unprecedented mass of information in the coded form of photographic density, magnetic variations in a tape, or some other analog record. To be of any use, these records must be decoded and presented in numerical form. Once this has been accomplished, we are confronted with endless pages of numbers, all ready for interpretation by the unhappy theoretician. Classical methods of data handling will be quite inadequate to utilize more than a tiny fraction of the information contained in the observations, and future progress depends very heavily on finding the means for breaking this bottleneck.

These problems of data reduction and analysis on a large scale are by no means limited to solar astronomy. Industrial and military needs have stimulated the development of information theory, the science of extracting the maximum possible information from a minimum of raw data in the least time. Devices for automatically performing various standard operations in data reduction, and computers which handle the numerical results with unimaginable speed, have been devised. The theoretical and physical machinery for the solution of the astronomical problem are now at hand, and the computers at least are already vigorously at work for astronomers in several fields. But as yet the automatic reduction of astronomical data to the point where they are ready to be fed into a computer has hardly been touched. The problem for the immediate future, therefore, is to develop the devices for bridging the gap between the output of a telescope and the input to a train of automatic reducing equipment already available. The output of such a train is numerical information, ready either for the computer or for direct analysis by the astrophysicist if the quantity is manageable. The importance of this problem should be emphasized. Unless it can be solved the effectiveness of many of the instrumental developments for solar research will be limited to a fraction of their real potential.

Astronomical Seeing and Scintillation[1]

By Geoffrey Keller[2]

Anyone who has made observations with large telescopes is only too painfully aware that the most serious limitations to their performance are usually connected in one way or another with problems of astronomical seeing. Images of stars are much larger than one would expect them to be were their size determined only by the aberrations of the telescope itself. Details of extended objects, such as the moon and the sun, are badly smeared when the seeing is poor. As a case in point, Baum (1955) gives the average image diameter seen with the 200-inch telescope at about 2.5 seconds of arc, whereas in the absence of bad seeing conditions the perfectly adjusted telescope should give images of diameter of the order of 0.04 seconds of arc. The total amount of light received from a bright star by a telescope of moderate size also fluctuates in an irregular fashion, and in a manner which can easily be shown to be due not to intrinsic fluctuations in the star but to the fact that the starlight must pass through regions of the earth's atmosphere wherein the density varies irregularly. Protheroe (1955a) has shown that with a telescope of 12½ inches aperture the fluctuations in brightness of a bright star will average around 10 percent of the mean, and will have frequencies ranging up to a thousand cycles per second. In pioneering investigations in this field Mikesell, Hoag, and Hall (1951) obtained similar results.

Similar effects are encountered in radio astronomy, and here also the responsible agency is a region of nonuniform index of refraction in the earth's atmosphere. Whereas in the case of optical scintillation the principal effects apparently are caused in the troposphere and lower stratosphere, the majority of the effects on radio waves seem to be caused by nonuniform electron densities in the ionosphere. Ryle and Hewish (1950) have observed fluctuations in the intensity of radio sources at meter wave lengths of the order of 10 percent and fluctuations in the apparent positions of the radio objects of the order of a minute or so of arc. Such variations give rise to serious observational problems, and, though some observational uncertainties due to scintillation and bad seeing may be overcome by making repeated measurements, the loss in efficiency is very great.

The most extensive efforts that have been made to date to minimize the effects of the earth's atmosphere on astronomical observations have consisted of more or less empirical comparisons of various possible sites for establishing new observatories. When a very large investment of this sort is to be made, it becomes economically feasible to spend a considerable sum on extended tests. Such tests were made prior to the construction of the Hale telescope at Mount Palomar, and currently a new series of tests is being made in connection with a search for a site for a proposed American Observatory. Such surveys generally use telescopes and record the fluctuations in size and brightness of a star such as Polaris (chosen frequently because of its relatively fixed position in the sky).

Another potential means of reducing seeing effects is through the use of instruments mounted on high-altitude balloons, rockets, and eventually extraterrestrial satellites. These methods might eliminate our seeing problems, but before adopting them we should know, for example, how high the instrument platform must be in order to be safely above the troublesome layers of the atmosphere. In the case of a radio telescope, the answer is likely to be of the order of hundreds of miles. There are obvious difficulties with such an approach

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[1] "Scintillation" is used here to mean only the changes with time of the brightness of the telescopic image of a star or other source. "Seeing" is construed to mean the degree of change in the position, shape, or size of a stellar image or of a detail of an extended object.

[2] Perkins Observatory, Delaware, Ohio.

when we attempt to apply it to large telescopes, so that it will probably be many years or even centuries before the bulk of astronomical observations can be made at extra-atmospheric stations.

Having picked a site where the disturbances caused by intrinsic seeing and scintillation are at a minimum, the astronomer is next interested in knowing how best to design his telescope and observatory so that thermal disturbances in the air caused by their structure may be minimized. A number of theoretical and observational studies of the behavior of scintillation have been made at the Perkins Observatory that seem to point more and more to the conclusion that the local thermal irregularities of the air may be the predominant cause of bad image distortion (as distinguished from bad scintillation). The work of the astronomers at Paris and Haute-Provence seems to have led them to similar conclusions, so that the new 193-cm telescope for the observatory at Haute-Provence is being very carefully designed to minimize the temperature irregularities in the air in the tube and just outside the dome (see Couder, 1953). Should these efforts be successful, a major improvement in the performance of large telescopes may result.

The importance of minimizing irregular refraction in the gas inside of auxiliary astronomical equipment has been well demonstrated by the experience of observers with the new 52-foot vacuum spectrograph at the McMath-Hulbert Observatory (McMath, 1955). The steadiness and sharpness of the spectral lines were greatly increased as the spectrograph was evacuated. Doubtless there are many other pieces of auxiliary equipment whose performances could be greatly improved by a similar procedure.

Although the writer knows of no successful instruments, so far devised, to compensate for (rather than eliminate) the effects of seeing, some have been envisioned and might well be investigated (Babcock, 1953). Any device which attempts to compensate for seeing must depend, first, on knowledge of what sort of optical irregularities exist in the air; this requires study of the distortion in the wave fronts in starlight which has just passed through a layer of irregularities. The device must then make, presumably by electro-optical methods, compensating adjustments in the optical system in the telescope. Thus, if the air in a portion of the light path is unusually warm, the corresponding index of refraction will be abnormally low and the velocity of light abnormally high. As a result, a wave front tends to advance farther than it should as it passes through this region. The compensating device attempts, in effect, temporarily to move the surface of the primary mirror farther back in the area where this portion of the wave front is reflected, so that after the reflection of the wave front the irregularities have been ironed out. Methods of this type have certain drawbacks. For example, we must observe objects that are sufficiently bright to give enough photons per second to activate the device which controls the compensator; yet, enough photons must be left over to make possible the primary astronomical observation.

In the preceding paragraphs we have looked at the problems of astronomical seeing from the point of view of the typical astronomer, to whom seeing is an unmitigated evil that must be avoided or removed by whatever means come to hand. To the atmospheric physicist and meteorologist, the situation may be quite the reverse. The fluctuations in the light of a bright star, known as scintillation, are known to be caused by the motion across the telescope objective of a complex pattern of lights and darks, known as the shadow pattern or shadow bands. This shadow pattern is caused by the passage of starlight through atmospheric irregularities which must occur at a considerable height. These irregularities diffract the light and cause interference and reinforcement of the wave front at various points along the ground. A fairly complete theory of the relation between the atmospheric irregularities and the pattern of lights and darks in the shadow pattern has been developed by van Isacker (1953). With a reliable means of studying the structure of the shadow pattern, much may be said about the pattern of the density variations in the air itself. A suitable method for observing the shadow pattern has been developed by the author (1955) and by Protheroe (1955b). There seems to be considerable promise that by the use and extension of this method we might be able to obtain considerable information about the nature of clear air turbulence, its motions, its height, and how these quantities vary with meteorological conditions. At the same time, more empirical studies of the relationship between scintillation and wind velocity are being made (Gifford and Mikesell, 1953; Gifford, 1955; Protheroe, 1955a; and Mikesell, 1955).

Studies of the scintillation of radio objects are also being made, and much information about the structure of the ionosphere is being obtained (Pawsey, 1955).

To summarize, the study of astronomical seeing and scintillation is of vital interest to the astronomer in the same sense that studies of optics and radio technology are of importance to him. There is much to be learned about the subject, and there is considerable promise that with more understanding will come ways and means of greatly improving the performance of telescopes. Although seeing may be a nuisance to the astronomer, it also is a tool for making both fundamental and routine studies of the earth's atmosphere.

A few observatories in this country and abroad are making studies of both kinds. Much exciting work remains to be done and it is very much to be hoped that additional astronomers can be persuaded to take an interest in the subject.

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Spectroscopy

By Charlotte E. Moore [1]

The outlook for future research in spectroscopy is highly promising. The rocket spectroscopy of the solar spectrum, for example, extends our horizon to the shortwave region, and thus provides a far more complete picture of solar spectroscopy than ever before. The O VI solar emission lines and other observations of equally far-reaching significance demonstrate the astrophysical importance of further study of high-ionization spectra in the laboratory (Johnson, Malitson, et al., 1955). Ultraviolet standards of wavelength must be established in the shortwave region, and more term values must be worked out, particularly in spectra of the more abundant elements. Fe IV is an outstanding example of a neglected spectrum urgently needed by the astrophysicist. The coronal spectrum, the nebular spectra, and now the spectra of distant galaxies, whose lines are shifted further and further to longer waves, all show that further study of ultraviolet spectra is extremely important.

In the longwave region, beyond the photographic range, the development of suitable heat detectors has extended the astrophysical vista, as well as that of the laboratory, to the far infrared, and microwave spectroscopy has extended it still further. With the astrophysical range from Lyman alpha (1215 A) to the 21-cm wavelength of hydrogen, our studies can no longer be limited to selected regions of the "visible" spectrum.

Among high-dispersion stellar spectra the sunspot spectrum is one of the most challenging. Hundreds of spot lines have not yet been measured; many of them are doubtless of molecular origin. Furthermore, no homogeneous set of sunspot spectrograms exists. During the coming sunspot maximum, high-dispersion sunspot spectrograms should be taken with the same spot, over the whole spectral range. This is a taxing but vital program.

Our knowledge of stellar spectra is far from complete. Any study of abundances requires correct identifications of the lines, together with a knowledge of the excitation and ionization energies of the separate atoms and ions. P. W. Merrill has recently reported that in the Se star, R And, there are some 275 unidentified absorption lines between 4000 A and 6900 A. J. Greenstein has observed several hundred unidentified lines in υ Sgr. (see Merrill, 1956). In the solar spectrum about 30 percent of the lines are still of unexplained origin. These and other similar examples demonstrate how much work is yet to be done in spectroscopy. This need is reflected in the persistent demand, among astronomers, for a new, large, revised multiplet table that extends from the far ultraviolet to the extreme infrared.

These demands impose upon the laboratory spectroscopist the task of observing and analyzing more atomic spectra, and also of selecting spectra to be studied that anticipate future astrophysical needs. The use of modern sources, such as electrodeless discharges and infrared detectors, is one of the most promising approaches to the subject. Earlier descriptions of atomic spectra are not only lacking in faint lines but are incomplete, also, because of masking by oxide bands. The electrodeless discharge has the advantage in atomic work that it can be controlled in such a way as to suppress molecular lines. More than 1,200 Fe I lines have been identified in the solar spectrum by prediction from the known atomic energy levels. A suitable laboratory source of excitation would doubtless excite these and many more faint lines. Kiess has already observed a number of the predicted Fe I lines in selected regions. Edlén's (1953) observations of CA II in the infrared have resulted in the identification of

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[1] National Bureau of Standards, Washington, D. C.

four new multiplets among solar lines. For many familiar spectra there exists no complete or homogeneous set of observations. Modern equipment and techniques could be used to good advantage in improving this situation.

The spectra of the rare earths are the most conspicuous group that needs study. Within the next 3 years it is planned to enlist the services of all available experts in attacking this difficult problem. Volume 4 of "Atomic Energy Levels" will be devoted entirely to rare-earth spectra. This program should provide the astrophysicist with a wealth of new data. In order to disentangle the intricacies of these spectra, the assistance of theoretical investigators to predict the positions of the terms of various configurations is needed. This problem leads to use of digital computers in solving large matrices. Here is a useful field of activity in theoretical problems that parallels the laboratory and astrophysical research.

The comments just given apply chiefly to atomic spectra, but a wide vista appears, also, in molecular spectroscopy. For example, the use of controlled flames as a source makes it possible to bring out certain band spectra and suppress others. Precise laboratory measurements and analyses, particularly for diatomic molecules of the more abundant elements, are sadly needed. The writer is continually receiving requests for a critical compendium of molecular data paralleling the volumes on "Atomic Energy Levels." In solar and spot spectra alone this subject is far from completed and promises interesting results in future astrophysical research.

Spectroscopy embodies, also, the study of line intensities, equivalent widths, and curves of growth—all rewarding subjects for future research, particularly with high-dispersion stellar spectra. Just as in the case of spectrum analysis, measured laboratory intensities are required to increase our knowledge of abundances of elements. This phase of the work must be carried on for years to come.

The door is open and the opportunity is rich for the student interested in spectra. The more unusual examples of astrophysical identifications—nebular lines, coronal lines, solar emission lines of high ionization, and technetium lines in the S-stars—all challenge the astrophysicist and in themselves more than justify active financial support of spectroscopic research in the laboratory, in theoretical fields, and in the observatory.

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Radial Velocities

By R. M. Petrie[1]

The measurement of the line-of-sight component of stellar motion ranks among the early achievements of stellar spectroscopy. The principle was announced by Doppler in the middle of the 19th century and was extended and elaborated by a number of astronomers and physicists soon after. The first applications were made by visual methods and are now of historical interest only. The subject did not attain full stature until the introduction of photographic methods during the closing years of the century, but it then became at once a highly successful and valuable technique of astronomy. Although radial-velocity work is thus about 60 years old, it is still of prime importance and promises to remain an indispensable tool in many branches of astronomy. The pursuit of this work is not successful without a considerable expenditure of patient effort, but the student may look to it to bring substantial rewards for his labors. He may, with profit, reflect upon the prophetic words of Huggins: "It would scarcely be possible, without the appearance of great exaggeration, to attempt to sketch out even in broad outline the many glorious achievements which doubtless lie before this method of research . . . ."

In this article attention will be directed to present activities and some probable future needs. The development of our subject from the beginning, outlined above, is described in the first part of Campbell's "Stellar Motions," published in 1913.

Spectrographs

After the introduction of photography the main question to be answered was how accurately the spectrograph could record the positions of stellar absorption lines with reference to some terrestrial comparison source. The Doppler shift is always small and great care is necessary to avoid spurious instrumental shifts such as, for example, those introduced by mechanical flexure, temperature variations, and faulty optical components. The development of reliable instruments such as those at Potsdam, Mount Hamilton, or Victoria may be studied in an article by Eberhard (1933). The main problems of design have now been solved, and there exists a considerable number of instruments capable of yielding accurate radial velocities.

Some problems of instrumentation remain as a challenge to the student. The following are examples of these.

Gratings.—The development of the "blazed" grating of high efficiency opens a field for application to radial-velocity work in the visual region. Spectral types of F 5 and later may be studied effectively in this way, which offers two important advantages. First, the spectra are simpler in the visual region, so that one can minimize the troublesome problem of using "blended" lines; and, second, many stars are brighter in the visual than in the usual photographic region. A successful grating spectrograph has been constructed and used by Merrill (1931), and of course the powerful coudé spectrographs of the largest telescopes employ gratings as the dispersive units. There is still room, however, for experiments in the most effective use of gratings in radial-velocity work with moderate dispersion.

Long-focus instruments.—The great power of modern coudé spectrographs lends itself well to radial-velocity investigations requiring the highest precision. It is not yet known with certainty whether the long-focus collimator and wide-slit spectrograph fed by a combination of three to five mirrors realizes the potential accuracy of the very high dispersion. We want to know, on the one hand, whether the wide

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slit (relative to the stellar image) has limited the accuracy because of the introduction of guiding errors; on the other hand, we want to know whether the multimirror system has preserved full "identity of source" between stellar and comparison spectra. Experimental work to answer these questions needs to be undertaken as a preliminary to radial-velocity work of the highest precision. As an example of the inherent possibilities, one may refer to Adams' (1941) spectroscopic determination of the solar parallax.

Comparison spectra.—Present practice generally is to use an arc, or spark, in air, with the most convenient metals being iron or titanium. These sources are fairly satisfactory but are not entirely constant unless a number of precautions are taken. It is possible that a better source can be found in some modification of a discharge tube such as the hollow cathode type recently described (Edlén, 1955).

The greatest obstacle to the study of stellar motions through radial velocities is the slow rate at which spectrograms and measures accumulate. The slit spectrograph, while accurate, is very wasteful of starlight and ordinarily utilizes only a few percent of the incident light. As a result we are, for example, almost totally ignorant of the radial velocities of stars of apparent magnitude 10 and fainter. Fifty years of work have yielded velocities for some 15,000 stars, but this sample is much too small for galactic studies, and current progress is slow. A major effort and a new attack are obviously required if the study of stellar dynamics is not to be hampered by lack of observations. Fortunately there is now some hope of improving matters through two different current developments.

Slitless spectrographs.—The idea of removing the spectrograph slit and collimator and thus photographing with one exposure the spectra of of a field of stars is an old one. An account of the early experiments with objective prisms is given by Millman (1930).

Until recently the objective-prism work fell short of its goal because of the presence of field distortions and instrumental errors exceeding many times the Doppler shift. However a series of important experiments by Fehrenbach (1947, 1948) have resulted in the development of an objective prism free from distortion, and studies by Treanor (1948) and Schalén (1954) have verified and extended this result. A wholesale accumulation of radial velocities of faint stars is now in prospect; continued experimentation and application are sure to bring rich rewards. Already the "mean errors" have been reduced to about ±6 km/sec, and this is sufficient for application to many problems in galactic motions and structure.

Image convertors.—Another promising development is the image convertor, which is capable of high efficiency and may ultimately replace the use of photographic plates in recording stellar spectra (Argyle, 1955). Considerable experimentation is now going on to improve this technique and to apply it to stellar spectroscopy. The subject is well worth the attention of the student who wishes to make a contribution to radial velocity work.

Measurement

Doppler shifts are, generally speaking, very small and their successful measurement calls for painstaking care and experience. The labor of measuring the stellar and comparison lines on several hundred spectrograms is considerable and often hampers the progress of a program.

The measurements were made originally with the aid of a direct-vision microscope mounted above a traveling micrometer, or, in the Hartmann comparator, spectra were matched against suitable "standards," again with the aid of a microscope. The fatigue accompanying this process was lessened, some years ago, by the introduction of projection methods (Petrie, 1937; Redman, 1939). A further improvement was made at Victoria when a new type of projection instrument (Petrie and Girling, 1948) allowed one to measure the Doppler shift directly upon the projected image and, by virtually eliminating the "reduction," gave a substantial increase in efficiency. Indeed, so useful is this projection comparator that the measurement and reduction of spectrograms is no longer a serious obstacle to the completion of a heavy radial-velocity program.

The obvious advance to be made now is the development of an automatic machine that will remove the subjective errors and allow an impersonal definition of the precise position of a stellar line relative to the comparison spectrum. A machine of this sort has been built by Johnson (1949), and another of different type by Hossack (1953). In spite of these ingenious machines there is still room for experimentation and development. The technical aids already exist and it is fairly certain that the present generation is the last that will be required to measure Doppler shifts with hand and eye. A real triumph awaits some student equipped with a sound knowledge of modern electronic aids.

A word of caution may be permitted here. An automatic machine does only half the job if it merely presents one with the measured positions of stellar and comparison lines. The calculation of a radial velocity from the engine readings requires nearly as much time as the original measurement. The ideal machine, therefore, will measure the *shift* of the spectral line from its zero-velocity position and so allow the rapid deduction of the radial velocity.

Wavelengths

The radial velocities deduced from the measured positions of spectral lines are, of course, very sensitive to the accuracy of our wavelengths. We recall that in the photographic region an error of 0.1 A is equivalent to 7 km/sec. A firm knowledge of wavelengths is a prerequisite to a significant knowledge of motions.

The practical difficulties are considerable. Radial velocity programs usually force one to employ a spectroscope of low dispersion and purity; with such an instrument all spectral features in types later than A 0 are blends of two or more lines. The effective zero-velocity wavelength of a feature depends upon the relative intensities of the blending lines, the spectrographic resolution, and the amount of stellar rotation and other line-widening influences. Even in early-type spectra difficulties sometimes arise because of blends, stellar rotation, and Stark effect.

At Victoria a good deal of attention has been devoted to the matter of effective wavelengths and it is believed that satisfactory methods and values have been established (Petrie, 1946, 1947, 1948, 1953; McDonald, 1948; Wright, 1952). The problems must be faced anew with each new spectrograph and vigilance is necessary to ensure that the deduced radial velocities are, in fact, motions and not spurious displacements arising from uncertain, or incorrect, wavelengths.

In spite of the work already done on this subject, more is required. We do not, for example, have a satisfactory set of standard wavelengths for O-type spectra and cannot, therefore, be entirely certain of their motions in star "associations" nor of their apparent "red shift" as members of galactic clusters. And, at the other end of the temperature sequence, we lack effective wavelengths for low-dispersion spectra of N stars. This is of some importance since we need to know the space motions of a larger number of these (apparently) faint objects.

Applications

The application of radial velocities leads us into the subjects of stellar dynamics, galactic structure, binary stars, etc. These topics are being discussed elsewhere in this compilation and the writer will therefore merely point out some of the possibilities awaiting the astronomer who devotes himself to radial velocities. The worker who undertakes to supply the fundamental observations of stellar motions can be sure that his contribution is of permanent value to astronomy. He must therefore be patient and content to see his work gradually increase as his programs and plans are completed.

The general problems of stellar motion remain with us: solar motion, star streaming, galactic rotation, and mean velocities in different parts of the galaxy. The need is always for more observations and observations of more distant stars. For a general description of present-day need one should refer to the report of the International Astronomical Union Symposium on "Co-ordination of Galactic Research" (Blaauw, 1955).

The measurement of galactic rotation is of prime importance. We require a more accurate knowledge of Oort's constant A in the neighborhood of the sun. Current programs of B stars at the Radcliffe and Dominion Astrophysical Observatories will supply about 1,000 new velocities, mostly within a distance of

1,500 parsecs of the sun. These, together with existing observations, should give a good determination of the coefficient of differential rotation in our part of the galaxy.

The more distant regions are quite imperfectly studied. With the recognition of spiral arms about 2,000 parsecs away, it becomes an exciting task to discover what velocity effects exist at the edges of the arms and between them. This means we must observe large numbers of spiral-arm objects—early B stars, Cepheids, and supergiants of types B 8 to A 3. At the same time we must measure the speeds of the interarm population which will probably consist of stars of Population II together with a number of stars that have wandered out of the spiral arms. Observations of the early-type stars will also reveal the motions of the interstellar matter.

A problem of considerable interest is the stellar velocity distribution perpendicular to the galactic plane. This may be found from radial velocities of stars near the galactic poles. The observation of the brighter stars of types A 0–F 5 within 10° of the north Galactic Pole is now nearing completion at Victoria. A companion program of fainter stars is proceeding at Mount Hamilton. In this branch of stellar motion work much remains to be done. Extensive observations are required among the later-type stars of the disk population and, on the other hand, of the faint blue stars of (probably) Population II. From the velocities of the disk population we can determine the density of matter in the galactic plane region, in the neighborhood of the sun.

The above proposals involve observations of many stars and are rather long-term projects, but much may be done in other directions where shorter programs will bring valuable results. Some of these are suggested very briefly in the following paragraphs.

Star clusters and associations.—These fascinating groups are of first importance in studies of stellar luminosity and evolution. Radial-velocity observations are needed to verify cluster membership and to calculate space motions. Careful and extensive observations of the "aggregates" and expanding associations must be made before we understand the kinematical properties of these groups. The study of clusters and associations is sure to yield important and exciting information.

Stellar atmospheres.—Recent work on supergiant stars and special eclipsing stars, such as 31 Cygni and ζ Aurigae, shows how radial-velocity measures reveal the existence of atmospheric motions. This is a little-explored field and requires study with highest possible dispersion. Comparisons between giant and main-sequence stars of the later spectral types will be valuable in promoting knowledge of the stability of stellar atmospheres.

Variable stars.—Experience has shown that variable stars should be studied with simultaneous spectroscopic and photometric measures. The observations of Sanford (1952) and Abt and Sanford (1954) on the Cepheid variable W Virginis and of Struve (1954) on BW Vulpeculae are good examples. The work to be done here is limitless, considering the great range of stellar variation. To be most fruitful, the highest possible dispersion must be used.

Binary stars.—The problems of binary stars are legion, but perhaps no other field offers more challenges calculated to advance our knowledge of stars.

Visual binaries should be observed continuously so that, ultimately, the combination of spectroscopic and micrometric data will tell us the dimensions and luminosities of the components. Similarly, eclipsing binaries should be observed assiduously, especially those with determinate light elements and those showing the spectra of both components. Our knowledge of stellar masses, radii, and luminosities, as well as further extensions and verification of the mass-luminosity relation, must come from this work. Radial velocity observers will find it a rewarding task.

The bewildering array of spectroscopic anomalies exhibited by the close binaries has been brought to our attention by Struve (1950). The observation and interpretation of radial-velocity curves are an endless challenge. One suspects that the most potent observational aids will be required to advance our understanding of these spectacular phenomena.

Stellar satellites.—The discovery of planetary systems is probably just within the powers of the most precise radial-velocity measures that can be made with existing equipment. This has been shown by Struve (1952), who proposed that a search be made. It may be that a major astronomical discovery will result from the meticulous observation of a number of our nearby and bright stars.

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Astrometry

By K. Aa. Strand[1]

Astrometry deals with the space-time behavior of the stars, and thus belongs to the classical field of astronomical studies. While the early investigations were directed mainly towards establishing a suitable frame of reference for determining the complex motions of the planets, studies of the positions and motions of individual stars, as well as of the various stellar systems, gradually developed.

If one examines the observational data accumulated in astrometry, the record is indeed impressive. During the past 150 years more than 370 catalogs of meridian observations of stars have been published. We have monumental astrographic catalogs like the Carte du Ciel, the Astronomische Gesellschaft catalog (AGK2), and the Yale zone catalogs, to mention only the largest. The Yale General Catalogue of Stellar Parallaxes lists the distances for nearly 6,000 stars measured since the beginning of this century, and the Burnham and Aitken double star catalogs collect more than half a million micrometer measures, the result of a century's work.

Considering this impressive observational record, it is not surprising that a person who has not worked in astrometry usually assumes, mistakenly, that most of the work has been completed. Our knowledge of such properties of the stars as their masses, luminosities, and motions depends directly or indirectly upon the available astrometric data, and any improvements to be made in these parameters will depend upon further work in the field.

What future work is needed in astrometry to broaden our general knowledge of astronomy? A whole series of problems confronts us. They range in size from those that can be investigated only by close cooperation among many observatories to those that can be solved by a few astronomers in a single observatory; and in complexity the problems range from setting up an accurate reference system of stars covering the entire sky to determining the parallax of an individual star.

A series of conferences held during the past two years at Groningen, Evanston, Pulkovo, and Brussels has resulted in general agreement that, to solve many present-day problems, astronomers must undertake an international program of meridian circle observations. The program, starting in 1956, will consist of observations of nearly 21,000 stars brighter than 9.1 magnitude north of declination −5°. The total number of observations, including those required of the fundamental stars, will amount to 260,000, since each star is to be observed 10 times. Twelve observatories will participate, and by using timesaving devices in both the observational and reduction phases of the program, they expect to complete it in 5 years. American astronomers should note with some pride that the U. S. Naval Observatory will carry out a substantial part of the observations and will also supply, on request, the reductions to the day and to the equinox 1950 for all the stars observed. The U. S. Naval Observatory will also compile the final catalog of positions for these stars.

What information will this large undertaking give us? It will provide a reference system of stars with greater density and precision than any previous system; and it will make possible the solution of problems that could not be solved without it, some of which may be summarized:

1. The program will provide a reference system for the AGK3, the second photographic observation of the stars in the Astronomische Gesellschaft Katalogs, which when compared with the AGK2 will lead to accurate proper motions for approximately 180,000 stars brighter than 11.5 photographic magnitude. Dr. Vyssotsky

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of the Leander McCormick Observatory and his associates will supply spectra for approximately 60,000 stars not previously classified.

2. About 11,500 of the stars in the reference system will be used in the Russian program on stellar proper motions relative to extragalactic nebulae.

3. The proper motions determined from the AGK2 and AGK3 will provide the systematic corrections that are needed to make use of many of the older star catalogs.

4. The results from the AGK3 will provide the necessary data to reduce to absolute the proper motions obtained from a reobservation of the Carte du Ciel plates.

5. The stars from the AGK3 could be used as reference stars for the Lick Observatory program, which expects to determine proper motions of stars with respect to extragalactic objects.

It is gratifying to note that it is still possible to undertake large-scale programs requiring careful international cooperation, for which astronomy is conspicuous among the sciences. However, it should be observed that the burden of American participation in the AGK3 rests solely upon the U. S. Naval Observatory.

Because the Lick program of deriving proper motions of stars with respect to extragalactic objects will yield important scientific results, it should receive the support necessary for its completion. The Lick program will provide absolute proper motions of stars down to the 17.5 photographic magnitude, resulting in data that can be expected to yield corrections to the adopted values of precession and lead to new determinations of solar motion and galactic rotation. The most distant stars in the Lick survey will have distances of more than 2 kiloparsecs and thus reach beyond the region of the maximum circular velocity, as indicated by the Oort model. This study should settle the present discrepancy between the data on galactic rotation, as obtained from proper motions and from radial velocities.

If the Lick survey is to attain the needed minimum accuracy, a time interval of approximately 20 years must elapse between first- and second-epoch plates. This means that the complete repetition of the Lick plates will not begin until 1967. How soon after that date the program will be completed depends upon the methods of measurement and of reduction. It is quite clear, however, that the program is of such magnitude that it requires the utilization of the latest developments in automatic or semiautomatic equipment to complete it without prolonged delay.

Since the value of the Lick program would be much enhanced if it could be extended to the southern sky which is not observable at the Lick Observatory, serious consideration should be given to extending the program to the Southern Hemisphere. In view of the small number of observatories south of the equator and the magnitude of the problems that already confront them, this program probably should be undertaken by an observatory in the Northern Hemisphere. It remains to be investigated whether a telescope identical with the Lick 20-inch Carnegie astrograph should be constructed or whether, as suggested by Dr. Luyten at the Meeting of the International Astronomical Union in Dublin, a limited number of plates taken with the Bruce telescope would serve the purpose.

Photographic astrometry with long-focus refractors is traditionally a field in which American astronomers have held the leadership; here, also, we face a series of problems which must be solved for further progress in astronomy.

It has long been known that the trigonometric parallaxes are affected by systematic errors; whether further statistical investigations of the existing observations will provide additional information on this problem remains doubtful. The systematic errors have, of course, the most serious effect upon the small parallaxes; but the absolute magnitudes of giants and subdwarfs, which are scarce in the solar neighborhood, are therefore derived from a relatively small number of small parallaxes and thus are also affected by large systematic errors. To improve this situation it is essential that many of the small parallaxes be repeated, and that the observational series for the individual stars be increased from the 20 plates or less used in the very early work to 50 plates or even more. These determinations would add to our knowledge of the absolute magnitude of the stars just mentioned, and would also serve as important statistical material for further investigation of the systematic errors in trigonometric parallaxes.

The stars of low luminosity in the solar neighborhood, discovered in the Luyten proper motion survey, are another group for which we need determinations of trigonometric parallaxes. The great majority of these stars, late-type M-dwarfs, subdwarfs, and white dwarfs, are considerably fainter than any we can observe with the telescopes now being used for parallax work. These telescopes cannot reach stars much fainter than the 12th magnitude, but most of the known white dwarfs are fainter than the 14th. For this reason, the commission on parallaxes and proper motions of the International Astronomical Union recommended at the recent meeting in Dublin that observatories possessing large reflectors seriously consider a program of determination of trigonometric parallaxes of faint stars.

Other aspects of the use of long-focus refractors are the positional study of the stars within 10 parsecs by an extended series of plates to discover perturbations for "single stars," and the subsequent orbital analysis of these perturbations. Quite recently such a study led to the visual discovery of a binary (Ross 614) in which the companion has only 8 percent of the sun's mass.

When we examine the relation of astrometry to the double stars, we find a series of problems which deserve the attention of modern astronomy. For the double stars within 20 parsecs, it is possible to derive stellar masses with an accuracy of 25 percent or better; to attain this accuracy, however, visual and, whenever possible, photographic observations of the relative motions are needed as well as extended series of plates from which the mass ratios and parallaxes can be derived with great precision. Much information in regard to stellar masses has been obtained in this way over the past 15 years, but much more is needed. This group of binaries constitutes only about 1/1000th of the approximately 40,000 known binary systems. To observe them all would clearly be an impossible task; nevertheless, many of them must be observed if we wish reliable data on such questions as statistical distribution of the orbital elements in binaries and combination of spectra in physical pairs. These are only two of the questions that have a bearing on stellar evolution and which we cannot answer by studying the small group of known binaries within 20 parsecs of the sun.

Problems of membership and internal motions in clusters will become even more important as the time interval between early- and late-epoch plates increases the accuracy. The early Carte du Ciel plates and those taken with the large refractors shortly after the beginning of this century are especially important in that respect.

One of the most recent additions to astrometry, the study of the age of the O–B associations from their expansion, deserves high priority, and it is to be hoped that the large meridian programs in connection with the AGK3 will still permit the stars selected for this study to be observed with utmost precision. A similar program on Cepheid variables, to trace the positions of the spiral arms in our galactic system, also deserves special attention.

Lack of manpower to carry out the many important problems just outlined remains a problem. We may summarize briefly what we require in instrumental developments to solve this question. The staff of the U. S. Naval Observatory has, over a period of years, introduced timesaving devices that have increased the speed as well as the accuracy with which the stars are observed, and because of the use of IBM machines the reductions of the observations are no longer lagging behind as in the past.

In photographic astrometry the use of automatic devices in guiding, plate transport, and timing has resulted in increased accuracy in certain problems, but the real problem here is to develop equipment that will effectively shorten the time required for measurement and reduction of the photographic plates. One measuring machine, allowing semiautomatic measurements and operated in connection with IBM machines, is already in use. Since the operating costs of this system are prohibitively high for most

American observatories, it seems desirable to look into other recent technical developments which might aid in reducing the time spent at the measuring machine without requiring a highly expensive computing system.

In this brief report it is not possible to mention all phases of astrometry that deserve attention. However, those outlined show that in spite of, or rather because of, the huge amount of work done in the past, there are still many interesting and important problems on which progress in astronomy depends; therefore, they deserve the attention of the active research workers in astronomy.

Photoelectric Astronomy

By A. E. Whitford[1]

The past two decades have seen increasing use of photoelectric methods in all branches of astronomy where quantitative measurement of radiation is important. This trend seems destined to continue. In the years ahead the photoelectric cathode may become the most widely used radiation detector in the astronomical tool kit; indeed, it may supplant the photographic plate in the same way that the plate supplanted the human eye 50 to 60 years ago.

A brief review of the links in the information chain along which knowledge about the external universe must pass will show the reasons for believing that photoelectric methods may assume a dominant place. The light beam from a distant luminous source, which carries all the information the astronomer will ever have about that object, arrives at the surface of the earth after some losses in the interstellar medium and in the earth's atmosphere. The atmosphere adds an unwanted background glow, and, at times of bad seeing, diffuses the beam somewhat. The potential information in the light beam suffers a loss and degradation before it enters the astronomer's instrument that are for the most part beyond his control. Some day the astronomer may get above the atmosphere, but he will not get beyond the interstellar medium. Meanwhile, he must make sure that his earthbound instruments do the best possible job of extracting all of the information remaining in the light beam.

The astronomical telescope has long since reached a state of perfection where the tranquility of the atmosphere, rather than the quality of the optics, determines the image quality. The astronomer may, in theory, gather more information by increasing the aperture, but the engineering difficulties and the cost both rise steeply for any considerable increase in size over that of existing telescopes. The final link in the information chain, the radiation detector at the focus of the telescope, is therefore the element which must be scrutinized for possible lack of efficiency. If the efficiency is low, improvements can be counted as equivalent to increasing the aperture of existing telescopes.

The various practical detectors in actual use can be evaluated by comparing them with a hypothetical ideal detector that recorded the arrival of each quantum, and did it with 100-percent efficiency for all accessible wavelengths of the astrophysical spectrum. The photographic plate cannot be given a very high mark in such a comparison. Since it is a saturable, nonlinear device, no unique quantum efficiency can be assigned. But in the range of densities favorable to contrast-judgments by the human eye, only about 1 quantum in 1,000 is recorded by producing a developable plate grain. Its ability to integrate a long exposure is the reason for its superiority over the eye in detecting faint stars and recording low surface brightness; the eye makes its decision in about ⅙ second. Within that ⅙ second the eye, as shown by Rose (1948), is a better detector than the photographic plate. The eye cannot, however, deliver the plate's objective record of thousands of details or the extremely precise positional information needed for astrometry.

The cesium-antimony cathode is the one most widely used in astronomical photometry. It has a useful range of 3100A to 6000A. The average quantum efficiency at the peak near 4400A is 12 percent, and exceptional tubes go as high as 25 percent. There is thus a superiority of a factor of the order of 100 over the photographic plate in the initial information made available in a given time from a given angular area on the sky. As presently used, only one chosen element or area may be measured at a time; if photometric information on

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many objects in one field is needed the photographic plate is a great timesaver. But the superior quantum efficiency of the photoelectric cathode is the basic reason why it seems destined to play an increasing role in measurements of astronomical radiation.

In order for the favorable quantum yield to be useful, there must be no instrumental background or amplifier noise large enough to degrade appreciably the information contained in the released photoelectrons. Existing techniques succeed quite well in approaching this ideal and further efforts can be expected to produce only small improvement. There is not much to choose between any of the three currently used methods of registering the output of a phototube: current measurement with a load resistor, charge integration with a storage condenser, and charge integration by pulse counting. At the lowest intensities integration methods will probably find increasing use.

The future uses of the photoelectric method in astronomical photometry are of course not entirely predictable. The only really safe prediction is that new and ingenious applications of the method, not now foreseen, will surely be devised. A projection of the presently successful techniques suggests activity in three main areas. In general, these exploit the basic advantages of the photoelectric process: high quantum yield, linear response, and wide spectral range.

Intensity comparisons: Magnitude systems

The range of intensity between the sun and the faintest stars yet detected is of the order of 10^{20}. Important astronomical conclusions, such as the cosmic distance scale, depend on the precision with which this range is covered. The superior accuracy of the photoelectric method rests in part on its higher quantum yield, in part on its linearity. Elimination of the step calibration needed by the nonlinear detectors such as the photographic plate not only saves a great deal of time but also removes a fertile source of accumulated error. An intensity range of 10^4 to 10^5 can be covered with one phototube and a single optical system.

The task of calibrating magnitude systems is already largely a photoelectric province. Photographic interpolation between photoelectrically established standards in the field of a star group such as a globular cluster (e. g., as by Arp, Baum, and Sandage, 1953) will continue to be used where photoelectric measurements of one faint star at a time would be too time-consuming. But for transfer of standards from Selected Areas, photoelectric methods appear to be needed for good accuracy. The time is rapidly approaching when every observatory which does any photometry at all will think of the plateholder and the photoelectric photometer as routine interchangeable attachments to the telescope, each to be used as occasion demands.

Since photoelectric methods require the use of the telescope for only one object at a time, and the reductions are also quite time-consuming, magnitude measurements have thus far been restricted to specific classes of stars, such as B-stars and Cepheid variables, and to the establishment of standards in Selected Areas or star groups under special study. A determined effort might provide instrumental and computing aids which would make mass production of magnitudes more economical. These might include better coordinate mechanisms for rapid identification and centering of stars, automatic subtraction of sky readings, automatic computation of extinction and correction of the star signal for it, a logarithmic amplifier to give direct reading magnitudes, and direct processing of telescope output onto data storage records such as punched cards. Then it might not be too enormous a task to do what Irwin (1955) suggests, and undertake to provide accurate photometric data for all the stars, say, in the Henry Draper Catalogue. A massive attack by one observatory could accomplish it; it would be a public-spirited endeavor, to be viewed as a repayment of the scientific debt owed to previous generations for the patient determination and compilation of star positions, spectral types, radial velocities, and proper motions. It would at least correct the present incongruous situation where the simplest and most fundamental datum about a star, its brightness, is often the least reliable entry in the catalog.

Color systems and spectrophotometry

The advantage of the photoelectric cathode in color studies stems partly from its wide spectral range, partly from its linearity. The simple ratio of the intensity through two color filters gives a good color index without the need of establishing two magnitude scales as in the photographic method. Because the photoelectric color index comes from a differential measurement, the internal accuracy is higher than for the magnitudes themselves. A two-color index provides the minimum amount of information about a star. The wide spectral range of a photoelectric cathode permits three or even five narrow-range colors with a cesium-antimony cathode. The range may be extended to 10,000A or more with a cesium-oxide cathode and the number of color filters extended to six or seven. The next step is to scan the whole range with an exit slit on a spectrograph. The observing time per star goes up because of the limitation that only one element of the spectrum can be observed at one time. High-resolution photoelectric scans of short portions of the solar spectrum have been made, and similar scans will undoubtedly be attempted for the brightest stars. Over the whole range, however, a resolving power of about 350 gives a reasonable observing time per star and adequate delineation of the main features of the continuous spectrum.

The color of a star is already recognized as a necessary part of a photometric determination of its distance in order to evaluate the interstellar reddening. For early-type stars, at least, three colors on the U–B–V system of Johnson and Morgan can give a measure of reddening when the spectrum is not known. Extension of this powerful method to later-type stars, and to the longer wavelength portions of the spectrum where the interstellar absorption is less, would be a great help in galactic and extragalactic distance determinations.

Determination of the absolute energy distribution in normal Type I stars will be worthy of considerably more work over the whole range that can be covered with existing photoelectric cathodes. From such studies can come better model atmospheres, and from these, in turn, higher accuracy in quantitative studies of nuclear abundances from line strengths. Comparison of these "normal" stars with Type II stars and peculiar stars by multicolor or scanning methods should be most informative. Examples would be subdwarfs, metallic line stars, and pulsating stars of all kinds. Differences of composition or structure may be expected to leave clues in the continuous spectrum; accurate photometry will be needed.

Composite sources are another fruitful field for multicolor studies. Globular clusters and galaxies are examples. The resolving power in distinguishing between various syntheses of the over-all energy distribution from hypothetical mixtures of known stellar types may never be very high. But a combination of spectra, of counts of brightest stars of identifiable types, and of over-all energy distribution may lead to fairly definite conclusions. The diffuse nature of these objects precludes anything but low resolution spectrophotometry by the scanning method, and for faint objects multicolor filter photometry may be the best that can be done. Their low contrast with the sky can be handled cleanly by the differential subtraction methods so easily applied in photoelectric photometry; and photoelectric accuracy will be needed. Photometry of distant galaxies for diameter and magnitude (as suggested by Baum, 1953) and for energy distribution (Whitford, 1953) will provide evidence of the state of affairs at a much earlier era in the evolution of the universe, and will thus be of interest to those concerned with cosmogony.

Differential measurements

Light curves of eclipsing binaries provided one of the early demonstrations of the precision attainable by photoelectric methods. The accuracy was due partly to the linear response, and partly to the differential comparison of variable and comparison star, thus minimizing variable factors in sky and apparatus. The fundamental information about stars derivable from precision light curves of eclipsing variables will continue to offer attractive possibilities to the photoelectric observer with a small- or medium-sized telescope. For reconnaissance purposes other methods will continue to be of value, but the precision needed for deriving properties like limb darkening requires photoelectric accuracy.

Linear response is a great aid in all manner of differential measurements because simple subtraction is possible. Alternation of fields once a minute or oftener is one way of doing this. The flicker or a. c. method is another, and it may give a better elimination of unwanted extraneous factors. One example is the measurement of very faint stars or galaxies which add only a few percent to the sky radiation that comes through the smallest usable focal-plane diaphragm. Nebulosity of low-surface brightness would be another example. Extension of flicker methods to this type of measurement would be a logical development.

Wherever it is possible to "put a tag" on the wanted signal, it can usually be lifted out of an overwhelming background by differential methods, often involving a. c. amplification. One example would be the polarization of starlight (Hiltner, 1949, and Hall, 1950); another would be measurement of solar magnetic fields (Babcock, 1953) where the modulating element again involves polarization. These flicker methods have been highly developed in radio astronomy where the signal may be 100 to 1,000 times smaller than the unavoidable noise. Further use of the technique in photoelectric astronomy seems likely.

Possible advances in technique

If photoelectric astronomy continues under the restriction of one picture element at a time, what developments might extend its range of usefulness? At the head of the list would come a more sensitive cathode for the red and infrared where the quantum efficiency is now 20 times poorer than for the blue. This region of the spectrum may assume increasing importance for two reasons: Interstellar absorption is greatly reduced, and discovery level or penetrating power correspondingly increased; and at very large red shifts, extragalactic systems carry not only their energy maximum but also all the parts of the spectrum ordinarily studied into the red region. A high-efficiency photoelectric detector would greatly facilitate investigations in these areas. A new tri-alkali cathode (Sommer, 1955) promises considerable improvement in the red as far as 7500A. Germanium phototransistors may be developed sufficiently to fill the need as far as 16,000A.

Some reduction in observing time can be realized by using two or more phototubes, fed by beam-splitters, or by several different outputs of a spectrograph. The most exciting development in photoelectric astronomy, however, would be an image tube that would preserve the high quantum yield of a cathode, while responding simultaneously yet separately to all the bits of information in the various area elements of the image plane. Such a development seems to be a definite possibility. The techniques being explored, as explained by Baum, have been reported by Struve (1955). Work is actively in progress in France, England, and the United States.

In its simplest form, that first introduced by Lallemand, the image tube consists of an electron lens system for focusing the accelerated photoelectrons in an image on a photographic plate at the end of the tube opposite to the cathode. Every electron sensitizes a plate grain, thus preserving the high quantum efficiency of the cathode. The same number of developable grains is achieved in a much shorter time than would be needed in direct exposure of the plate to light. A fine-grain plate may be used without loss of speed, thus increasing the number of bits of information in a given image area before saturation sets in. As yet, exposure times adequate for showing an intensity level as low as the night sky have not been possible, and the anticipated gain in threshold detection level has therefore not been realized.

A proposed alternative scheme involves storage of the released charge on a mosaic, as in the image orthicon. This is later wiped off by a scanning electron beam, and the effect on the beam is the signal from that element.

While a great deal of hard work remains, there appear to be no insuperable difficulties in the way of final success. If such a tube comes, what will be the first applications? Reduction of prohibitively long exposure times in photographic spectroscopy would be one of the first. All-night exposures would be reduced to a few minutes. Spectra of faint galaxies, so important in considering cosmological questions, would become fairly routine. On direct pictures of the sky a detection limit 2.5 magnitudes fainter should result, because 100 times as many countable events go into the decision as to whether one picture element (say the size of the seeing tremor disk) has received a statistically significant excess of photons from a star during the exposure time.

While high quantum efficiency and accurate imaging can be realized in an image tube, it may be doubted whether the linearity and other photometric advantages of a single phototube can be preserved through the whole process. Nevertheless a successful image tube would bring many observations, now utterly unattainable, into the realm of the possible. In the rich harvest that would follow its introduction, there would almost certainly be some unexpected discoveries.

Conclusion

As one looks ahead, it seems clear that the next decade will see increasing use of the photoelectric process in astronomical photometry. Wherever two quantities of radiation have to be compared, the photoelectric method will be the preferred method if time permits. Should the image tube come into common use, a revolution in astronomical observing methods may ensue. It is not impossible that the whole field of the detection and measurement of radiation may pass from the present state of low efficiency to something approaching the ideal state where every quantum is counted. It would then resemble the present state of optics as an astronomical tool: no revolutionary improvements could be expected. But even then, as now, astronomical advances will depend quite as much on the skill and ingenuity of the astronomer as on the tools he has at his disposal.

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Interferometers in Radio Astronomy

By B. F. Burke[1] and M. A. Tuve[1]

Only a faint glimmer of an idea yet exists as to how astronomical objects can radiate, apparently with a fair degree of conversion efficiency, electromagnetic waves some tens of centimeters or even meters in length. The discovery phase is probably over; only a few such objects are known, but these are enough to face us unequivocally with the problem. "Plasma oscillation" is an easy phrase, and where the electron densities are high, as in the solar atmosphere, these words seem to offer a plausible explanation, but when one is confronted with the problems of boundary conditions and the mechanism for escape of the radiation to free space the plausibility disappears. Additional difficulties arise for the low apparent electron densities in gas clouds. Strong and perhaps turbulent magnetic fields combined with violent streaming motions, perhaps even with shock waves, may resuscitate the hypothesis, but theory has yet to rescue the observer in this field.

Progress toward solution of this problem may still lie in the hands of the observer, however, as there exist only a dozen or so sources which have been specifically located and for which "color" information (in the radio spectrum), for example, has begun to be available. When at least several hundred sources, thermal and nonthermal in their radiation characteristics, have been cataloged and their radiation properties described in some detail, the puzzles may diminish. Large arrays of antennas, mainly dipoles or helices, connected and used as interferometric devices, are the principal technical basis for obtaining observations at the longer wavelengths. Parabolic reflectors of any reasonable size cannot be expected to give the necessary precision of location in the sky; at 20-cm wavelength even a 500-foot parabola would still cover an area 5 minutes of arc in diameter. Arrays of great size and interferometer spacings of as much as a mile are simple by comparison to such a dish.

It should not be surprising if a new branch of science raises difficulties in its early days, and radio astronomy has not been disappointing in this respect. In the past few years, this young branch of astronomy has provided a large variety of both physical and astronomical problems. A striking feature of the earliest investigations has been that most of the intrinsically strong sources of radio noise are relatively insignificant optical objects, a circumstance that adds to the difficulty of examining in detail their physical behavior. The handful of optically identified discrete sources all exhibit one feature in common, however, which provides some indication of the nature (and difficulty) of the problem, for in all cases we seem to be dealing with highly turbulent gas whose constituents are in high states of ionization. Other general or special requirements may exist, and they will have an important influence on any theory of how such a tenuous but violently agitated gas becomes a relatively efficient emitter of radio noise. For example, the polarization of the light from the Crab Nebula (pl. 1) provides evidence for the existence of a magnetic field and large quantities of highly energetic electrons, which also could be efficient radiators in the radio spectrum, but whether this is a general characteristic of all radio sources or a peculiarity of this one object only the future will tell. It appears certain, however, that the necessary highly turbulent gas can be produced in a variety of ways. In our own galaxy, cataclysms such as supernova explosions are known means of providing a turbulent medium that is capable of strong radio emission; but although all discrete galactic

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sources may possibly be supernova remnants, many of them may also represent an entirely new class of objects.

The extragalactic sources, which are intrinsically more powerful emitters of radio noise, require a correspondingly more violent origin. The collision of two galaxies seems to be a sufficiently drastic occasion, but there are peculiar galaxies such as M87 which evidently require some other means of excitation.

The existence of two different populations of radio sources raises the important question of how to distinguish between them, and how to establish, if possible, a distance scale. The only reliable method at present seems to be identification with a visual object, but as time goes on this method must prove increasingly difficult. Even now it is clear that if a pair of colliding galaxies as violent as the Cygnus source exists, but 10 times farther away, we have little hope of observing it visually even though it would still be an observable radio source. Similarly, many galactic objects, conspicuous in the radio region, are undoubtedly so obscured by dust that optical observation will be difficult. In both cases, however, a distance scale would certainly bring to light interesting new problems. For example, the distribution in space of extragalactic radio sources may provide a clue to important cosmological problems, since it is probable that many observable radio sources are situated at great distances, approaching the limits of the visible universe. So far, only statistical methods have been employed, and at present there appears to be a serious discrepancy between observations. The results of the Cambridge interferometer radio survey indicate an unusually large number of faint sources, implying an actual increase in apparent spatial density of radio sources in the universe at great distances. On the other hand, preliminary observations by Australian radio astronomers show a number-magnitude relation that implies a nearly uniform space density of radio sources. The resolution of this direct observational conflict is certainly one of the most pressing problems in radio astronomy today. The solution may lie in an understanding of the techniques involved, for both surveys utilized interferometric techniques but in radically different forms.

All the sources we have been considering are characterized by their nonthermal nature, since nonequilibrium processes appear to be involved. An equivalent black body in order to exhibit an equal surface "brightness" in the radio region not only would have to be at an extraordinarily high temperature but also would have to have an equivalent temperature that rises with increasing wavelength. In the meter-wave region, where many sources are sufficiently intense to be seen with relatively simple equipment, they appear superimposed on a smooth background of radio noise, most of it evidently of galactic origin.

Interferometric techniques are particularly valuable in removing the effects of the background, "labeling," as it were, the signals originating in discrete sources. Figure 1 illustrates the principles of the phase-switching interferometer first described by Ryle (1952). In the upper drawing, two antennas are arranged symmetrically to form the radio analog of the Michelson interferometer. If a radio source is directly overhead, or is off-axis by an amount sufficient to result in a path difference of an integral number of wavelengths, the two signals constructively interfere. Therefore, by switching the phase of one antenna at a regular rate the signal from a discrete radio source is modulated, while the slowly varying background is not, and we can distinguish the noise from such sources by looking for a modulated component in the total signal received. The system has other advantages as well. If a source is at a half-power point of the interference pattern, the signal received will be the same whether a half wavelength has been inserted or not, and consequently at these positions the signal from a discrete source is unmodulated. As a result, position measurements can be made by a null method, with much greater precision than is possible with a pencil beam. Furthermore, the relative amplitude of the interferometer signal as a function of antenna spacing gives a measure of the angular size of the source, effectively constructing the Fourier transform, just as in the optical Michelson interferometer. It is possible, therefore, to obtain information with relatively small antennas that otherwise could be obtained only with a single antenna of prohibitively large size.

The Crab Nebula. Photograph from the Mount Wilson and Palomar Observatories (200-inch photograph).

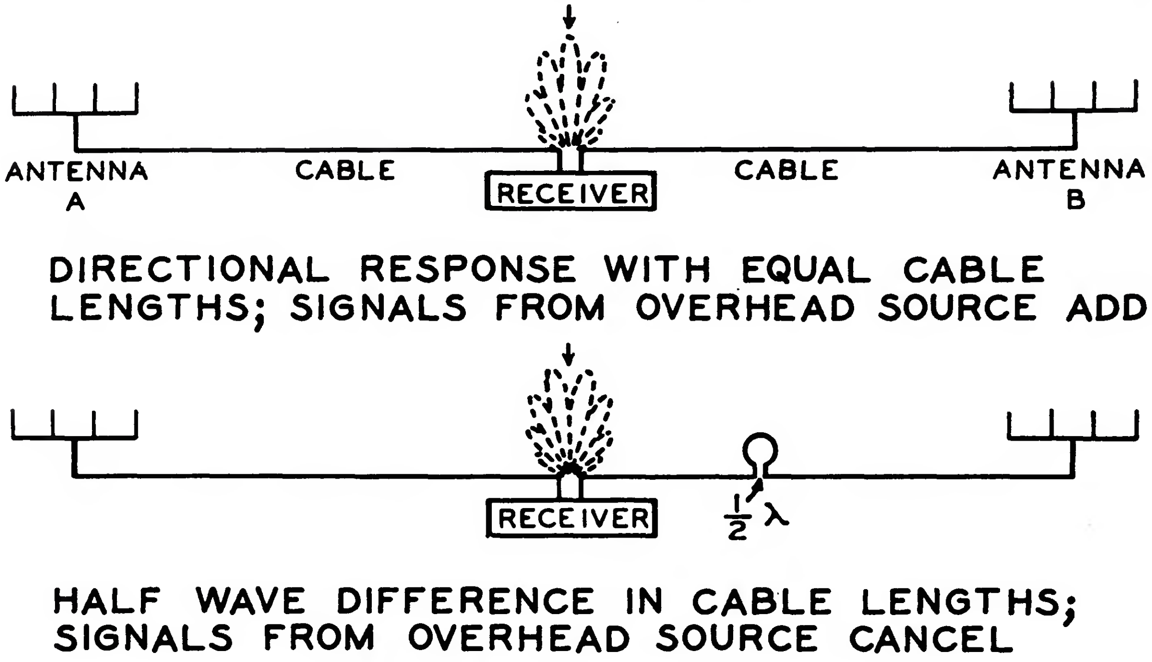

FIGURE 1.—Phase-switching interferometer.

There is danger in the method, however, which must be guarded against; if more than one source is being received, the interferometer will measure the combined effect of the two, and, unless one reconstructs the Fourier transform by going to sufficiently large spacing, a single source will appear to be observed where in reality there are two. The effective gain of the interferometer is the geometric mean of the gains of the two antennas, and at first sight it would appear that if we simply make the antennas larger, and thus see fewer sources per beam width, this difficulty would be circumvented. It is true that the confusion of stronger sources may be resolved by this technique, but the increased antenna gain then makes it possible to detect a still larger number of sources per beam width, and since one naturally wishes to examine these, also, multiple spacings are still required. At the longer wavelengths, particularly, where a pencil beam of the order of a minute of arc or less requires an array of prohibitively large size, interferometric techniques are indispensable, but they must be applied with caution and full knowledge of the difficulties involved.

The study of the sun is an interesting special case, for the radio emission at longer wavelengths provides a useful tool for probing the corona; here interferometers have already proved their value, providing us with a qualitative picture of the sun at a number of different wavelengths. The detailed appearance of the sun, particularly at the longer wavelengths (greater than 4 m) needs much more study, and there is little doubt that interferometric techniques must prove necessary.

It was remarked earlier that the effective sensitivity pattern of a pair of antennas used as an interferometer is equal to the geometric mean of the gains of the individual antennas. This fact is utilized in the special case of the Mills Cross (Mills and Little, 1953), which, in reality, is a zero-spacing, phase-switched interferometer utilizing two linear arrays at right angles. Figure 2 gives an illustration of the principle. Each array has a fan-shaped sensitivity pattern, but when connected as a phase-switched interferometer the effective sensitivity is the geometric mean of the two antenna patterns, which is a pencil-beam whose resolving power is equivalent to a square array containing many more

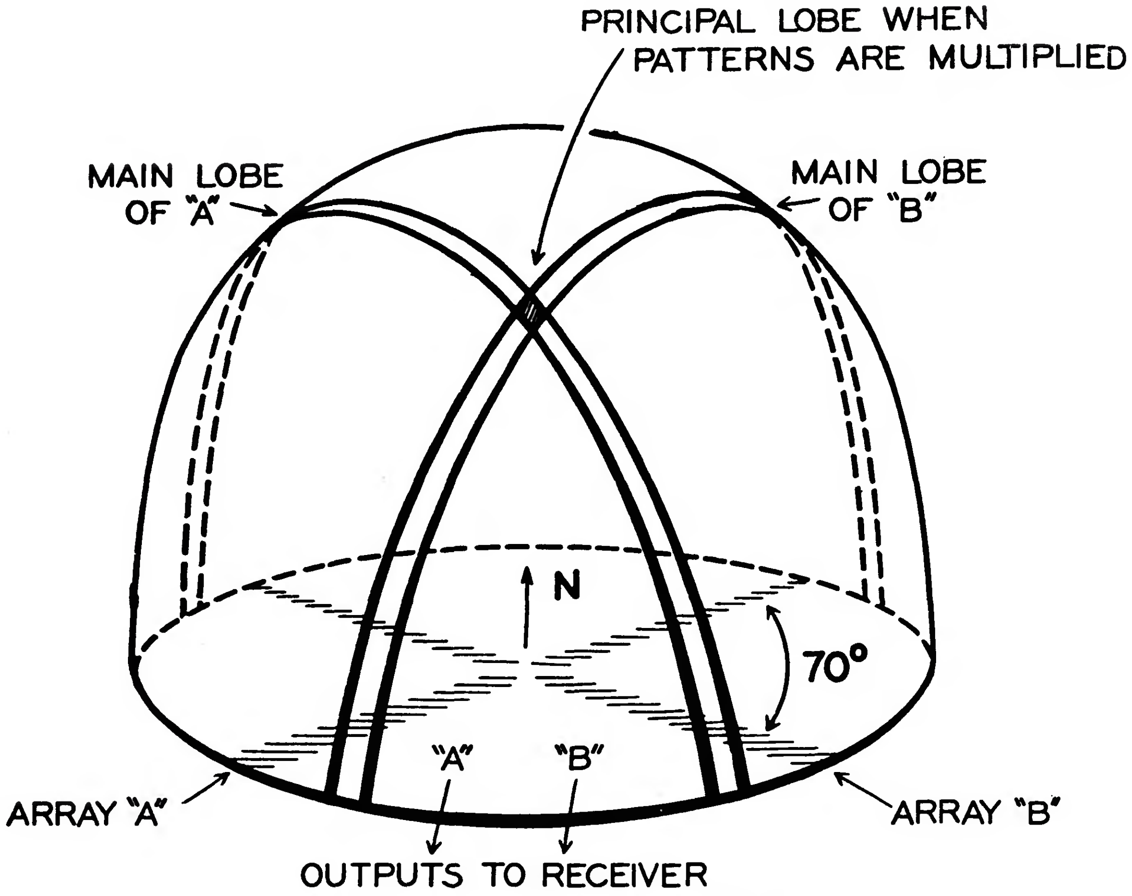

FIGURE 2.—Antenna diagram of the Mills Cross interferometer.

elements. At the longer wavelengths this provides us with a technique for producing a pencil-beam with simplified arrays, and the future will undoubtedly see arrays based on this principle but of far larger dimensions than those in use today, since a pencil-beam is unquestionably the best way to investigate extended sources. As in most experimental and observational fields, the advantages of this method are accompanied by disadvantages as well, for this system is troubled by spurious responses arising from its unusual diffraction pattern. It is possible for a strong source, passing well outside of the main pencil beam, to appear as a weak source, and great care must be exercised to avoid, if possible, or at least to identify such spurious responses. (See fig. 3.)

The longer wavelengths, of the order of a meter or more, have been emphasized since the observation of a large number of sources at these wavelengths can probably be accomplished more conveniently by interferometric techniques than by an equivalent array, while the measurement of angular size of small sources is probably possible by no other means. The phase-switching technique has the further advantage that the noise originating in discrete sources is "labeled" by modulation, and if, in the future, it is possible to investigate the intrinsic properties of source noise this feature may be invaluable in distinguishing the desired signal from the galactic noise background. All present interferometric systems have weaknesses, however, which must be appreciated if the important work on weak radio sources is to have reliable significance.

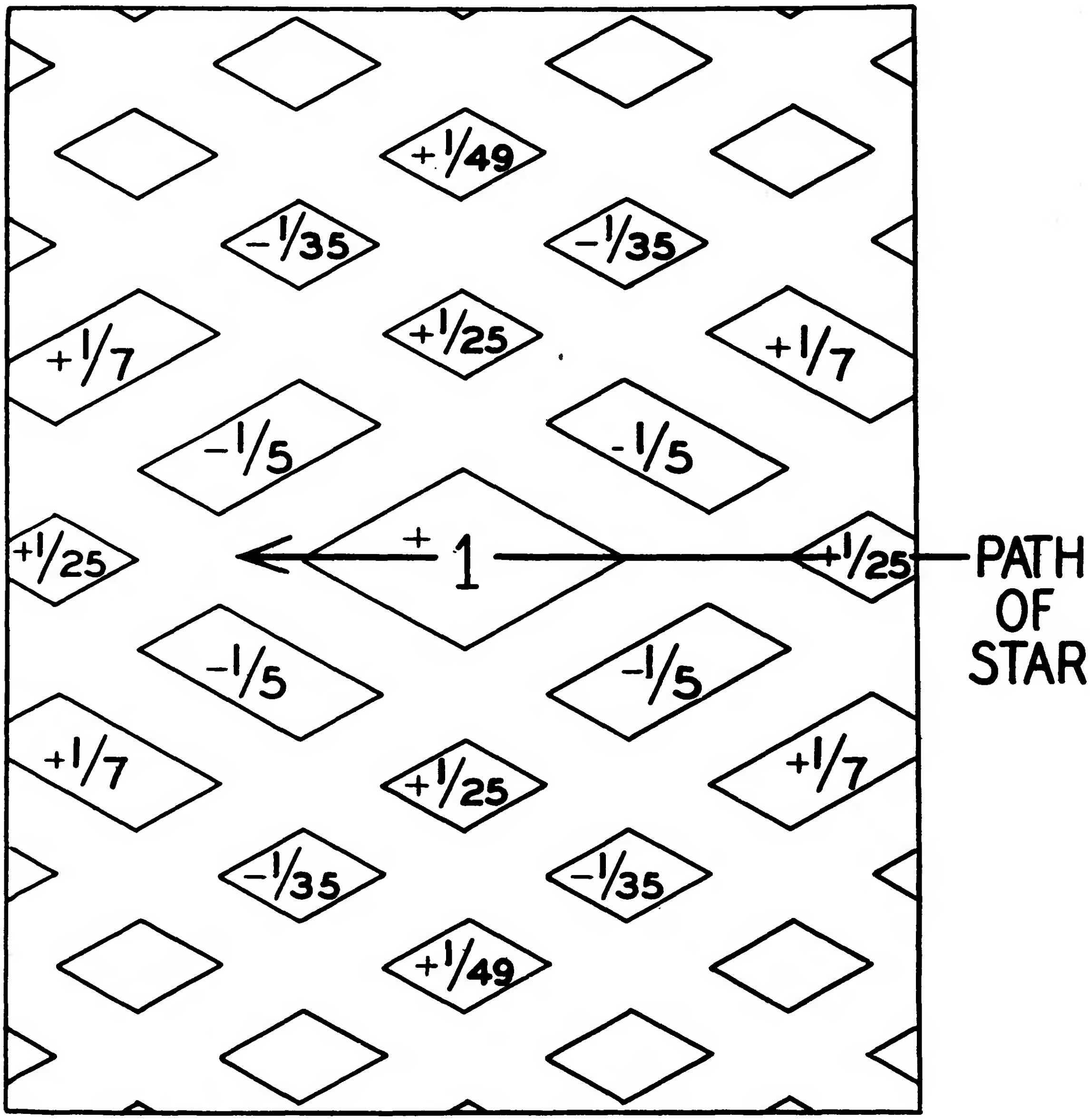

FIGURE 3.—Detailed antenna pattern of a Mills Cross interferometer.

In our concern with equipment it is important that we not lose sight of the larger issues. The cosmological problem has been outlined, but other important questions also exist. What is the cause of radiation in the case of those galaxies that are not, apparently, colliding with anything? What is the significance of the distribution of radio sources in our own galaxy? And, what are the physical conditions necessary for the emission of radio noise from large, turbulent gas clouds? Are magnetic fields essential? The answers to these questions, and others as well, depend on an increase in the information concerning discrete radio sources. Larger interferometers will certainly play a role in the gathering of this information.

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Related Sciences

Rocketry

By R. Tousey [1]

For many years astronomers the world over have dreamed that sometime it might become possible to discover the nature of the extreme ultraviolet and X-ray spectrum of the sun and the stars. Research in this field became possible at the conclusion of World War II as a result of the development in Germany of the V–2 rocket, which was capable of carrying scientific equipment to altitudes far above the main absorbing regions of the earth's atmosphere. The V–2 rocket and the American Viking and Aerobee rockets which followed have opened the field of rocket astronomy. The cost of this research is large, but the stakes are very high, for it seems probable that the key to many unsolved astrophysical problems may be found in the nature of the spectrum of the radiation of very short wavelengths emitted by the sun and the stars.

The difficulties of conducting astronomical research from rockets are many. The space available for instrumentation in all but the largest rockets is rarely more than 10 cubic feet, and the payload is of the order of only a few hundred pounds. The time available for observation is 2 to 5 minutes. It is difficult to keep instruments pointed at the celestial object under study since rockets roll and turn in an unpredictable fashion. Flight preparations are time consuming and complicated, so that the firing time is often determined by circumstances other than those that are optimum for the experiment.

In spite of the vicissitudes of research from rockets, during the past several years great advances have been made toward the solution of the problems involved in rocketry; yet, there is much still to be desired. Astronomers are most anxious that the work be carried ahead as vigorously as possible.

Improvements needed in rocketry

Although the V–2 rocket was capable of carrying a tremendous payload to an altitude of 100 miles, which is adequate for many experiments, it was extremely complicated, difficult to launch, expensive, and more often than not it misfired. Two American rockets were designed to replace the V–2 for upper atmosphere research: the Aerobee, a small, comparatively inexpensive rocket with a peak altitude of about 120 km; and the Viking, similar to the V–2 in complexity and size, capable of 200-km altitude, and stabilized during flight. A number of Vikings were flown with successful experiments, but the trend toward economy has forced scientists to use and improve the Aerobee rocket for research.

The Aerobee uses an acid-aniline fuel, is launched with a booster from a tower, and costs at present about $30,000. This rocket is quite satisfactory for many experiments. It can be launched at sea, though not as easily as is desirable. The early type of Aerobee did not reach altitudes sufficient for many experiments. The Aerobee-Hi, now in production, will ascend to 200 to 300 km with payloads between 150 and 250 lbs.; thus, it has performance characteristics that are satisfactory for almost all types of research. Although it is a much simpler and cheaper rocket than the V–2 or Viking, the Aerobee is still too expensive to be used as frequently as would be desired in astronomical research.

The preparation of a rocket and the launching are complicated. Furthermore, at land bases such as the White Sands Proving Grounds, the scientist is limited to firing at a particular time, when the range is ready and clear and the winds are favorable, even though he may wish to fire, say, during the onset of a solar flare.

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The improvement most needed in rocketry, therefore, is a really inexpensive rocket that can be made ready and flown without elaborate preparations and precautions. Recent advances encourage hope that such a rocket, employing a solid fuel propellant, can be developed in the next few years. A rocket that will carry 100 pounds to 300 km and can be launched by a few persons, perhaps by the scientists themselves, at a cost of perhaps $5,000 no longer seems unattainable. Such a rocket might best be launched at sea, or at least flown out to sea from shore. This would avoid complicated and restricting safety requirements. Sea recovery methods would have to be worked out, since most astronomical experiments are photographic. This involves the sealing and flotation of the section containing the instrumentation and the development of a system for locating the floating section.

For flights over land, recovery of photographic film may be achieved simply through the use of a strong casette, but ordinarily the equipment is completely ruined. Recent advances in parachute techniques, however, make it possible now to salvage the equipment for further study or reuse. The cost of the parachute assembly must be greatly reduced, perhaps to the neighborhood of $500 to $1,000, before its general use will be warranted economically.

One of the most difficult and important problems in rocket astronomy is that of keeping the equipment accurately pointed at the celestial object being studied. Although it may be possible to stabilize a rocket in flight, the precision of equipment stabilization required for many experiments can be far more easily and cheaply provided by stabilizing only the instrument. So far, attempts at pointing have been limited to the sun. The most successful of several "sun-followers" is the "Biaxial Pointing Control" developed by the University of Colorado under Air Force sponsorship and described by Stacey, Stith, Nidey, and Pietenpol (1954). This device kept a spectrograph flown in a U. S. Navy Aerobee on February 22, 1955, pointed at the sun within an average error of ±1 minute of arc during a total exposure time of 2 minutes. The cost of this equipment is high, therefore safe recovery is mandatory if many experiments are to be conducted.

Further development of pointing controls in the direction of lower cost and greater load-carrying ability and simplicity is very important for rocket astronomy. With such controls the study of the bright stars from rockets may become possible. This will probably require a pointing control that operates from the moon, or the sun, and the earth's magnetic field, or possibly from simply the moon and the sun; the star itself may provide the final signal for precise pointing.

The fields of rocket astronomy

The experiments already conducted from rockets cover many fields of research in astronomy and the physics of the upper atmosphere. The work already accomplished has been most recently summarized by a collection of papers presented at the Gassiot Committee meetings (Boyd and Seaton, 1954). Many fascinating new experiments have been proposed. In this section an attempt is made to cover some of the most interesting.

The solar spectrum.—The sun is certainly the most important and the least difficult celestial object to study. From the rocket work conducted by the Naval Research Laboratory (Tousey, 1953a, 1953b; Wilson et al., 1954; Johnson et al., 1955), by the University of Colorado (Rense, 1953), and by the Air Force Cambridge Research Center (Jursa et al., 1955), its ultraviolet spectrum is now known in considerable detail to 977 A. Friedman (1955) and coworkers (Havens et al., 1955; Friedman and Chubb, 1955; Byram et al., 1955), using photon counters, have measured the sun's X-ray emission in several wavelength bands between 100 A and 5 A, and also have obtained much information about the Lyman alpha line of hydrogen and the dissociation of oxygen in the upper atmosphere.

Down to 2085 A the ultraviolet solar spectrum resembles, generally, the visible spectrum in having many deep Fraunhofer lines. The intensity continues to fall below that of a 6,000° K black body, and at 2100 A has reached a brightness temperature of approximately 5000° K. The photon counter measurements indicate

4,050° K at 1450 A and 3,900° K at 1250 A. At these wavelengths the continuous spectrum must come from the very coolest layers of the sun's atmosphere. At 2085 A strong continuous absorption of unknown origin sets in; although nearly obliterated, the Fraunhofer lines can still be seen, the lowest so far identified being at 1700 A. The continuum itself has been photographed to 1550 A.

Below 1650 A the solar spectrum consists, in the main, of emission lines. So far, 32 emission lines have been identified. These include Lyman alpha and beta of hydrogen, the two resonance lines of O VI at 1032 A and 1038 A, one resonance line of N V at 1239 A, the line of He II at 1640 A corresponding to Hα, and various (mostly) resonance lines of silicon and carbon up to three times ionized. The intensity of Lyman alpha has been measured on several occasions, both photographically and with photon counters, with results varying from 0.1 to 1 or more ergs/cm^2/sec, suggesting that the emission in this line may be quite variable, depending on solar conditions. The soft X-ray intensities measured with photon counters appear to be roughly those expected from a corona at 750,000° K. They have been shown by Havens, Friedman, and Hulburt (1955) to be quite sufficient to produce the E-layer of the ionosphere.

There remains a great deal of fascinating research on the sun to be done from rockets. In this field only the surface has been scratched. While the data already obtained bear closely on the structure of the sun, much more needs to be learned to make possible the formulation of a complete picture of the solar atmosphere. The solar spectrum from 977 A to 100 A is still completely unknown, and from 100 A to 5 A it has been measured only in broad chunks. In this spectral range lie the resonance lines of most of the highly stripped atoms present in the corona. It is now possible to study this region. The requirements are a good pointing control and a rocket that will spend several minutes above 200 km. A scanning spectrograph with a photon counter detector and telemetering may be the simplest approach, at least to obtain information without great resolution. In the end, however, spectrum photographs should be obtained.

Special studies of the sun.—The solar spectrum is most easily studied by using the light coming from a considerable area of the solar disk. It is important, however, to learn exactly where on the disk the various emissions originate, and how their intensities depend on the height in the solar atmosphere. Several approaches to this problem have been proposed.

Some information can be obtained with a stigmatic spectrograph on whose slit the sun's image is held stationary to within 1 minute of arc with a pointing control. Spectra obtained in this fashion by Johnson et al. (1955) show, for example, that the O VI line at 1032 A has a greater ratio of limb to center of the disk intensity than does Lyman beta at 1026 A, as would be expected. More measurements of this sort would make it possible to improve greatly the model of the chromosphere and corona.

Ideally one would like to fly a spectroheliograph and to measure the intensity distribution over the disk and corona of all lines in the vacuum ultraviolet. For the Lyman alpha line, which has very high intensity, such an instrument is feasible. A possible design was published by Behring et al. (1954). Several Lyman alpha spectroheliographs or cameras will be flown in the next year or two. Following this, weaker lines of higher excitation energy should be investigated, including the ultimate lines of He I and II at 584 A and 304 A, respectively.

Another method of studying the distribution of Lyman alpha over the disk, suggested by Friedman, employs a photon counter of a narrow field of view, sensitive to this line only. By using a television scan of about 20 lines resolution, a crude picture could be transmitted to ground.

Once these experiments have been successful it becomes of immediate interest to study the spectrum and the distribution of the spectrum over the disk under disturbed solar conditions and during an intense flare. The solid propellant rocket and sea recovery are almost a prime requisite for this purpose because they make it possible to fire at almost the instant a flare takes place. Though this may also be possible with Aerobee-Hi, it will be difficult indeed, owing to the safety requirements associated with launching from ground and because of the great complications surrounding the use of an acid-aniline fuel.

A first approach to the question of the change of ultraviolet and X-ray emission during a flare is planned by Friedman and his coworkers. They will instrument a number of "Rockoons." These small rockets are carried aloft at sea with balloons, and launched from an altitude of 80,000 feet; they reach approximately 80 km, which is sufficient for studies of Lyman alpha and hard X-rays. When they are launched at sea they can be watched during the entire day and fired at the moment a flare appears. Each rocket will carry a photon counter sensitive to Lyman alpha only, another to detect the possible presence of 1–2 A X-rays, and a third device to search for a burst of γ-ray Bremstrahlung that may be produced in a shock wave in the solar atmosphere associated with the flare. It is also possible to have several Rockoons ready to launch in sequence, a few minutes apart, to study the time history of the radiation from the flare. Such experiments can be done far better from a simple solid propellant rocket, since this would carry the instruments much higher than the Rockoon, to altitudes where soft X-rays and regions of the ultraviolet other than Lyman alpha can also be studied. Furthermore, if no flare should appear during the day the rockets would not be launched, and so would not be lost, as are Rockoons.

Still another interesting experiment would be to study the extreme ultraviolet and X-ray solar spectrum during a solar eclipse. It is not out of the question to do this spectrographically with solid propellant rockets launched at sea. A further development would be required to enable a pointing control to track accurately in spite of the enormous change in solar light. It would also be quite possible to photograph the flash spectrum, and the results would be most important for deducing the correct model of the chromosphere.

Friedman has proposed studying the sun with photon counters and Rockoons during an eclipse. Here one would hope to determine the distribution of intensity in the corona of radiation in several bands of the X-ray region, and the distribution of Lyman alpha with height in the chromosphere and corona. This experiment would be much better performed with a solid propellant rocket, since the balloon may drift out of the eclipse path prior to totality.

The stars.—It would, of course, be of tremendous interest to use rockets to study the short-wavelength spectrum of the stars. Though their faintness in the visible makes the problem appear extremely difficult, certain of the O and B stars are so very hot that their extreme ultraviolet and X-ray spectrum may well be sufficiently intense. Exploratory investigations can be accomplished with photon counters, and here again Friedman has planned several experiments, both by day and by night. For the first experiments the sky will be scanned, as the rocket rolls and yaws, by a Lyman alpha photon counter of high sensitivity and also by certain other ultraviolet and X-ray counters. In later experiments the counter will be directed with a pointing control. By day the situation is complicated by the expected presence of scattered Lyman alpha radiation from the sun, which in itself is worth studying. At night, however, Lyman alpha and X-rays may be expected from stars, nebulae, and other galaxies, and there is even the possibility of detecting these radiations in the zodiacal light. The relation between the F-corona and the zodiacal light could be studied by visible or ultraviolet light photometry of the sky from a rocket at altitudes where the Rayleigh sky background is very dim.

Many experiments can be imagined if an accurate stellar pointing control were developed. For example, A. Boggess and J. E. Milligan have suggested photographing the stars in the ultraviolet with a Schmidt camera and objective prism. The energy distribution of ultraviolet spectra, worked out from these spectra, would be of great interest in connection with stellar atmosphere studies. It might also be possible to extend knowledge of the wavelength dependence of interstellar reddening into the ultraviolet. Ultraviolet spectroscopy of the planets might well give information concerning possible absorbing atmospheric constituents. Perhaps most exciting of all, however, is the possibility that the spectra of many of the stars could be photographed in the vacuum ultraviolet.

Particles.—There are other fields of astronomical research which can be pursued by means of rockets. One of these is the study of micrometeorites. These tiny particles are thought to bombard the outer atmosphere in such abundance that it may be possible to detect acoustically their impacts on a rocket, or even to collect a sample and parachute it to earth for study. Experiments of this sort are being conducted by both the Navy and the Air Force.

Another field is the analysis of the primary cosmic radiation. This is difficult at low altitudes because of the modifications and showers that take place due to the stopping effect of the air. At rocket peak altitudes, however, it should be possible to study the real primary radiation.

Upper atmosphere physics.—Finally, there is the large field of research on the physics of the earth's upper atmosphere, a field claimed alike by astronomy, geophysics, and meteorology. Rocket work has already solved the problem of the origin of the E-layer, and when higher flying rockets are available the radiation responsible for the F-layers will certainly be discovered. Direct measurements of the composition of the upper atmosphere have been made, and the density of ions of various sorts has been measured with mass spectrometers. The electron density through the E and F_1 layer has already been measured from rockets by a radio propagation method by Seddon (1954) and coworkers (Seddon et al., 1954). This work should be carried on at many points over the earth and under varying ionospheric conditions. The pressure and density of the atmosphere have been measured from rockets and the work should be continued at many places over the earth and at different seasons. It may be noted that the density measurements of Friedman (1955), made by studying the absorption of X-rays by the atmosphere, do not agree with measurements made close to the rocket with pressure gages. This interesting conflict of results must be resolved.

Finally, it is hoped that the origin of aurorae can be explained by means of rockets. It is expected that during the International Geophysical Year rockets can be launched within the auroral zone and flown into actual aurorae. The nature of the incoming particles will be studied. Emission of Lyman alpha will also be looked for, since it may be expected from recombining protons and electrons.

Outside the auroral zone spectacular displays are infrequent, but there is still present the night airglow, an emission of light from the upper atmosphere. The origin of the various emissions in the airglow and their possible connection with the aurora are not well understood; and opinions differ concerning the altitudes at which the various spectral lines are emitted. Experiments from rockets designed to study directly these emissions are underway; they should be continued until the airglow is well understood.

For all these experiments the development of the solid fuel propellant rocket is most important. Since many experiments will be required, at special times and locations, a cheap and simple rocket is essential.

Satellite

A satellite vehicle is simply a special type of rocket that is projected at a velocity proper to place it in a stationary orbit. It is especially suited to experiments that require a long observing time. In the foreseeable future, however, the space and weight limitations on instrumentation are very severe, and there can be no thought of recovery.

There have been proposed several important experiments that cannot be done with ordinary rockets and may be feasible from a satellite. Perhaps the simplest experiment is the study of solar ultraviolet and X-ray radiation over a long period of time in order to determine the type of intensity variations that may occur. Such variations are considered to be a cause of sudden changes in the state of the ionosphere and radio transmission, and may also have an important effect on weather. Photon counters would be used.

Friedman and coworkers have proposed a search of the sky for radiation hot spots by means of detectors in a satellite. The Lyman alpha line would be the radiation chosen for the first experiments because of its probable high intensity and possible correlation with known regions of high concentration of hydrogen.

The earth's magnetic field could very well be studied from a satellite. Since the satellite's orbit would cover a large fraction of the earth during a day, it would be possible to study the variation of the earth's magnetic field with latitude and longitude, and, if the orbit were elliptical, also with altitude. Experiments of this sort are important in connection with the Chapman-Størmer ring current. An actual experiment from a satellite to determine the magnitude of the ring current has been proposed by J. P. Heppner.

The satellite would, of course, be ideally suited to the study of micrometeorites so small that they do not penetrate far into the earth's atmosphere but which probably ionize the upper atmosphere in process of being stopped. Even more important, however, may be the study of primary cosmic rays of energies so low that they do not penetrate far into the atmosphere. Particles of this sort are believed to exist and, in fact, many of them may come from the sun. The satellite also offers the possibility of studying the distribution in space from which cosmic radiation arrives, and perhaps of providing clews to the origin of this mysterious radiation.

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Computing Machines in Astronomy

By Paul Herget[1]

The impact of computing machines upon scientific research in recent years is not fully appreciated outside of a small group of actual machine users. When an electronic computation center is installed in a scientific or technical institution, almost invariably a workload quickly develops that requires more than the available running time on the computer. This is a "snowballing" situation in which the demonstration of what can be done on one problem soon leads to the exploration of similar possibilities in related problems.

The next effect is that nearly all nondefense and pure research projects are crowded out, for lack of priority. The National Science Foundation has recognized this situation and called an *ad hoc* committee in February 1955 to consider the need for computing facilities in university research centers in general. Astronomy was represented by Schwarzschild and Herget. More recently other groups have recognized the need to stimulate the development of computation centers in universities.

The need for electronic computing machines in classical astronomy is mentioned in another paper in this series, "The Minor Planets." As additional examples, we may note that Brouwer, Clemence, and Eckert, using these machines, have completely recomputed the motions of the outer planets and Herget has prepared a uniform system of coordinates for Earth and Venus. Clemence has recomputed a new general theory for Mars which is nearing completion. In studying the secular variations of the elements of the major planets, it is now feasible to compute second order effects simply by recomputing the coefficients under the appropriately varying conditions at intervals of, say, 1,000 years. An extensive computational program is also a significant part of the meteor studies currently being conducted by Whipple.

In astrophysics, one large group of problems concerns stellar models. The equations of state and equilibrium conditions for stellar interiors form a system of ordinary differential equations in one independent variable, the radius. Similar mathematical but different physical conditions exist in stellar atmospheres. Recently Henyey has elaborated on the problem of stellar interiors by taking into account the evolutionary changes within the star. Again, if one deals with pulsating stars, not only the stellar radius but also the time must be used as an independent variable. Then there are such specialized problems as the search for a mechanism that can explain the occurrence of spicules on the sun.

Another new field of computational problems is now arising from considerations of magnetohydrodynamics. These are even more difficult because they involve partial differential equations. The whole field of "wave equations" is of this same type. Much work has been done by L. C. Green, L. H. Thomas, and others, but it is always necessary to restrict the equations somewhat because even the largest computers in existence are still inadequate to deal with this problem in its entirety. This problem is of interest not only for the light astronomical atoms but more or less for the whole periodic table up to the fissionable and heaviest elements.

Examples of problems in stellar atmospheres may be found in the Proceedings of the National Science Foundation Conference held at Indiana University in October 1954. Other typical problems are given in the report of the Joint Meeting of the American Astronomical Society and the Association for Computing Machinery held at Ann Arbor, Mich., June 1954. One interesting problem was the computation of the history of a globular cluster (in two dimensions)

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in which the individual stellar trajectories were carried forward simultaneously until, eventually, two out of a hundred stars evaporated from the cluster.

Optical design, lens computations, and ray-tracing have been revolutionized by the development of high-speed computers. Thus the cost of experimenting with a novel design is greatly reduced, since all the effects can now be so readily computed. Highly efficient methods have been developed, especially by Baker, but there is still room for further study as the capabilities of newer machines are improved. The design of radio antennas for special purposes is another new computational problem in astronomy.

It is significant that, in nearly every one of these astronomical problems, the researcher has been able to develop his own facility in the use of an electronic computer as a research tool even though he has not been primarily a computer. The use of computing machines in astronomy will undoubtedly grow exponentially as each successful solution breeds more problems, and each new experience inspires more ideas.

Turbulence

By S. Chandrasekhar[1]

An aspect of theoretical investigations in astronomy and geophysics that is not often recognized is that matter and motions, in the large, may exhibit patterns of behavior that one might never suspect if one restricted oneself to matter and motions in the small. While several examples can be cited to illustrate this, the most striking is that which requires all motions in systems with large linear dimensions to be turbulent; for turbulence will be the natural state of motions if the Reynolds number is sufficiently large. And since the Reynolds number contains the linear dimension of the system as a factor, it is clear that hydrodynamical motions which occur in astrophysics and geophysics must necessarily be turbulent. Indeed, "turbulence" is the refuge under which astronomers most commonly seek protection whenever they do not understand a particular phenomenon. At present, however, our understanding of the nature of turbulence is no greater than was our understanding of the dynamical theory of gases, before Maxwell and Boltzmann.

Since a deductive fundamental theory of turbulence is a prerequisite for a rational comprehension of many astrophysical and geophysical phenomena, an attempt to follow current developments in the theory of turbulence should be an integral part of astronomical education. The need is the greater in view of the increasing importance of magnetism in astronomical thinking; we have only to recall in this connection the problems of interstellar polarization and magnetic fields, the synchrotron radiation from the Crab Nebula, the galactic corona, and the still unsolved problem of the earth's magnetic field.

Hydrodynamics and hydromagnetics are bound to play central roles in future astronomical developments and the part of turbulence is only one aspect of this.

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Astroballistics

By Richard N. Thomas [1]

Over the postwar years a small group of astronomers have found themselves acting as midwives at the birth of a new subject, astroballistics, conceived on the common borders of astronomy, aerodynamics, ballistics, and chemical reaction-kinetics. Its multiple origin provides an excellent example of the preoccupation with crossfield research in contemporary astronomy. Its evolution exhibits the trend, beginning with spectroscopy, which is changing astronomy from a wholly observational and theoretical science to one demanding extensive laboratory investigations. Its future depends on our success in establishing this crossfield work; that is, on our continuing to produce a group of investigators who feel at home in at least the overlapping parts of the four areas—astronomy, aerodynamics, ballistics, and chemical reaction-kinetics.

Origin and scope

The motion of planets and planetoids was for years a conventional part of study in astronomy. In other papers of this group appear descriptions of some of the exciting new data and theories which have deflected our interest in these objects from their kinematic to their physical properties. We recognize, however, that we can hardly claim a satisfactory knowledge of our planetary system until we can also specify the properties of those objects so small that they cannot be observed individually. In general, our information on these objects is wholly statistical, coming from studies of their collective scattering effect on sunlight, action as a resisting medium, etc. One notable exception is the study of meteors; for these, the earth serves as a sampling box, sweeping up the interplanetary material, with the earth's atmosphere as a fluorescing medium, responding to the entrance of each meteor. If we completely understood all the processes that occur when a solid object moves through a gaseous atmosphere, we would have a fine method for inferring the corresponding properties of each meteor observed. We do not yet have such an understanding, however, and the science of astroballistics has arisen from our attempts to remedy this lack. Our present knowledge of meteors, as a part of the interplanetary medium, is discussed elsewhere in these papers. Here we consider the meteor only as it represents a solid object moving through a gaseous atmosphere, under one variety of conditions.

When a solid moves through a gas, several things may happen. The solid loses momentum to the gas and is decelerated. The amount of deceleration depends critically upon the mass, shape, and velocity of the body, and upon the composition and thermodynamic state of the gas. The solid loses energy as it decelerates, and the energy contributes heat to both body and gas. The partition of heat between the two depends critically upon the velocity, shape, composition, surface structure, and thermodynamic state of the body, and upon the composition and thermodynamic state of the gas. The heat transfer to the solid may result in thermal radiation and ablation (either by melting or by vaporization) from the surface, as well as in a simple temperature rise throughout the interior. The heat transfer to the gas may result in excitation and ionization, and thus in radiation, if the temperature rises sufficiently. Moreover, the material ablated from the solid may interact chemically with the gaseous atmosphere, serving either as a heat source or sink, depending upon the reaction.

The astronomer can make at least three types of measures on a meteor moving through the atmosphere: (1) He can measure directly time and position, and so obtain velocity and deceleration; (2) he can measure the total radi-

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ation, and possibly its spectral distribution; and (3) by radar, he can infer the ionization produced by the meteor. Ideally, he would like to have available a set of tables which he could enter with these data, and so read off the physical characteristics of a single body which alone could have produced such a disturbance. At worst, he might expect to obtain a range of such bodies, and this range would represent his uncertainty of the properties of the particular meteor observed. These properties he could compare with those of rare meteors that were large enough and slow enough for the bodies to survive passage through the atmosphere, and be recovered as meteorites.

Unfortunately, when we attempt to find or even to prepare such a set of tables, we find a disheartening situation. Meteors impact on the earth's outer atmosphere at speeds ranging between 10 and 75 km $\sec^{-1}$. The ballistician and aerodynamicist, to whom we might expect to turn for information, have just since the war become really conscious of the velocity range that is of interest to the meteor astronomer. They, in turn, have looked to the astronomer, hoping for insight into just those problems we pose to them. Only during the last war did the aerodynamicist develop a keen interest in speeds as high as that of sound, $\sim\frac{1}{3}$ km $\sec^{-1}$. While the ballistician customarily dealt with speeds several times that of sound, his knowledge was primarily empirical, and his empirical investigations were limited by his accelerating devices. The experimental investigations reported in the unclassified literature do not deal with objects of known geometry whose speed exceeds ~ 2 km $\sec^{-1}$. At these speeds, interest lies in air-resistance; aerodynamic heating of the body is negligible. By analogue devices such as the wind tunnel, deceleration properties of bodies of known shape at equivalent airspeeds of ~ 3 km $\sec^{-1}$ have been studied. Theoretical investigations have made rapid progress in interpreting and correlating these empirical studies. On the whole, we may say that the deceleration problem is in a most satisfactory state, not only in the range covered by the experiments but, for purposes of extrapolation, considerably beyond that range. But deceleration measures alone do not suffice to permit an inference of the physical properties of the meteor. For that, one must turn to luminosity and ionization studies; and here, the cupboard is essentially bare.

Ballistic and aerodynamic studies of objects moving at such high speeds that ablation occurs are virtually nonexistent, at least so far as we can infer from the unclassified literature. A few simple free-flight experiments have been made, with velocities reaching ~ 6 km $\sec^{-1}$ at maximum. We find an equally small number of wind-tunnel studies, involving always substances requiring but low heat transfer for ablation. From a theoretical standpoint, the situation is equally bad. The study of the aerodynamic flow pattern about a body that is losing mass at its leading surface has hardly been discussed. Indeed, the most satisfactory theoretical work on any aspect of the field probably lies in a few studies, made in collaboration by astronomers and chemists, relating to ablation in the meteoric regime—high velocity and very low gas density.

When we consider the data available on excitation and ionization caused by the ablated material ejected into the gaseous atmosphere, we find the bleakest situation of all. In the late 1920's and early 1930's theoretical atomic physics was striking out into the areas opened by the new quantum mechanics, and experimental physics was entering those areas opened by improved instrumentation. Problems of radiative transition probabilities, while not completely solved, were at least understood. On the other hand, problems of collisional excitation were vague, expecially those involving exchange reactions, and particularly atom-atom inelastic collisions. A number of preliminary experimental investigations were reported in the energy range of interest to the astronomer, <1 kev. Unfortunately, from our present standpoint, the early 1930's were also the era of the crucial experiments in the then infant science of nuclear physics. The focus of interest rapidly shifted, and concern with this area of low-energy atom-atom collisions diminished. An extensive base of data upon which to draw never developed, and it is only in recent years, among relatively small groups of physicists and chemists, that interest in these problems for their own sake has reawakened. The astronomer's interest arises largely from his meteor studies, and occasionally from phenomena in stellar atmospheres where, however, his chief concern lies in electron-atom inelastic collisions. As the instrumental range increases, particularly in studies of very strong shockwaves, the aerodynamicist also is increasingly preoccupied with the details of these atomic collision processes, excitation, ionization, and thus radiation.

To categorize and collate the variety of problems just described, the science of astroballistics developed. Its province includes the study of those phenomena arising out of the motion of a solid through a gas at such speeds that ablation occurs. Interest in and data on various of these phenomena arises in astronomy, aerodynamics, ballistics, and chemical physics. Investigations that combine the points of view of the several sciences involved will have a better perspective and are more likely to solve the various problems than a study based on any individual science alone.

Evolution of the science

The field of astroballistics, as such, developed when astronomers recognized that it would probably be necessary to set up a systematic program that linked astronomical observations of meteors with laboratory studies in ballistics and aerodynamics. The immediate postwar period found ballisticians and aerodynamicists still preoccupied mainly with measures of the system of aerodynamic forces on a missile or aircraft and, to a lesser extent, with problems of strong shockwaves. A number of advances in experimental techniques, however, made it possible to begin, at least, to bridge the gaps between meteor observations and the data and theory of ballistics and aerodynamics.

A certain amount of development of new launching devices, and considerable improvement of the old, plus the use of low melting-point materials, together have made it possible to simulate ablation from meteors. Newly developed free-flight firing ranges permit studies under varying conditions of the atmosphere through which the solid moves. Advances in high-speed photography allow us to make inferences of the spectral distribution of luminosity along the axis and trail of an artificial meteor, which we have been able to accelerate up to speeds of 6 km sec^{-1}. Microwave equipment facilitates studies of the ionization caused by the same type of artificial meteor. Theoretical studies already begun, based on the insight developed in these first investigations, will help guide subsequent research. Thus, we are laying a solid foundation from which to study the problems described earlier as largely unsolved. We should, however, stress one aspect of all these investigations: the results of these first attempts have been invariably crude and preliminary, and progress in extending them has been dishearteningly slow. We will return to this point. At present, the one satisfying feature the results have in common is the simple fact that they exist.

These first experimental investigations had one very stimulating outcome. The first spectral observations, though crude, demonstrated that it is possible to observe details of the chemical reactions involving ablated material and atmospheric atoms. Meteor observations have never provided such data, primarily because of the unfavorable conditions of (1) high velocity, which inhibits the exothermic chemical reactions expected when a metallic spray hits the atmosphere; and (2) low atmospheric density, which permits considerable diffusion before conditions are such that the reaction may occur. In the laboratory, such inhibition and diffusion effects may now be studied. Thus, a very fertile method for studying chemical reaction kinetics appears. Even more, all these occur in a high-speed stream of gas, so that we have an approach to an aerodynamic flow problem of exciting possibilities. For the astronomer, who is just now acquiring a deep interest in gas-dynamical problems in stellar atmospheres, such observations are invaluable in providing a physical insight otherwise inaccessible. In the laboratory, it is hard to provide gas streams having sufficient internal energy that atomic and molecular excitation change appreciably and observably. Consequently, such data as the above become highly desirable. The remark made above, however, should be repeated; these studies are chiefly preliminary. The field has just been opened.

Needs and future of astroballistics

The gross problems of astroballistics may be clearly delineated. A very great deal of experimental work must take place, both to provide the empirical constants required in any theoretical or interpretive work and to establish the basic physical feeling for the problems without which the theory cannot proceed. At present, facilities for such work are largely nonexistent or inadequate in comparison with our needs. Consequently, the field can develop only slowly.

For a long time the chief characteristic of American astronomy has been the size, quality, and quantity of its telescopes. Astrophysics in America has grown largely through the output of observational data. Several spectroscopy laboratories are contributing invaluable work on wavelengths and transition probabilities. Aside from these, however, we have no corresponding astronomical *laboratories* devoted to the study of astroballistics, of conditions underlying particle growth in the interstellar medium, and of magnetohydrodynamic properties of plasmas and the like. It is of course true that some phase of each of these subjects may be under investigation at a dozen places throughout the country. But in how many of these places is there an astronomer working as a member of the research group, both contributing and gaining information? How much of the information gained is accessible in the open literature? We should recognize two problems here. First, we have need for a national astrophysical *laboratory* that can operate with considerable latitude to investigate problems such as those in the field of astroballistics. Its staff should comprise astronomers as well as scientists from "related" fields, and it should include both permanent members and those on a temporary basis. Second, we must urge our graduate schools to help produce the staff for such an institution by emphasizing in their program the experimental aspects of astronomy as much as the observational. Astroballistics is hardly unique in requiring these supports; it is, after all, but a small field in astronomy. The needs of astroballistics, however, are a prototype of those existing in contemporary astronomy in general, and the future progress of the field may serve as a significant example.

Electrodynamics of Fluids and Plasmas

By Max Krook[1]

Sufficient evidence has accumulated to establish the widespread occurrence of large-scale electrodynamic phenomena in astrophysical contexts. To understand such phenomena and to interpret them quantitatively we must investigate the origin, nature, and behavior of cosmic electromagnetic fields and their interaction with cosmic matter. These tasks naturally involve considerations of fluid electrodynamics and, from a more general and fundamental point of view, considerations of the kinetic theory of plasmas.[2] Since these latter branches of physics are still in a very rudimentary stage of development, there is considerable scope for research not only in astrophysical applications but also in the fundamental physical disciplines themselves.

An appreciable fraction of cosmic material consists of ionized, and hence electrically conducting, gas. The dynamical behavior of such conducting fluids is determined in part by forces exerted by the electromagnetic field on electrical charge and current distributions in the fluid. But equally, the dynamical behavior of the electromagnetic field is determined in part by the fluid motions. In general therefore, conducting fluid and electromagnetic field have to be treated simultaneously and on an equal footing as interacting components of a system. The study of systems of this kind is termed *fluid electrodynamics* (or *magnetohydrodynamics* or *hydromagnetics*) when the fluid is treated as a continuum, and is termed *kinetic theory of plasmas* when the fluid is treated microscopically.

Our aim here is to emphasize unsolved problems and to discuss possible future trends. No attempt, therefore, is made to review the literature in any comprehensive way. In a discussion of this kind, it is not possible to do justice to the individual contributions of the many authors in these fields, but some published reviews which include extensive bibliographies are listed at the end of this article.

Fundamental equations

In the kinetic theory of plasmas, the state of a system is specified by the following:

(1) State-variables for the electromagnetic field. These are the usual parameters of the Maxwell-Lorentz theory; i. e., electric intensity $\vec{E}$, magnetic intensity $\vec{H}$, charge density ρ_e, current density $\vec{J}$.

(2) State-variables for the matter. These are parameters which give a statistical description of the microscopic state of the plasma.

With any dynamical process in a plasma is associated some characteristic length L, and some characteristic time τ. If L and τ are both "sufficiently large," the plasma may be treated as a continuum whose dynamic and electrodynamic properties are specified by a set of material constants; e. g., dielectric constant κ, magnetic susceptibility μ, kinematic viscosity ν, electrical conductivity σ (which may have directional properties), etc. In this macroscopic theory, applicable also to conducting liquids, the state of the fluid is specified by the usual variables of fluid dynamics, i. e., pressure p, density ρ, temperature T and flow velocity $\vec{v}$.

The fundamental equations of the continuum theory are made up of the Maxwell electromagnetic equations together with the equations of fluid dynamics, but with the following modifications (which represent coupling between electromagnetic field and fluid motion):

(a) The momentum and energy equations of the fluid include terms which involve electromagnetic

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[2] In this article the term "plasma" will be used in a general sense to mean any partially or wholly ionized gas.

variables; e. g., a form for the momentum equation is:

$$\frac{\partial\vec{v}}{\partial t}+\left(\vec{v}\cdot\nabla\right)^{\rightarrow}=-\frac{1}{\rho}\nabla p+\frac{1}{\rho}\vec{F}+\nu\nabla^{2}\vec{v}+\frac{1}{3}\nu\nabla\left(\nabla\cdot\vec{v}\right)+\frac{\mu}{\rho c}\left(\vec{J}\wedge\vec{H}\right)$$

where $\vec{F}$=external force density, and c=velocity of light.

(b) The constitutive equation for the current density is altered, e. g., to the form:

$$\vec{J}=\sigma\left[\vec{E}+\frac{1}{c}\vec{v}\wedge\vec{H}\right]$$

On account of the complexity of this system of equations, it is generally extremely difficult to solve dynamical initial- and boundary-value problems of fluid electrodynamics, and especially so in cases of astrophysical interest. For this reason, effort has been concentrated on investigating simple and idealized types of problems and on exploring the consequences of various kinds of assumption. It is hoped that insight into the electrodynamic behavior of fluids gained in this way may shed some light on the real dynamical problems and eventually lead to their solution.

Some general principles of the subject may be obtained by analyzing the mathematical structure of the fundamental equations. Dimensional considerations, for example, show that significant mutual interaction of fluid motion and magnetic fields can occur only when the "scale" of the system is large enough. For systems of ordinary laboratory size we would generally require high magnetic intensity, or high electrical conductivity, or low density, or some combination of these factors. This explains why magnetohydrodynamic behavior appears more naturally in astrophysics (where linear dimensions of systems are large) than in terrestrial physics.

The development of fluid electrodynamics would be advanced immeasurably by the elaboration of techniques for performing controlled experiments on a laboratory scale and over a wide range of behavior. The experiments so far carried out with liquid mercury and liquid sodium barely touch the fringe of the problem; and similar remarks apply also to plasma kinetics. Although certain aspects of plasma physics have been studied extensively in laboratory experiments, e. g., with electrical discharge tubes, many dynamical aspects of particular interest in astrophysics remain practically unexplored.

Ionospheric studies are also capable of yielding valuable information about plasma dynamics. And conversely, plasma dynamics can play an important part in interpreting ionospheric behavior. The structure of the earth's upper atmosphere can be studied extensively and accurately by various techniques. Quantitative predictions of the theory can therefore be subjected to more stringent checks in the case of the ionosphere than in most astrophysical cases.

Cosmic magnetic fields

In 1908, Hale discovered the strong magnetic fields of sunspots ($H\sim2{,}000$ gauss) by utilizing the Zeeman splitting of spectral lines. Great improvement in this technique, particularly by H. D. and H. W. Babcock, has resulted in the detection of fluctuating fields in the solar atmosphere ($H\sim1$ to 20 gauss), and of strong variable fields in many stars ($H\sim6{,}000$ gauss). The polarization in the light of distant stars and its correlation with reddening have been attributed to orienting effects of interstellar magnetic fields on elongated dust particles ($H\sim10^{-5}$ gauss). A circumstance which is probably significant for the theoretical interpretation is that astrophysical magnetic fields generally vary with time.

The coupling of material motions and electromagnetic field implies that, in a conducting fluid, mechanical energy and electromagnetic energy are convertible one into the other. Since relative motions are commonplace in astrophysical plasmas, we can understand in a rough qualitative way why magnetic fields might exist there. (In a conducting fluid, magnetic field energy is generally much greater than electrical field energy, except possibly under transient conditions.) Quantitatively, and even from a detailed qualitative point of view, however, we are still far from having a satisfactory theory of astrophysical magnetic fields.

Order of magnitude estimates are often based on a so-called equipartition theorem, which asserts that the average density of kinetic energy $\frac{1}{2}\overline{\rho v^{2}}$ in a system equals the average density of magnetic energy $\overline{\mu H^{2}}/8\pi$. For the interstellar gas, this would imply fields of the order 5×10^{-6} gauss. The theorem has so far been verified only in a small number of comparatively trivial cases, and its real range of validity is not known. Even for systems in which the theorem could be true, the equipartition state may not be possible because of very long relaxation times; this question can be decided only by examining the mechanisms which operate to convert mechanical energy into magnetic energy and vice versa.

Our knowledge of such mechanisms is still severely limited. On general grounds it appears that an efficient process for amplifying an initially small magnetic field might be provided by the interaction of turbulent fluid motions with the field. Very little progress has yet been made in the study of magnetohydrodynamic turbulence, especially in astrophysically interesting cases of compressible fluids. Much of the difficulty of this subject is due to the fact that the sort of questions in which we are interested cannot reasonably be answered by combining a *statistical* theory of turbulence with a dynamical theory of the electromagnetic field. When a dynamical theory of turbulence is eventually developed, great strides will be possible in the theory of magnetohydrodynamic turbulence.

On account of many uncertainties in our knowledge of the magnetic properties of interstellar dust, our knowledge of galactic magnetic fields is correspondingly very inexact. It is therefore important to look for further observable consequences of galactic fields which might lead to more exact and detailed information on their structure and behavior.

One promising line of approach appears to be through problems of generation and propagation of primary cosmic ray particles in the galaxy, although it is still too early to anticipate where, or how far, this approach will lead. These problems present a wide and attractive field for future research.

Preliminary calculations with the Fermi mechanism have yielded some results which are consistent with the observational data and some results which are not. In this model, which is capable of some elaboration, particles of sufficiently large initial energy increase that energy by successive encounters with magnetic fields "frozen" into interstellar gas clouds. The low-energy cosmic ray particles are supposed to be injected into the galactic accelerator by stars, and this is not inconsistent with recent evidence which indicates that the sun itself may be ejecting low-energy cosmic rays.

It has recently been found that optical, continuous radiation from the Crab Nebula is strongly polarized. This has been interpreted as synchrotron radiation from electrons in magnetic fields of order 10^{-3} gauss. An intensive study of this and similar nebulae in both optical and radio frequencies may well prove invaluable in our understanding of mechanisms for generating cosmic rays.

Magnetic fields and other electrodynamic phenomena can play a significant role in problems of structure, behavior, and evolution of astrophysical systems. There is considerable scope for research in problems of this kind. The structure of a star may, for example, be modified appreciably in regions where magnetic pressure is comparable with gas pressure; also, magnetic fields may have profound effects on the stability of configurations. Further, a general galactic origin of cosmic rays, as in Fermi's model, implies a heavy drain on the mechanical energy of gas clouds; this would have a substantial effect on galactic evolution.

Kinematic models

Since solutions of proper dynamical problems are difficult to obtain, kinematic models can play an important part in the development of the theory. In the kinematic approach we assume that the motion or configuration is of a particular type and then examine the consequences with the fundamental equations. The dynamo mechanisms proposed by Elsasser and Bullard to account for the permanent field of the earth are of this kind, as are models of torsional oscillations of the sun in its own magnetic field. The most fruitful line of attack on questions of the origin and behavior of sunspots appears, at present, to be through investigations of a variety of kinematic models.

In general, kinematic models cannot properly be accepted as solutions of real dynamical problems until their consistency has been established by stability investigations. Such stability problems are usually rather difficult, so the validity of most of the existing kinematic solutions has remained untested.

Linearized equations

The nonlinearity of the basic equations is a major source of difficulty in the theory. A linearized form of the equations may be used for treating motions of small amplitude; e. g., propagation of magnetohydrodynamic waves. Limited but valuable information can be obtained from the discussion of such problems, especially for systems with boundaries and with gradients of the physical parameters; e. g., density.

One of the more important applications of linearized theory is in the investigation of stability of systems against small disturbances. The stability of a number of simple systems in external magnetic fields has been examined in this way, but very little is known about stability of systems for which the magnetic field is wholly internal (cf. kinematic models).

Kinetic theory of plasmas

The material constants σ, ν, etc., that appear in the continuum theory are not determined by that theory but have to be obtained by experiment or from a different theory. A kinetic theory of plasmas, on the other hand, implicitly includes the phenomena of electrical conduction, viscosity, etc., in its basic equations. Such a theory is in fact invoked to calculate σ, ν, etc., for use in the macroscopic theory. In addition, however, there are many cases of interest, characterized *inter alia* by "sufficiently small" values of L or τ, for which the continuum theory is not valid and for which we then have to use kinetic theory.

Several problems of a fundamental nature already occur in the very task of formulating basic equations for a kinetic theory of plasmas. The Liouville equation, although useful for certain formal investigations, is far too complex to serve as a basis for attacking practical problems. At the opposite extreme is the very crude model of a plasma as consisting of intermingled positive, negative, and neutral fluids with frictional coupling. Between these extremes there are many possible formalisms with varying degrees of generality.

At present, the most fruitful compromise between generality and mathematical tractability is the theory based on the use of single-particle distribution functions $f_\alpha(\vec{v}_\alpha, \vec{r}, t)$. ($\vec{v}_\alpha$=velocity of particle of type "α".) Particle interactions have then to be represented in idealized form—"close" interactions as binary collisions, and "distant" interactions as average internal electromagnetic forces. Static and dynamic effects of particle correlations are neglected in the first instance but allowed for roughly by the introduction, *post hoc*, of the Debye screening radius. The basic equations of this theory consist of the Maxwell equations together with a set of Boltzmann equations or of Fokker-Planck equations; e. g., for particles of type "α":

$$\frac{\partial f\alpha}{\partial t}+\vec{v}_\alpha\cdot\frac{\partial f\alpha}{\partial\vec{r}}+\frac{e_\alpha}{m_\alpha}\left[\vec{E}+\frac{1}{c}\vec{v}_\alpha\wedge\vec{H}\right]=\left(\frac{\delta f\alpha}{\delta t}\right)_c$$

where e_α=charge, m_α= mass of particle, $\left(\frac{\delta f\alpha}{\delta t}\right)_c$ is a sum of Boltzmann collision integrals, and $\vec{E}$, $\vec{H}$ include contributions of internal fields. Investigations of a fundamental character to determine the range of validity of the theory would be highly desirable.

In addition to the length L and frequency $\omega=\frac{2\pi}{\tau}$ which characterize a particular dynamical process, the plasma is characterized by a set of intrinsic fundamental lengths and fundamental frequencies. Typical frequencies associated with particles of type "α" are the plasma frequency $\omega_\alpha^{(p)}=[4\pi n_\alpha e_\alpha^2/m_\alpha]^{1/2}$, the gyro-frequency $\omega_\alpha^{(g)}=\frac{e_\alpha H}{m_\alpha c}$, and the collision frequencies with particles of type "β", $\omega_{\alpha,\beta}^{(c)}$; ($n_\alpha$=particle density). The modes of dynamical behavior of a plasma depend intimately on the relative magnitudes of the various characteristic lengths and frequencies. These modes have not yet been sorted out in a completely satisfactory way for the general case.

The macroscopic theory can be derived from the kinetic theory by the Chapman-Enskog procedure in the limiting case of "high" density (e. g., the $\omega_{\alpha,\beta}^{(c)} \gg$ all other fundamental frequencies), and "small" gradients (e. g., $L \gg$ all mean free paths). To any type of problem originally formulated in terms of the continuum theory, there corresponds a more general formulation in terms of kinetic theory. The general microscopic problem is of course more complex than the special continuum problem. Some simplification is introduced in another limiting case, that of "low" density (neglect of collisions), and "small" gradients (linearized theory). For a gas of neutral molecules this limit would correspond to linearized free-molecule flow; for a plasma, however, cooperative behavior persists through the agency of internal electromagnetic fields.

Linearized kinetic equations

The nonlinearity of the equations is again a source of complication in the kinetic theory of plasmas. The development of the theory as reported in the literature has been confined almost wholly to the linearized theory and, in particular, to problems of small-amplitude plasma oscillations. Such oscillations can be studied comparatively easily in the two opposite limiting cases of high density (collision frequency dominant), and of low density (collisions neglected); the intermediate range between high and low density presents difficulties even though the equations have been linearized.

For an infinite, uniform plasma in thermodynamic equilibrium, dispersion relations (i. e., relations between frequency ω and wave number $\vec{k}$) have been obtained for the above two limiting cases. Qualitative and semiquantitative results have been found for the intermediate range by using approximate kinetic equations which incorporate the physical properties of the Boltzmann equation but are mathematically more tractable. In the absence of external fields, relatively undamped sound waves at high density go over continuously into relatively undamped, longitudinal (electron) oscillations at low density, with heavy damping in the intermediate region. The character of the oscillations in the presence of external fields has not yet been studied in complete detail. In this case transverse and longitudinal waves are in general coupled; magnetohydrodynamic waves are the high-density analogue of low-density, free electromagnetic waves, etc.

Some attention has also been devoted to the investigation of systems consisting of beams of charged particles interacting with one another and with a plasma. The examination of the stability of such systems is involved in the question of excitation of plasma oscillations by such beams.

There is considerable scope for development of plasma electrodynamics even within the framework of the linearized theory. For the astrophysical applications, we are particularly concerned with boundary-value problems, with the effects of gradients in the physical conditions (density, etc.), and with modes of exciting plasma oscillations; e. g., by supplying mechanical energy. An important question, still unresolved, is that of conditions under which oscillations in a bounded plasma can provide significant radiation in radio frequencies. Even though the radio emission of objects like the Crab Nebula may eventually be shown to consist predominantly of synchrotron radiation, plasma oscillations probably will still be important in accounting for radio noise from other sources; e. g., solar bursts, and for various other electrodynamic phenomena.

In order to interpret observations of radio frequency emission by the sun and other sources, we require to know how electromagnetic waves are propagated in plasmas. Such propagation problems are usually discussed in terms of the magneto-ionic theory. They can be treated more consistently and generally in terms of the kinetic theory dealt with above, although the two methods give concordant results over a wide range in the small-amplitude case.

Nonlinear phenomena

Since the fundamental equations are nonlinear, plasmas are capable of types of dynamical behavior not subsumed in the linearized theory; e. g., the generation of discontinuities from initially continuous motions. These modes of behavior have not yet been investigated in any systematic way.

Many of the astrophysical phenomena to which we would wish to apply the theory (either microscopic or macroscopic) are so violent as to make it extremely unlikely that an adequate treatment of the phenomena would be possible in terms of linearized theory. Nonlinear plasma electrodynamics presents a whole new range of possibilities in our attack on various astrophysical problems; e. g., generation of cosmic rays, generation of radio noise, etc. On account of the intrinsic complexity of the subject, it will probably be necessary to examine first a large number of simple and idealized cases in order to gain insight into nonlinear modes of behavior.

A rather limited range of nonlinear behavior can be described in terms of oscillations of the linearized theory with cross-modulation that is determined by treatment of the nonlinear terms as a perturbation. There are several interesting problems of this kind concerned with the propagation of electromagnetic waves of "moderate" amplitude through plasmas. Some of these have a direct bearing on ionospheric propagation.

A typical nonlinear phenomenon, not reasonably representable in terms of cross-modulation, consists in the generation and propagation of shock waves. Some aspects of magnetohydrodynamic shocks have been discussed in the literature. To study the physical processes which may occur in the presence of shock waves in a plasma, we must examine the detailed microscopic structure of shock fronts and their stability. Such investigations must be based, of course, on the full nonlinear equations and are generally rather complicated.

Certain variations of the magnetic field of the earth have been attributed by Chapman and Ferraro to clouds or streams of ionized gas ejected by the sun and impinging on the earth's magnetic field. Such clouds are also supposed to be responsible for various other observed phenomena; e. g., aurorae. Very little is known about the dynamical behavior of such clouds and their interaction with external fields. Still less is known about the particular kinds of instability in the sun's atmosphere which result in the ejecting of clouds and about the dynamics of the ejection process.

Our discussion of problems in the electrodynamics of fluids and plasmas is by no means exhaustive. Many aspects have been treated only in cursory fashion; other aspects have not even been mentioned. The development of the subject has barely begun and the field is a wide open one.

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Hydromagnetic and Plasma Problems[1]

By Eugene N. Parker[2]

An ionized gas or plasma possesses two obvious general classes of dynamical modes as a consequence of its being a mixture of two electrically coupled gases. In the electron gas the velocity of sound is much higher than in the other constituent, the ion gas, so that if the plasma is deformed sufficiently rapidly, the ion gas will lag behind the electron gas; this will result in separation of charge and in large electrostatic forces that tend to restore the initial relative configuration. The resulting oscillations of this "electric" mode are called *plasma oscillations.* In the absence of magnetic fields, the oscillations have a fundamental angular frequency

$$\omega_p = (4\pi e^2 n/m)^{1/2}, \tag{1}$$

where e is the charge of an electron in electrostatic units, m is the electron mass in grams, and n is the number of electrons per cm^3. The frequency defined in equation (1) is called the *plasma frequency,* and we might add that in the presence of magnetic fields there are three possible frequencies that are algebraic combinations of ω_p with the electron gyrofrequency Be/mc (Westfold, 1949).

If the disturbances initiated in a plasma are slow compared to the plasma frequency, then obviously the electron and ion gases will move together. In this case the plasma is well approximated by a conducting classical fluid (Elsasser, 1954, 1955a). Since the motions of an electrically conducting fluid interact with magnetic fields, and in astronomical phenomena are so generally associated with magnetic fields, this plasma mode may be termed the "magnetic" mode. The study of the dynamics of conducting fluids in the presence of magnetic fields is variously referred to as *hydromagnetics, magnetohydrodynamics,* and *fluid electrodynamics.*

Hydromagnetics

The importance of hydromagnetics in astrophysical phenomena may be seen from the fact that much of the region within the galaxy, including stellar atmospheres and interiors, is occupied by gas in various degrees of ionization and readily transports electric charge. Both direct observation and theoretical inference now generally support the belief that much of interstellar space, together with a large fraction of the stars, is permeated by magnetic fields with an energy density comparable to the kinetic energy density of many of the gas motions. Thus, the magnetic field stresses are comparable to the Reynolds stresses. The high conductivity of the matter indicates that it is strongly coupled to the pervading field, so that in treating most fluid motions of astrophysical interest, instead of the hydrodynamic equation,

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \frac{\nu}{3}\nabla(\nabla\cdot\mathbf{v}) + \nu\nabla^2\mathbf{v}, \tag{2}$$

one must use the hydromagnetic equations,

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) + \frac{1}{\mu\sigma}\nabla^2\mathbf{B}, \tag{3}$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \frac{\nu}{3}\nabla(\nabla\cdot\mathbf{v}) + \nu\nabla^2\mathbf{v} + \frac{1}{\mu\rho}(\nabla\times\mathbf{B})\times\mathbf{B}. \tag{4}$$

Here σ represents the conductivity of the fluid and μ the permeability in mks units.

The complexity of the nonlinear hydromagnetic equations indicates that the general problem must be divided into the several basic physical processes; consequently, the study of hydromagnetics involves the investigation of individual effects, one at a time. Instead of a

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formal general solution of equations (3) and (4), we will ultimately achieve a general understanding based on quantitative understanding of the many basic concepts (Elsasser, 1955b).

To mention but a few of the physical principles, let us consider first a fluid of very high conductivity. Then equation (3) reduces to

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{v}\times\mathbf{B}). \tag{5}$$

From equation (5) it is readily shown that the lines of force move exactly with the fluid. Formally, if C represents a contour moving with the fluid, and S the area enclosed by the contour, then

$$\frac{d}{dt}\int_S d\mathbf{S}\cdot\mathbf{B}=0. \tag{6}$$

The lines of force retain their identity, since any two elements of fluid threaded by the same line of force will remain so connected. Equation (5) is the same as the Helmholtz vorticity equation for an inviscid fluid. Cauchy's integration gives **B** as an algebraic function of the derivatives of the Lagrangian coordinates of the fluid particles (Brand, 1947).

If the conductivity is not essentially infinite, then of course the lines of force slip relative to the fluid. Besides the slipping, however, they lose their identity by continually changing their pattern of connection. Thus, for instance, a loop in a long tube of flux may detach itself from the tube, giving a magnetic ring and the original, more or less straight tube. This detaching process forms one of the basic steps in the regenerative hydromagnetic dynamo discussed below.

The forces exerted on the fluid by the magnetic field are derivable from the magnetic stress tensor, B_iB_j/μ, $(i, j=1, 2, 3)$, representing tension along the lines of force, and the isotropic magnetic pressure, $B^2/2\mu$ (Cowling, 1953), in mks units. Thus the total pressure is $p+B^2/2\mu$. Within a region of magnetic field the gas pressure p will tend to be less than it is outside by the amount $B^2/2\mu$. The gas density tends to be less within the field, resulting in the phenomenon of *magnetic buoyancy* (Parker, 1955a).

The tension in the lines of force and the mass of the fluid clinging to them indicate that the lines are analogous to stretched strings, allowing the propagation of transverse waves with a velocity whose square is equal to the stress density B^2/μ divided by the material density (Alfvén, 1950). These hydromagnetic waves are transverse, and for this reason are generated more copiously by the transverse fluid motions of subsonic hydrodynamics than are the longitudinal acoustical waves. As the magnetic energy density becomes large compared to the kinetic energy density of the fluid, all hydromagnetic motions reduce to hydromagnetic waves (Parker, 1955b). It is interesting to note, however, that the presence of the magnetic field may enhance the generation of acoustical waves (Kulsrud, 1955).

The fundamental problem of the convective stability of a rotating conducting fluid in the presence of a field has been solved by Chandrasekhar (1953b; see also 1952, 1953a, 1954a) with remarkable results. Simple Bénard cells do not occur. Instead, competition develops between the rotational and magnetic effects and results in two unstable regimes. One might say, very roughly, that the magnetic field tends to stiffen the fluid, producing stability, and the Coriolis forces tend to produce instability. The results of Chandrasekhar's analytical formulation of this very difficult problem have been given experimental confirmation (Nakagawa, 1955).

Chandrasekhar (1955) has also treated the problem of hydromagnetic turbulence and finds that there are two statistical modes, with either the fluid motions or the magnetic field dominating at large wave numbers. The analysis shows that there is not a *close* approach to equipartition of energy between the fluid motion and the magnetic field, but, on the other hand, it does indicate that $\frac{1}{2}\rho v^2$ and $B^2/2\mu$ will not differ by an order of magnitude.

The origin of the stationary dipole field of earth and that of the migrating solar fields resulting in sunspot formation are beginning to be understood on the basis of hydromagnetic dynamo effects whereby two magnetic fields in a region are each generated from the other by fluid motions. The so-called toroidal field is produced by simple shearing from the poloidal field; the latter is then regenerated by cyclonic motions in the fluid, forming loops from the toroidal field (Parker, 1955c; Elsasser, 1955b). Presumably a sunspot is formed from the solar toroidal field through a combination of magnetic buoyancy, hydrostatic equilibrium (Parker, 1955a), and the observed cooling of the interior of the spot, though most of the details remain to be treated quantitatively.

Probably nowhere does one find more phenomena whose origin so obviously cannot be explained on hydrodynamic grounds than in the violent phenomena of solar activity, such as spicules, active prominences, flares and surge prominences, the ejection of ion clouds, and cosmic ray bursts. The origins of these phenomena are today not at all understood, but one presumes that at least some of them admit of a hydromagnetic origin. The terrestrial consequences make solar activity a particularly pressing challenge to hydromagnetic research.

Understanding the terrestrial effects is important, but it has often been suggested that solar activity may prove also to be the "little brother" to some of the grander phenomena that result in the Wolf-Rayet stars, flare stars, and Babcock's magnetic variables where prominence activity, flares, and sunspots have developed to pathological proportions.

Solar activity apparently ejects field-bearing clouds of gas into interplanetary space. At the earth the clouds are somehow responsible for the aurorae, magnetic storms, certain ionospheric disturbances, the configuration of the terrestrial weather pattern, and the observed interplanetary gas density of as much as 500 hydrogen atoms per cm^3 (Storey, 1953; Siedentopf, Behr, and Elsasser, 1953; Behr and Siedentopf, 1953). Further, cosmic ray intensity variations not directly due to the immediate emission of new particles by the sun are now generally regarded (Neher, 1955) as being due to the antics of interplanetary clouds. It becomes important, therefore, to investigate the dynamics of such clouds. If at the same time the dynamics of ejection from the sun can be expounded, we will be able to check our ideas by both solar and terrestrial observations.

Cosmic rays are presumed to be accelerated by interaction with the magnetic fields carried by moving matter. The acceleration is presumed to take place in the galaxy and solar flares. One consequence of the high conductivity of most matter is that the electric field in the frame of reference moving with the fluid is very small. Thus, it is readily shown that

$$\mathbf{E}=-\mathbf{v}\times\mathbf{B}, \qquad (7)$$

where **v** is the fluid velocity, and there can be no large electrostatic acceleration effects. The general solution of the motion of a charged particle in slowing varying hydromagnetic fields, as well as calculations of several cases of abruptly varying fields, indicate that there are no hydromagnetic accelerating mechanisms other than Fermi's mechanism (Fermi, 1949) and the betatron effect (Swann, 1953; Riddiford and Butler, 1952). Since both mechanisms require that the particles initially have energies of the order of 0.5 Bev per nucleon to avoid the enormous ionization losses at low energies, one presumes that there is some more vigorous mechanism capable of accelerating particles from thermal energies in spite of the tremendous energy losses. Finding such a mechanism is obviously of fundamental importance.

The assumption that cosmic rays are accelerated throughout the galaxy (Morrison, Olbert, and Rossi, 1954; Unsöld, 1955; Parker, 1955b; Elsasser, 1955a) presents energetic difficulties. Davis (1955b) has suggested that the gas ejected from the sun forms a cavity in the magnetic field of the galaxy capable of trapping particles in the solar system, though the mechanism apparently cannot account for the cosmic ray cutoff with the attendant correlation with the sunspot cycle. A galactic origin of cosmic rays and the sweeping away of galactic cosmic rays by outgoing magnetic interplanetary clouds seems to give a suitable cutoff, but so little is known about the nature of interplanetary clouds and Davis' cavity that the details of the mechanism are entirely speculative.

Besides the evidence from the polarization of starlight (Davis and Greenstein, 1951), it has been shown (Chandrasekhar and Fermi, 1953) that the observed properties of the spiral arms of the galaxy require a magnetic flux density of about 10^{-5} gauss along each spiral arm. A magnetic field of this strength permeating the interstellar medium will be important in determining the characteristics of stars formed by gravitational collapse of the interstellar medium, for, although it does not directly affect Jeans' instability criterion (Chandrasekhar, 1954b), the field will strongly influence the nature of the fluid motions against which work the gravitational forces of collapse. Hydromagnetics evidently plays an important role in the formation, structure, and evolution of galaxies, though little has been done on the integrated problem.

The pulsations of some variable stars suggest (Chandrasekhar and Fermi, 1953; Chandrasekhar and Limber, 1954; Ferraro, 1954) that the general magnetic fields of the individual stars play an important role in determining the form and period of the oscillations of the stellar body. The tremendous general stellar field that is required implies a hydromagnetic dynamo of immense power.

Plasma problem

The extraordinary number of modes of oscillation of the electron gas in a plasma is exhibited in Bailey's (1950, 1951) general electromagnetoionic theory. Starting with a plasma in the presence of a magnetic field, and using Maxwell's equations, the equation of continuity, etc., neglecting damping by collisions, and considering small sinusoidal deviations from uniformity, Bailey finds a number of steady state modes with frequencies that are simple algebraic combinations of the plasma frequency ω_p and the gyrofrequency ω_e, which is the angular velocity of an electron in the given magnetic field. Besides these usual modes, however, there are modes which grow or decay exponentially by energy transfer to the over-all drift velocity of the ions. The presence of the magnetic field enhances the exponential growth effects. Since the theory neglects the second order terms, one does not know to what extent the exponential growth is limited.

The response of a plasma to electromagnetic waves results in an index of refraction that can be real, imaginary, or complex, and the propagation of electromagnetic waves through a nonuniform plasma is complicated and of fundamental importance (see Pawsey and Smerd, 1953). Consider the solar atmosphere in the absence of magnetic fields. The plasma frequency decreases outward so that escaping radio waves of low frequency can only have originated in the outer corona. Higher frequencies may originate farther into the atmosphere. The observed cutoff frequency at the low end of the frequency spectrum affords an indication of the level of the source in the solar atmosphere; the time rate of change of the cutoff frequency is an indication of the velocity of the source. But, at the same time, the refraction of the waves in the solar atmosphere complicates the problem of determining the heliographic position of the source.

The presence of a magnetic field further complicates the propagation, producing, among other things, a tendency of the transverse electromagnetic waves to propagate parallel to the magnetic field, as a consequence of the electrons' circling around the field. This effect appears in the terrestrial phenomena of atmospheric whistlers investigated by Storey (1953). The propagation depends upon the interplanetary gas density near the earth and so gives information on the interplanetary medium.

The anomalous sources of radio noise in the sun and elsewhere are often associated with high velocity gas or particle streams. The rate of decrease with time of the observed frequency of a given solar burst suggests that the excitation might be due to clouds that are moving out through the solar atmosphere with velocities of the order of 600 km/sec (Pawsey and Smerd, 1953); intense galactic sources have been identified with galaxies in the process of passing through each other (Baade and Minkowski, 1954). The radio emission presumably arises from the collisions of the interstellar gas clouds contained in the interpenetrating galaxies (Greenstein and Minkowski, 1954). The presence of high velocity streaming and the general difficulty with thermal mechanisms (requiring temperatures up to 10^{15} ° K) in the more intense sources suggest the investigation of vigorous macroscopic phenomena such as the exponentially growing plasma oscillation (Bailey, 1950, 1951; Haeff, 1948, 1949; Pierce, 1948; Bohm and Gross, 1949, 1950; Buneman, 1950; Malmfors, 1950; Blum, Denisse, and Steinberg, 1951; Twiss, 1951). To establish whether plasma oscillations are responsible for the intense sources, one will have to obtain a detailed knowledge of the streaming which supposedly excites the oscillations. Then one must investigate the effects of the nonlinear terms and the actual boundary conditions found in nature in order to determine to what extent the oscillations will grow and whether the electromagnetic radiation generated by the radiations can escape. The question of escape has already been investigated but with conflicting results.

Perhaps the acceleration of cosmic rays is closely associated with the origin of radio noise; both might seem to require, or are observed to have, association with violent fluid motions. Hydromagnetic processes seem unable to furnish the injection energies needed for Fermi's mechanism and for the betatron effect. Thus, obviously, investigations of violent plasma phenomena should be carried out with cosmic rays as well as radio noise in mind.

But in contrast to this point of view is the recent discovery that the visible and radio spectrum of the Crab Nebula can only be explained as synchrotron radiation from electrons with energies of the order of 1 Bev, which by definition are cosmic ray particles (Shklovsky, 1953). The radio emission from the galactic halo seems to require a similar mechanism. Thus, because we are ignorant of the "basic" energy source, cosmic rays become the apparent prime mover.

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Solar System

Earth's Magnetism

By Walter M. Elsasser [1]

An explanation of the phenomena of geomagnetism is of interest to theoretical astrophysics not just because the earth happens to be a celestial body, but mainly because to reproduce such phenomena in a conventional laboratory is extremely difficult if not nearly impossible. Physical processes in the universe clearly fall into two classes: those that have a readily accessible laboratory equivalent (e. g., spectroscopy, nuclear reactions), and those that do not (e. g., radiative viscosity, large-scale turbulence). The phenomena we choose to designate as hydromagnetic, of which geomagnetism is the prime example, belong to the second class. The nearest hydromagnetic phenomena beyond the confines of the earth are those on the sun, particularly in sunspots, but their study has shown them to be exceedingly complex.

Babcock's now classical investigations of stellar magnetic fields started as a search for magnetic fields in early-type stars. These were chosen because many of them are known to rotate rapidly and a connection between rotation and magnetic fields was suspected. The conditions under which stellar magnetic fields can be ascertained are extremely stringent: the stars must be bright enough (≥7th mag.), and the *average* magnetic field over the visible face of the star must be at least several hundred gauss. Of the stars investigated, 65 had to be rejected as spectroscopically inadequate for the analysis, 35 yielded measurable magnetic fields, and in another 20 magnetic fields are suspected but not yet assured (as of 1953, the date of Babcock's review). As Babcock points out, this is an extraordinarily large yield even from a purely statistical viewpoint, and the presumption is justified that very many stars possess magnetic fields of appreciable magnitude. There is also reason for the belief, based on the investigations of A. Deutsch, that phenomena equivalent to sunspots, but sometimes of much larger extent, occur in many stars. Perhaps it is useful to recall that the magnetic field is the dynamically essential feature of a sunspot, as evidenced by the fact that the mechanical forces exerted by the magnetic field exceed all other forces acting in a sunspot.

The main interest in cosmic magnetic fields centers on two problems: first, the way in which they influence observable astrophysical phenomena, stellar atmospheres, interstellar gas motions, radio noise, the acceleration of cosmic rays, and others; and second, the manner of their generation. The first class of problems lies outside the domain of this paper, but is dealt with elsewhere in this volume. The earth does furnish us with a prime example of the mechanism of generation of large-scale magnetic fields; indeed, there is reason to believe that geomagnetism lends itself somewhat more readily to the construction of a consistent theory than do the phenomena in the solar convection zone which give rise to sunspot and solar magnetism, not to speak of the magnetic fields of stars whose details are barely, if at all, accessible to observation.

The ubiquitous presence of magnetic fields in the universe leads one to accept a model of the generation of the earth's magnetic field which demonstrates that magnetic fields can be generated, and maintained, by inductive amplification in an electrically conducting fluid of sufficiently large dimensions. This is the *dynamo* theory for which a great deal of observational evidence now exists. In keeping with the nature of this volume we shall not dwell on the evidence in detail, but shall emphasize the basic dynamical features and their implications.

The geomagnetic dynamo is located in the earth's liquid core (diameter 0.55 of that of the

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earth). There seems little doubt that this core, which seismological evidence has shown to be fluid, consists of molten iron. It may be shown by an analysis of the observed field that the sources of the geomagnetic secular variation are located near the boundary of the core. The geomagnetic secular variation is a very remarkable phenomenon; it is the only effect originating in the *interior* of the earth whose spectrum has periods of order of some tens up to some hundreds of years, whereas all geological processes are of course measured in millions, at the best in hundreds of thousands of years.

The earth's magnetic field (if we ignore the very small component that originates in the ionosphere) consists of a dipole inclined by 11½° relative to the earth's axis, and of an irregular part made up of all the higher terms of a spherical-harmonic analysis. If the time dependence of the irregular field is considered, it is found that in all probability this irregular field does not have a component constant in time. The dipole axis also changes in longitude and latitude, but much more slowly than the higher spherical harmonics. There is at present a good deal of evidence from paleomagnetism (the study of the remnant magnetization of rocks) to the effect that the present angle between the geographical axis and the magnetic dipole axis is larger than it was in the (r. m. s.) average over past geological periods, and that the statistical distribution of these angles is centered about the geographical axis. This result indicates the reality of a close connection between the earth's rotation and its magnetic field which the dynamo theory postulates.

The secular variation (which is essentially the time derivative of the nondipole component of the geomagnetic field) originates in a relatively thin layer at the top of the core. The reason for this is that a layer of metal acts as a screen for time-dependent fields, and the periods of the secular variation are such that they would be effectively screened off by a layer, say, 100 km thick. Thus the secular variation cannot give us information about the interior of the core where the essential part of the dynamo mechanism is located, but it does teach us something about the outer layers of the core and, incidentally, about the relation of the core and the solid part of the earth, the mantle, surrounding it.

In order to explain the observations it is necessary to assume that the mantle has a small electrical conductivity. This is plausible considering the temperatures of perhaps 2,000–4,000° prevailing in the lower mantle. Some of the magnetic field generated in the core on penetrating into the mantle sets up a mechanical force there. As a result of the action of this force, there is a small difference in angular velocity between mantle and core, the mantle rotating slightly faster than the top layers of the core. In the stationary state a balance is achieved between the accelerating force just mentioned and an opposing eddy friction, the latter probably also of a magnetic nature. The differential rotation has been observed and analyzed; it is known as the westerly drift because for an observer stationed at the earth's surface, the individual features of the irregular magnetic field seem to undergo a slow average motion toward the west. It has also been shown that this motion is suffering fluctuations of moderate size over periods of 10–20 years. These fluctuations appear correlated with the fluctuations in the earth's (more precisely, the mantle's) rate of rotation which are directly observed in positional astronomy of the moon and planets. Theoretical analysis has led to the result that these fluctuations in the earth's angular velocity can be satisfactorily explained in terms of a slightly variable magnetic coupling between core and mantle. The required fluctuations of the magnetic fields near the boundary of the core are quite in keeping with what we might expect on the basis of our general knowledge of the earth's magnetic field. The fluctuations may be either in the over-all field producing a torque on the mantle or may be due to changes in the (magnetic) eddy friction which counterbalances the accelerating torque. In any event, this explanation of an important astronomical phenomenon seems now to rest on a sound geophysical basis.

As we go into the interior of the core there appears a type of magnetic field which has no counterpart on the outside, the so-called toroidal field. In a pure toroidal field the field lines would be circles about the earth's axis (the actual field in the earth is a superposition of more than one type and hence more complicated). The toroidal field, since it cannot be observed directly, had to be inferred from solutions of the electromagnetic field equations, but its existence does not underlie any serious doubt since its existence is mathematically necessary. The toroidal field apparently is appreciably larger than the dipole field in the interior of the core, being perhaps of order 20–40 gauss. Its counterpart also exists in the solar convection zone, and there is reason to believe that it provides the field from which the sunspot fields are ultimately formed.

Some 20 years ago C. T. Cowling showed that a fluid in which the motion is confined to meridional planes cannot form a dynamo. This result may be generalized to the statement that no fluid motion of rotational symmetry about an axis can maintain a dynamo. There are good theoretical reasons, furthermore, to believe that no two-dimensional motion, that is, no motion in which the fluid particles are confined to surfaces, is capable of providing dynamo action. Hence dynamos have an essentially three-dimensional geometry; this makes the structure and dynamics of even the simplest models so complex that we prefer not to expound them here in any detail. Instead, we shall confine ourselves to a discussion of the essential ingredients of dynamos, the general theorems on which their operation is based and which make their existence plausible. So far as we can judge, these principles are most likely to be the same for all hydromagnetic dynamos, the terrestrial one as well as the solar and stellar ones.

The simplest formal conditions appear in the limit of infinite electrical conductivity. One can then show that

$$\frac{d}{dt}\int B_n\,d\sigma=0, \qquad (1)$$

a theorem which states that the magnetic flux normal to a given arbitrary surface remains constant in time as this surface is carried with the fluid. This result, first given by Cowling, has sometimes been expressed by saying that the magnetic lines of force are "frozen" in the fluid and are bodily carried along by it. It may readily be seen, then, that the magnetic field can be sheared or twisted locally by the fluid motion so that *amplification* results. It remains to be demonstrated that amplificatory processes can be organized in such a way that they can maintain the magnetic fields observed on the earth, sun, and stars. This turns out to be an exceedingly difficult mathematical problem. Those who seek a formal solution after the manner of existence proofs for the solutions of differential equations are likely to remain disappointed. The problem is essentially nonlinear (clearly, no linear system can exhibit self-sustained amplification) and our understanding of the behavior of nonlinear dynamical systems is still in an extremely rudimentary state. Those making an analysis must, for the time being, be content with inadequate rigor and must rely to some extent on intuition, keeping in mind that there are definite phenomena waiting for explanation. The present writer finds this situation rather challenging to the theoretician, but he realizes that it does not always appeal to the more mathematically inclined analyst.

Equation (1) applies only to a medium of infinite conductivity. In such a fluid we could not have a steadily operating dynamo because the continued stretching and twisting of lines of force would (as Bondi and Gold have remarked) result only in a progressive confusion of magnetic fields, not in a stable pattern. In a fluid of finite electrical conductivity, the right-hand side of (1) is no longer zero. The ratio of the right-hand to the left-hand side is then measured by a nondimensional quantity known as the "magnetic Reynolds number,"

$$R_m=LV\sigma \qquad (2)$$

where L and V are length and velocity, used in the manner known from the conventional hydrodynamic Reynolds number, and σ is the conductivity of the fluid (in e. m. u.). R_m is large, that is, the conservation theorem (1) is approximately fulfilled when we are dealing with large linear dimensions. In the core of the earth and still more in the stars, R_m is as a rule quite large numerically. This fact can be expressed in a rather concrete physical language by saying that for large R_m, the time required for spontaneous decay of the electromagnetic fields in the fluid is long compared to the periods of the mechanical fluid motion; R_m as defined by (2) can be shown to be indeed the ratio of these two time constants. In the laboratory R_m is as a rule numerically small; this cannot readily be remedied since all three factors on the right of (2) are clearly limited in laboratory experiments. Since the functioning of hydromagnetic dynamos depends essentially on the field's being carried along by the fluid, that is on large R_m, it follows that hydromagnetic dynamos are essentially a matter of cosmic physics; namely, of very large linear dimensions. This substantiates our previous contention that the earth is the nearest thing to a laboratory of hydromagnetism, at least so far as dynamos are concerned.

If the magnetic lines of force are continuously stretched and twisted, as is the case in the turbulent regime of a conducting fluid, the average result may be shown to be amplification of the existing field. This increase is likely to stop when a state of equipartition is achieved where there is an amount of average magnetic energy equal to the average kinetic energy of the fluid motion. Hydromagnetic turbulence fields are of great astrophysical interest (they have been investigated by Chandrasekhar) but it is clear that they do not constitute dynamos. The latter are called on to produce and maintain observed magnetic fields which are of a high degree of regularity; e. g., the earth's dipole field.

We have mentioned before that a fluid can act as a hydromagnetic dynamo only if its motions are essentially three-dimensional. Thus a stably stratified fluid where motions can at best take place in the approximate direction of equipotential surfaces cannot act as a dynamo. Under the actual conditions of geophysics and astrophysics the fluid must be thermally unstable and hence in convective motion. We do not know the exact causes of convection in the earth's core. We are better off with regard to the sun and stars; there we can be rather certain that the hydrogen convection zone is the seat of amplifying processes that lead to hydromagnetic dynamos.

A relation between rotation and dynamo action is clearly indicated by the behavior of the earth's magnetic field and is corroborated by much astrophysical evidence. Theoretical arguments lead to the conclusion that rotation of the conducting fluid is essential for dynamo action. If a convective layer rotates, the convective transport of angular momentum leads to an average state where the layer rotates nonuniformly, the outer parts of the layer rotating less rapidly than the inner. If we assume a dipole field in the interior of the earth's core, such a field will be drawn out by the nonuniform rotation so as to give rise to a toroidal field. The toroidal field in turn sheds magnetic eddies which, under the influence of the Coriolis force, may be shown to behave in such a way that reinforcement of the "poloidal" (dipole) field results. Through the theoretical investigations of recent years it has become very probable that dynamo action results from the interplay of mutual amplification of two types of field components, the toroidal and poloidal fields. They correspond roughly to the two coils, say the stator and rotor of a conventional electrical generator. In the analysis of the geomagnetic dynamo this mechanism appears fundamental; the stellar dynamos are perhaps somewhat more complicated, but ultimately should reduce to a similar type of interaction.

A conspicuous feature of dynamo mechanisms of this type is their low geometrical symmetry. Convection excludes any motions that do not have a radial component, and the Coriolis force which is not invariant with respect to the interchange of east and west leads to patterns of fluid motion that do not have rotational symmetry about the earth's axis. The fluid motions required for the terrestrial dynamo do not seem to have any geometrical symmetry, and this is probably characteristic of hydromagnetic dynamos in general. Even in technical generators the system of wires, commutators, etc., forms a low-symmetry structure. In this requirement of low symmetry, hydromagnetic dynamos differ from most of the traditional problems of classical dynamics where it has been the custom to make problems accessible to solution by using symmetry operations for their mathematical simplification. This situation might account for the slow pace with which the theoretical explanation of the phenomena of terrestrial and solar magnetism has developed in the past, in spite of the fact that many of the observations are far from recent. It is hardly necessary to say that under these conditions the subject offers many challenging opportunities for analytical investigations of fundamental importance to astrophysics. The going will admittedly be difficult and new analytical techniques seem to be called for before one can hope for major successes.

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Time

By William Markowitz[1]

The problems of chief interest concerning time are the precise nature of the variations in the speed of rotation of the earth and the relation between the gravitational and atomic time scales.

The first problem deals with the basic properties of the earth. The second deals with a fundamental physical property of the universe. Although we do know that variations in the speed of rotation of the earth occur, we are not certain of the details. In fact, within the last few years many of the ideas on the subject have been drastically revised. As to the second problem, we have no idea at all, at present, whether or not the gravitational and atomic time scales are the same; this must be decided by experiment.

It has been known for some time that the speed of rotation of the earth is subject to changes, which may be classified as periodic, irregular, and secular. These variations made the mean solar second unsatisfactory as the fundamental unit of time for scientific and technical purposes. Accordingly, in September 1955 at Dublin, the International Astronomical Union redefined the unit of time as a specified fraction of the tropical year for 1900.0. The new unit is identical with the second of Ephemeris Time, and is obtained in practice from observations of the moon.

I shall briefly describe recent developments concerning studies of the rotation of the earth and the instruments and clocks used in determining time.

The yearly and semiyearly periodic terms were found by Stoyko at Paris in 1937 and were confirmed at Greenwich. Later, large changes in these terms from year to year were indicated. However, a homogeneous solution based on observations made with the photographic zenith tubes (PZT's) of the U. S. Naval Observatory (Markowitz, 1955) showed little change from year to year for the interval 1951–1954. Short-period terms due to tidal action of the moon were also found.

It was formerly believed that sudden changes in speed of rotation as large as several milliseconds per day occurred at irregular intervals. Brouwer (1952), however, has been led to the hypothesis that the irregular changes are caused by small, cumulative, random changes in speed of rotation and that the large sudden changes do not occur.

Tidal friction tends to slowly diminish the speed of rotation. Holmberg (1952) has recently pointed out that atmospheric tides may increase the speed of rotation, an idea due to Lord Kelvin. Hence, we do not know whether the earth is slowing down or speeding up.

The quartz-crystal clock, which has replaced the pendulum clock in precise timekeeping, had been developed by 1950 to the point where it could reliably be used to determine the periodic terms in the speed of rotation of the earth. In 1955 the announcement was made that an atomic standard of high precision had been constructed which can be compared with astronomical observation (Essen and Parry, 1955).

A program is now under way to obtain the frequency of the atomic standard in terms of the Ephemeris second as determined at the U. S. Naval Observatory with the dual-rate moon position camera. If the frequency changes in the course of time, the gravitational and atomic time scales are not alike. An answer may be obtained within 10 years.

The atomic standard will also be used to study variations in the speed of rotation of the earth by comparing Universal Time with atomic time.

Thus, we shall shortly be comparing atomic time with astronomical time—Ephemeris and Universal—to provide information on the problems cited. The atomic standard apparently

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[1] Director Time Service, U. S. Naval Observatory, Washington, D. C.

reproduces the behavior of the cesium atom to one part in 10^9, and higher accuracies will probably be attained. At present the frequencies that can be obtained from astronomical observation have precisions of several parts in 10^9. The probable error of the differences between atomic time and astronomical times will be due almost entirely to uncertainties in the latter. Hence, it is the astronomical determination of time which must be improved. An artificial satellite which does not move within the earth's atmosphere could provide another determination of Ephemeris Time. We must wait and see, however, what particular satellites are created and how well the position can be determined. In general, we must look forward to continuing and improving the present techniques in time determination.

We shall now consider what needs to be done. The Committee on Needs in Astronomy asks where financial aid might prove most beneficial in aiding progress. Dr. Struve (1955), in his article "The General Needs in Astronomy," asks a more basic question; namely, should more attention be given to the type of positional astronomy carried out at the U. S. Naval Observatory, and should more research be done in this country with respect to the earth as a body?

I should like to answer these questions for the fields of meridian astronomy and for time determination. Both types of observation provide basic astronomical data which can not be obtained in any other way. Hence, research in both fields should be encouraged in order that results of the highest possible precision may be obtained.

The determinations of time and of fundamental positions have become highly specialized fields, and are carried on in the United States only at the Naval Observatory. The observing techniques have been improved over the years, and other astronomers in the United States have been relieved of the necessity of doing similar work. On the other hand, these astronomers have become isolated from developments in these fields. In the United States instruction is not given at any school or observatory in time determination or meridian astronomy as currently practiced. The end result is that, because of the general shortage of scientists and of astronomers as a whole, there is a particularly acute shortage of astronomers entering these fields.

For the past few years the Naval Observatory has not been able to fill vacancies in the Time Service and Transit Circle Divisions with astronomers, and the outlook for the future is not encouraging. What is desired is that enough astronomers be trained so that work in these fields can be actively pursued at the Naval Observatory, and so that, in addition, research—at least in theoretical aspects of the problems—can be pursued at some other observatories or schools.

From time to time foreign astronomers and students have come to the Naval Observatory for study and research. Such visits could also be made, with considerable benefit, by American astronomers and students. The minimum useful period would be about 2 weeks, while for research and thesis purposes at least a semester would be required.

Hence, if money is to be spent to promote advances in these fields, it can best take the form of grants for study at the Naval Observatory. Grants could be made to teachers and writers of textbooks in astronomy and even to a few undergraduates. At the present time money is available for research grants, but few requests for research in these special fields will be received until there are more astronomers able to use the grants.

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Geographical Positions

By John A. O'Keefe [1]

The determination of position on the surface of the earth is the subject of two branches of astronomy; namely, field astronomy and geodesy. The latter is not always considered as a branch of astronomy, but Simon Newcomb in the Encyclopedia Britannica has given us a precedent for doing so; and it seems very reasonable on historical and logical grounds.

It is the function of field astronomy to provide the initial orientation and position for the surveys which determine geographical position. Geodesy then extrapolates these positions by means of measurements on the ground to cover a whole country, or even a whole continent, without further reference to the stars, except for orientation. The role of extrapolation in geodesy is unique, so far as I know, in science. If it were physically possible, the geodesists would certainly prefer to have only a single astronomical determination for the whole world and to rely on geodesy for all other determinations. The reason for this is, of course, that because of the irregularity of the earth's crust, the direction of the vertical at any point is not exactly what would have been expected on the basis of a perfectly ellipsoidal earth. So long as we are thinking only of navigation at sea these errors, which very rarely amount to as much as one nautical mile, are insignificant. But when we deal with precise land surveys, we can extrapolate relative positions halfway round the world from the measurements of triangulation more precisely than they can be found from on-the-spot measurements by field astronomy.

As a consequence, vast nets of triangulation have developed which must, for the best results, be adjusted simultaneously. The feat of adjusting systems of equations that involve several thousand unknowns has been accomplished repeatedly in the last few years.

Because he cannot measure vertical angles with anything like the precision with which horizontal angles are measured, the geodesist lives in a mathematical world which is exactly like the Flatland of Abbot's famous book, so long as it is a question of geographical positions. He knows the lengths of his lines and the angles between them, but he does not know the space configuration of the surface upon which he works—the sea-level surface and its prolongation under the land. The maneuvers by which he succeeds in avoiding the unanswerable questions about the space situation bear a remarkable resemblance to the squirming of the relativists when asked how their curved space would look from the outside. The resemblance is a family one, since C. F. Gauss is the father of both systems of thought.

Of course there are techniques for finding heights, but these are only with relation to this sea-level surface of unknown form.

The principal application of the techniques of field astronomy in geodesy is therefore in determining the form of the sea-level surface of the earth, for each measurement of an astronomical position determines the slope of the sea-level surface at a point. The difference between the astronomically measured position and the geographical position determined geodetically is, in fact, the slope of the sea-level surface at that point (if we assume that the slope at the initial point was zero). From a large number of such determinations of slope, the form of the sea-level surface can be found by integration.

Finally, we may also seek to find the form of the sea-level surface of the earth from the measurements of gravity. There is a famous theorem, called Stokes' theorem, which connects the form of the sea-level surface of the earth with the measured values of the intensity of gravity.

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[1] U. S. Army Map Service, Washington, D. C.

Thus the classical approach was to deal in terms of known angles and known distances on a largely unknown surface, the determination of whose form was left to a small group of geophysicists, since the mathematicians had found ways to bypass the requirement for it. By extrapolation, vaster and vaster systems of triangulation have been constructed, until now we have most of the Western Hemisphere on one system, and most of the Eastern Hemisphere on another.

The new techniques

The geodimeter is rapidly replacing the invar tape for the measurement of baselines. The geodimeter is essentially the result of reversing the Fizeau method of getting the velocity of light so that, from the known value of the velocity, the distance is found. The toothed wheel is replaced by a Kerr cell, modulated by ultra high-frequency voltages. The new technique has proved remarkably successful in trials over the last few years, since it measures directly the triangulation sides. The old invar tape method could be employed only on relatively short lines, which then had to be related to the long lines of the regular chains by an elaborate base-expansion net.

The employment of radar for the measurement of great distances is rapidly expanding. The most useful tool at the present time is the modification of the wartime Shoran, which is known as Hiran. The principal new feature of Hiran is the attempt to reduce the signal intensity correction by the use of gain control. The Mediterranean has been bridged by this method from Crete to Libya; the North Sea from Scotland to Norway; and the Straits of Florida from Key West to Cuba.

For yet longer lines, radar techniques do not seem to work. The methods that go over the horizon depend on the ground wave; and the velocity of the ground wave depends, it seems, on the nature of the ground. Repeatability is rather easily secured; but the interpretation of the results offers considerable difficulty at the present.

The moon is now being employed for measures over the horizon. The parallax of the moon, unlike that of any other celestial object, is large enough to furnish a method for the determination of place on the earth. There are several ways of using this fact; each of them deals in its own way with the twin difficulties of the remoteness of the moon and the irregularity of its surface.

The most perspicuous method is that of Markowitz, who simply photographs the moon in a star-field and measures the distances from points of the moon's limb to the stars. Simple as the theory is, its practice was not mastered until recently. The light of the moon must be reduced by a filter so that it can be observed on the same photograph as an eighth magnitude star, 100 million times fainter. The motion of the moon during the time required to obtain an image of an eighth magnitude star amounts to several miles; this must be allowed for by a special optical device which, in effect, arrests the motion of the moon relative to the stars for a few seconds. The measurements are made with great care with a precise measuring engine, and the effects of limb irregularities are taken out by averaging about 30-odd points. The result of a pair of plates has a probable error of 0.15 second of arc in each coordinate, which amounts to about 900 feet on the ground because of the moon's remoteness. To obtain more precise results on relative positions, it is now planned to obtain a long series of observations.

A second method, which aims to obtain greater precision in the individual observations, makes use of eclipses. Near the moments of second and third contact, the relative positions of the sun and moon may be determined from photometric measurements of the flash spectrum or of the Baily beads. Since the limbs of the sun and moon are alined *in space*, there is no disturbance from atmospheric refraction of this relation. In addition, the resolution theoretically obtainable far exceeds the resolution of the best telescopes.

The weakness of this method is that the photometric observations are disturbed by scintillations of the beads. This is a serious matter because the diminution of brightness at the sun's limb is not instantaneous; hence it is necessary to fix an arbitrary level of brightness as corresponding to the limb. The precise determination of the moment when this brightness is reached is troubled by the scintillation.

The precision of a tenth of a second in arc which is required for the success of these methods is thus difficult to reach even for an individual bead. For the elimination of the irregularities of the lunar limb, reliance is placed on the averaging of large numbers of points.

A very similar technique starts from observations of the occultation of stars by the moon. For precise results it is not sufficient to rely on visual observations because of the relatively long and uncertain reaction time of the human nervous system. Photographic observations are likewise excluded because of the relatively low efficiency of the photographic plate in detecting faint stars in a short time. The only practical method has turned out to be photoelectric.

As compared with eclipses, occultations are relatively sharp and well-defined phenomena, consequently there is relatively little disturbance from scintillation. The precision with which the angles can be measured is of the order of 0.005 second of arc, which partly compensates for the moon's remoteness. On the other hand, there is no chance to allow for the lunar irregularities by averaging, since a single occultation refers to a single point of the moon's limb. To remove the effects of the irregularities, it has been found necessary to place the observers in such a way that all observers of a given occultation see the star disappear behind the same point of the moon's limb. This means that the telescopes must be portable and that special computations must be made to determine the points at which they are to be placed. Not more than two occultations can be observed per month by a single astronomical party because of the problems of movement and survey.

The lunar methods of determining position do not fit into the conventional picture of the old triangulation. They do not fix either the direction or the distance between the points involved; rather, they yield condition equations involving both the horizontal and the vertical positions. They represent the approach of a new point of view in geodesy.

The geodesy of the future

A development that will most certainly come with the future is the three-dimensional attack on geodetic problems. In aerial photography as a method of mapmaking, we have already seen the entry of the three-dimensional approach into the actual preparation of the topographic map. With the development of aerial triangulation, we are witnessing in our times the gradual but steady superseding of the lower order triangulation. At present, in advanced mapping projects, only the first-order triangulation is felt to be required, unless there is a question of cadastral mapping. Even for cadastral projects, there are reports that the necessary accuracy has been attained by aerial methods.

The most important change in the geodesy of the future will come, perhaps, from the application of the satellite. Its use will present a genuinely three-dimensional problem, so that the determination of height with respect to the center of the earth will be on a par with the determination of ground position.

The satellite can be employed like the aircraft of the Hiran and flare observations. That is to say, its position can be fixed from one set of ground stations while another set of positions in a new area is fixed from the satellite. This procedure parallels the procedure in flare triangulation, where the aircraft position is fixed by one group of stations by intersection while the positions of the unknown stations are fixed by resection (three-point fix) from the aircraft. However, there is one important difference. In speaking of positions in the flare problem, we mean only the horizontal coordinates; in fact, the vertical coordinate is not normally measured. In the satellite case, the vertical angle will be measured along with the horizontal angle, since the altitude above the horizon will be sufficient to permit this; and hence we shall have what the photogrammetrists call the problems of space intersection and space resection.

There is another difference, however, which arises from the fact that the satellite position can be successfully extrapolated forward, or interpolated, so that the observations of intersection and resection do not have to be simultaneous, as they must be in the case of aircraft. This greatly increases the flexibility and range of the method.

In addition, the satellite can be used to determine more precisely the parameters that fix the size and shape of the earth. This subject, which belongs under another heading in this book, is yet germane to the discussion of geographical positions because the assumed numerical values of the size and shape of the earth are formally involved in all surveys or maps which are expressed in latitudes and longitudes. Although this question could be avoided by the use of rectangular coordinates, as a practical matter it is not; and hence we can expect that the establishment of definitive values of the earth's semimajor axis and of flattening will materially assist in the international coordination of survey and map material.

Celestial Mechanics

By G. M. Clemence[1]

The unsolved problems in celestial mechanics are very numerous; in fact, relatively few problems have been solved with all the rigor, generality, and elegance that may be desired.

The problems are of widely varying degrees of generality. In the most general case we may study the character of the motions of any system of bodies, real or imagined, under any initial conditions whatever. In the least general case, we must be able to calculate the actual orbit of a particular body for a limited time and to compare it with observed positions of the body; our purpose in this case may be either to find the body on a future occasion or to study the discrepancies between theory and observation.

It probably is not possible to say that one such problem is more important than another, in an absolute sense. I have selected for discussion here two that seem especially interesting because of the many practical applications that could immediately be made, once the solutions become known, and also because fast calculating machines will be of no assistance in solving them. Thus I may disprove the common belief that such machines can supply all the answers to problems in celestial mechanics.

The first may be called the problem of the generalized planetary theory. The solar portion of the lunar theory has been brought to a high degree of formal perfection; the coordinates of the moon relative to the earth, as affected by the disturbing action of the sun, are represented as the sum of trigonometric series, each term of which is strictly periodic with a constant coefficient. Thus the series may be evaluated for any value of the time whatever. In the development of the series, advantage is taken of the smallness of the ratio of the distances of the moon from the earth and sun, with expansions being made in powers of this ratio.

The heliocentric motion of a planet under the disturbing action of another planet is a very different case, since the corresponding ratio is so large in general that expansions in its powers are not practicable. In the methods so far used, the difficulty has been overcome by allowing the time and its positive integral powers, reckoned from an arbitrarily chosen initial epoch, to appear as factors of the trigonometric terms, outside of the arguments. Thus the terms lose their strictly periodic character. As the time increases without limit so do the coefficients, and the series necessarily loses its physical significance at times very remote from the initial epoch. In the applications of the method so far made, the practical value is limited to a few thousand years at most.

The ability to construct a planetary theory having the same generality as the solar portion of the lunar theory has long been recognized as very desirable, and several unsuccessful attempts have been made to devise a practicable method. The failures should not deter anyone from taking up the problem again. The qualifications needed are a sound basic knowledge of the principles of celestial mechanics and of the art of practical computation, acquaintance with the power and limitations of electronic calculating machines, and a readiness to discard the traditional methods for new and unconventional ones.

The second problem to be mentioned is that of adapting the conventional planetary theory to automatic electronic calculating machines. By conventional planetary theory is meant the kind already mentioned, where the time and its powers appear as factors of the periodic terms. In spite of its limitations the theory is of great value and deserves many more applications than it has had. The principal difficulty in adapting it to automatic calculation is that the most discriminating judgment is required

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at all stages of the work if the amount of arithmetic is to be kept within reasonable bounds. For example, the actual calculations involved in Hill's theory of Jupiter and Saturn, which occupied him for 8 years, could be performed in a very few hours with a modern machine if it were practicable to incorporate all of Hill's judgments in the automatic program. But to devise such an elaborate program might well require 8 years of detailed planning, with even more liability to error than was the case with Hill's own work. The obvious alternative, to simplify the program at the cost of letting the machine do unnecessary calculations, is not attractive; it appears that with the most simple program conceivable the machine would do about a million times as much arithmetic as is necessary, and that with the sort of program that could be laid out in a year the machine would still work for some thousands of hours. Another possibility is to start and stop the machine a thousand times in the course of the work in order to give the astronomer an opportunity of exercising his judgment. But the most attractive method would be to recast the form of the developments completely so as to avoid the numerous multiplications of pairs of trigonometric series, which have to be integrated term by term, and to substitute for them a more easily controlled numerical representation of the disturbing forces. It may reasonably be expected, although it is not certain, that the new method would involve more numerical work than the old; we would willingly accept any increase up to, say, a hundredfold.

Meteorites

By John S. Rinehart[1]

Meteorites are bits and pieces of extraterrestrial matter which have survived the rigors of their passage through the earth's atmosphere. Small ones and some quite large ones are recovered. They are our only ponderable extraterrestrial material. As such, they are a storehouse of information to the astronomer.

The science of meteoritics embraces a wide diversity of technologies: geochemistry, geology, physics, chemistry, aerodynamics, astronomy, astrophysics, minerology, and metallurgy.

The meteoriticist carries out a variety of activities. He may simply collect, catalog, and display meteorites. He may study their metallurgical and crystallographic structures and cogitate on the cosmological significance of his findings; he may measure the relative abundances of chemical elements in meteorites and try to relate them to the universe as a whole; he may investigate the craters that have been formed by meteorites striking the earth, or the debris that a meteorite spewed about as it hurtled through the air.

In contrast to many other branches of astronomy, meteoritics, in a broad sense, has been seriously neglected by scientific investigators. Although much has been written about meteoritics in recent years, we still lack a well integrated concept of the science. The goal of future studies must be to effect this integration. Before this can be accomplished, a multitude of specific problems will have to be defined and solved.

Where do they come from, these metallic and stony calling cards from outer space? What are they like? How many are there? The answers to these questions will tell us a great deal about the origin of the solar system, the structure of the major and minor planets, and the relative cosmic abundances of the elements.

The classification and description of meteorites is in good order. Meteorites are named according to the locality in which they are found. They may be classed roughly as irons, stony-irons, and stones. The irons contain three main constituents in varying proportions: kamacite, which corresponds to the α-phase in the pure iron-nickel alloys (up to 6.2 percent nickel by weight); taenite, corresponding to the pure γ-phase; and plessite, which may consist of a microscopic octahedral arrangement of kamacite and taenite or may be of a granular nature. If the meteorite contains more than 6 percent nickel, kamacite and taenite bands appear interlaced in an octahedral pattern, known as Widmanstatten figures. Occasionally an iron will have inclusions of iron sulfide, iron phosphide, diamonds, graphite, and other minerals. The stony irons are of two kinds, those in which the iron is distributed as nodules and those in which veins of iron are intertwined with siliceous material. The stones consist largely of siliceous material, through which are interspersed only flakes or fine veins of iron.

Meteorites have been described in a variety of ways. X-ray studies have established the crystal structures of kamacite and taenite and the crystallography of the Widmanstatten figures. Neumann bands have been identified as mechanically twinned regions. Gross compositions and densities of a large number of meteorites are known. The relative abundances of elements, particularly the rarer ones, have been found by the use of neutron activation and isotope dilution techniques.

The classical method of fixing the age of a meteorite is to determine the relative amounts of helium, uranium, and thorium it contains. Originally, investigators assumed that all of the helium was derived from radioactive disintegration of uranium and thorium. Recently, the existence of helium generated by

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cosmic rays has been demonstrated and allowed for in age calculations. An argon-potassium method, which is limited in application to stony meteorites, an isotopic lead composition method, and a strontium-rubidium method are all in use. The apparent ages of the stony phase of meteorites determined by each method are in substantial agreement, approximately 4×10^9 yr. Iron meteorites are much younger, 3×10^8 yr, according to the uranium-helium method; but the tritium measures by Fireman on recently fallen irons indicate that some billions of years would have been required for cosmic rays to produce the observed He^3. These age discrepancies need resolution. Is it possible, as Urey has suggested, that radioactive He escapes while cosmic-ray He remains—a consequence of radioactive substances crystallizing only on grain surface?

Physical metallurgy has contributed significantly, though not extensively, to our knowledge of the origin and age of meteorites. The approach here is indirect. Consideration is given to the combined pressure and temperature conditions, aging, and constraints that could have produced the observed metallurgical structures. Especially important are the Widmanstatten figures, the local concentration of nickel within elements of the figures, and phase transitions indicative of pressure changes. Research in this area has been exploratory and fragmentary. The need for more work both on terrestrial alloys and meteorites is great. The influence of pressure on the phase diagram of the iron-nickel system is not known, nor have the diffusion coefficients of nickel in iron been established. The segregation of elements on a microscale is a completely untouched though most fertile field.

Neumann bands, slickensides, distorted layers, crushed nodules, cleaved surfaces—each has its story to tell if we can but read it. Mechanical metallurgy is almost completely unexplored.

At least 10 authenticated large meteorite craters exist on the earth. The moon contains some 2,000 craters believed to be of meteoritic origin. These craters are important geological and selenographical features. They are, moreover, positive evidence of encounters between substantial chunks of fast-moving planetary and interplanetary material. Study of the craters gives us much insight into the cosmological role of such physical encounters. It is only recently that such craters have been recognized for what they are, and it is still difficult in most instances to state unambiguously the velocity and mass of the meteorite that made the crater. Indeed, it is frequently difficult to know for certain that the crater is of meteoritic origin. If we are ever to know the rate of accretion of matter by the earth, we must first solve the riddles that reside in and about the craters. We must examine the geologic havoc that has been wrought, we must collect meteoritic debris from within and without the crater, and we must conduct high-speed impact tests of our own.

Meteors

By Fred L. Whipple [1]

In these days of expanded research potentialities, the study of meteors has matured as a research area and many of the major problems of yesterday are now solved; for example, the controversial problem of hyperbolic meteors. Both the precise photographic measures of brighter meteors and the radar measures of the fainter meteors have failed to prove the existence of hyperbolic meteors. If such meteors exist, they represent a minority below the 1-percent level. Furthermore, the photographic and visual meteors are clearly of cometary origin except for a small fraction not exceeding 10 percent that *may* be of asteroidal origin. Most photographic and radio meteors, however, move in direct orbits of relatively low inclination to the ecliptic; their aphelia tend to lie beyond the asteroid belt and usually beyond Jupiter's orbit, but many of the fainter radio meteors exhibit quite small aphelion distances. The cometary meteoric mass is proved to consist of extremely fragile, crumbly material that is probably of very low density. The spectra by P. M. Millman indicate a composition something like that of stony meteorites, but it is unlikely that any sizable pieces have reached the ground. Micrometeorites, on the other hand, may well represent the cometary solids.

Although photographic and radio techniques have been exploited to an amazing degree in the past several years, serious gaps remain to be bridged before we can reach a satisfactory understanding of meteoric phenomena and of the origin of these tiny bodies from interplanetary space. I should like to mention briefly certain of these difficult observational problems and devote most of my attention to the almost untouched areas in laboratory and theoretical work. As long as these areas are unexplored, our knowledge of meteors, their nature, and their origin will remain conspicuously incomplete.

In the area of two-station direct photography of meteors for velocities, trajectories, deceleration and light curves, the J. B. Baker Super-Schmidt cameras in the Harvard Meteor Program have largely completed the basic observational research in terms of their present-day capabilities. Analysis is being carried along rapidly and effectively by L. G. Jacchia, R. E. McCrosky, and A. F. Cook. I must point out, however, that no serious effort has yet been devoted to the use of the television image tube in optical meteor methods. There is every reason to believe that the sensitivity can be increased more than an order of magnitude, since the transient character of the meteoric radiation is highly suited for the present-day photoelectric techniques. Utilization of the image tube, on the other hand, requires a major effort since the telescope and the receiver must be integrated into a new and specialized form. Such a technique shows promise of reaching to the ninth magnitude visually for very slow meteors, and to the sixth apparent magnitude for the fastest meteors. Applied as in the Harvard Program, the image tube may accomplish a corresponding improvement (some four magnitudes) in the registration of persistent meteor trains shortly after the meteors have passed. Thus, measurement of upper winds as a function of altitude in the range from 80 to 112 kilometers could be systematic and highly precise.

The train type of observation is important not only for the understanding of upper atmospheric turbulence but also for solving the basic problem of meteoric masses. The "coasting motion" in meteor trains presents to date the only direct method of measuring meteoric masses, via their momentum transfer to the ambient air. Either photographic or image-tube methods should be applied with larger base

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[1] Harvard College Observatory, Cambridge, Mass., and Director, Astrophysical Observatory, Smithsonian Institution.

lines than those of the present stations, about 50 rather than 20 miles, to clarify the question as to the average masses associated with meteors of a given brightness and, from a more fundamental point of view, the question of the densities of cometary solids. A single example leads to a density of only 0.05 gm/cm^3!

It has not yet been possible to utilize the full power of the Baker Super-Schmidt meteor cameras for the photography of faint meteor spectra. Relatively coarse transmission replica-gratings with a high concentration of light in one first order have not yet become available for use on fast cameras of large aperture. Coupled with image tubes, such coarse gratings might lead to remarkable progress in the understanding of the spectra of fainter meteors and of train and wake phenomena for brighter meteors and might make it possible to determine the composition of cometary solids.

D. W. R. McKinley at Ottawa, Canada, and A. C. B. Lovell with his colleagues at Jodrell Bank, England, have made remarkable strides in measuring the velocities of faint meteors by radio techniques. J. G. Davis has now developed a three-station method for measuring radiants, and, therefore, orbits as well. Only a major effort utilizing this technique can provide the many data critical to our understanding of the orbits and origins of meteors, as well as their interaction with the atmosphere. In particular, it is essential that such a system be used with a number of receiving stations in order that observations may be made along the full length of meteor trails to determine ionization as a function of distance and height, diffusion effects at great altitudes, deceleration in the atmosphere, precise correction to outer atmospheric velocities and orbits, heights, winds, and other important meteoric observables. Such a program is being undertaken at Harvard under the technical direction of G. S. Hawkins. This technique should be carried to its practical limit.

Fortunately, many radio groups are studying the properties of forward-scatter by meteors because of its importance in communication. In the near future, such information needs to be collated, summarized, and interpreted with a view to increasing our understanding of the nature, decay, and diffusion of the electron clouds produced by meteoroids.

There is every reason to hope that the planned Earth Satellite Program of the United States and the International Geophysical Year of the National Academy of Sciences will provide direct above-the-atmosphere measures of small meteoroids in space, so far undetectable by any of the meteoritic methods. It is extremely important that such observations be made in order to clarify the relationships among comets, meteors, and the zodiacal light and the effect of corpuscular radiation on small particles in interplanetary space.

Although sound observational techniques for the study of meteors are being utilized vigorously, the opposite can be said of the theoretical and laboratory research which should now be underway to consolidate these observational gains. The basic meteoric phenomenon still remains unexplained in terms of even an approximate physical theory. This deplorable situation exists not only because the problem is difficult, with many facets, but because no serious effort has been directed towards the laboratory determinations of the fundamental data required in such a theory. Desperately needed are measures of atomic and molecular cross sections for dissociation, excitation, ionization, attachment, and recombination for meteoritic and atmospheric elements in the energy range up to 10^3ev. These quantities are needed for such elements as silicon, iron, nickel, magnesium, sodium, calcium, manganese, and others in air, or, better, in pure atmospheres of nitrogen or oxygen. Such laboratory measures coupled with the remarkable progress of recent years in shock-tube research and ultra high-velocity phenomena should make it possible to utilize the observations of meteors to establish the beginning, at least, of a satisfactory basic theory for meteors. The needs in the area of astroballistics are elaborated in a paper of this volume by R. N. Thomas.

Artificial meteors, either in evacuated ranges or at moderate altitudes in the atmosphere, could provide extremely valuable information regarding the meteoric phenomena under conditions in which the nature and mass of the meteoric body would be known. Such research, started under the direction of J. S.

Rinehart at the Naval Ordnance Test Station, Inyokern, Calif., should be pursued vigorously to provide the confirmation of theories based upon the laboratory measures.

In quite a different area of meteoritic studies, laboratory measures would also be of extreme value. Corpuscular radiation from the sun almost certainly plays an important role in the disintegration of meteoroids in space. We require laboratory measurements of the sputtering phenomena produced by protons in the energy range 10^4–10^6ev on common meteoritic surfaces—stony minerals as well as nickel-iron. A knowledge of the rate of disintegration under these circumstances would greatly increase our understanding of the cometary meteoroid. Once such a body has been ejected from a comet, it is subjected to corpuscular radiation which causes it to spiral inward towards the sun and also to disintegrate. There seems little doubt that cometary particles are the major source of scattering and diffraction of sunlight in the solar Fraunhofer corona, in the zodiacal light, and in the Gegenschein. We cannot integrate our information concerning comets, meteors, the corona, the zodiacal light, and the Gegenschein until we know the effect of corpuscular radiation on small meteoritic particles.

Similar laboratory measures of atmospheric components impinging on meteoritic material with energies in the range 10–10^3ev would provide a sound foundation for an understanding of the interaction of extremely small meteoroids with the upper atmosphere. If the sputtering effects produced under these conditions are sufficiently small, then "micrometeorites" can indeed pass through the upper atmosphere without destruction; by black-body radiation at temperatures below the melting point they can radiate away the heat derived from atmospheric encounter. Such sputtering information would be of extreme value in interpreting the observations of meteoritic dust in the atmosphere and in deep sea oozes. It would also help clarify the question of whether micrometeorites provide condensation nuclei to initiate heavy rainfall at extremely great altitudes.

In the laboratory-ballistic area of measurement, particularly needed are the values of such physical quantities as the heat transfer coefficient and the luminous efficiency. These quantities are, respectively, the percentage of the available translational energy of the medium that is transferred to the surface of the meteoric body and the percentage energy of the ablated material that is transferred into observable radiation. A corresponding quantity is the ionization efficiency, measuring the number of electrons freed in the meteoric process by each atom of the meteoroid. These quantities are, naturally, functions of the velocity and very likely are functions of the air density and composition of the meteoroid.

The physics of the meteoric process involves the integration of physical data, physical phenomena, and meteoric phenomena into a coherent whole. The development of such a theory has obviously been the goal of much research. In one area, there is hope that such a theory can be developed without so much subsidiary information, viz, the theory of the persistent meteor train. The evidence points strongly to the conclusion that meteoric energy is transferred rapidly to some retentive agency in the atmosphere, such as active nitrogen, and is transformed slowly into radiation after the meteoric phenomenon is ended. Such a theory will be closely integrated with the problems of the physics of the upper atmosphere but does not seem to be hopeless in terms of our knowledge at the moment.

A number of theoretical problems fall in the realm of celestial mechanics. The problem of the "Jupiter barrier" requires much more attention. The Jupiter barrier arises from the perturbational disturbances by a large planet which tend to prevent a particle spiraling in towards the sun from reducing its aphelion distance below the perihelion distance of the planet. Perturbations by close approaches to the planet necessarily throw the particle into an orbit that will return near the point of encounter, and thus an orbit with aphelion beyond the planet's orbit. Many of the perturbational problems of interactions between the planets and small particles of the solar system take on a stochastic character and, in fact, are soluble by modern stochastic theory.

An interesting problem combining stochastic theory and celestial mechanics concerns E.

Öpik's suggestion that perturbations of asteroidal material by Mars are responsible for the existence today of asteroidal material crossing the earth's orbit. Here we require a more comprehensive theory of the perturbative effects of a smaller planet upon microparticles in the solar system.

This enumeration of problems in the field of meteors is far from complete; in particular it omits a number of important questions in the category of correlation-interpretation-theory. These questions involve the relationship between the orbits of comets and meteors, the distribution of particle orbits to produce the observed zodiacal light, the nature of the Gegenschein, the development of meteor streams, identification criteria for meteor streams of great diffusion or low population, and a number of problems relating to the orbits of comets, meteors, meteorites, and asteroids.

The author hopes that this report, incomplete though it is, will at least tend to eliminate complacency with regard to the present completeness of meteoric research.

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Minor Planets

By Paul Herget[1]

The techniques and methods of observing the minor planets have not improved substantially for more than half a century. Within the last decade, however, the development of electronic computing machines has increased the possibilities for computational work by a factor of nearly a thousand. Advances in technology have improved photographic emulsions so that we can observe planets much fainter than those observed formerly, but there is no immediate prospect of improving methods of blinking, measuring, and reductions based on stellar comparison positions from star catalogs. Minor planets will continue to be discovered more or less at random, and each one must be followed almost individually for several months in order to secure its orbit and to predict the following opposition.

One of the most difficult problems for the Minor Planet Center occurs when the observer assigns an erroneous identification to the object whose position is determined. As fainter and fainter objects are observed, the likelihood of making such misidentifications increases greatly and can be avoided only by securing a confirming observation from two to four weeks later. In very doubtful cases even a third observation is needed so that an independent orbit can be computed, if necessary. For this same reason, it is now increasingly important to provide much more accurate ephemeris and perturbation computations than in the past.

In 1950 Kuiper launched a large-scale observing project in which the minor planet zone of the sky, about 23° on each side of the ecliptic, was observed in the neighborhood of opposition continuously for a period of 20 months. The main objective of this program was to gather fairly homogeneous data on the magnitudes of the minor planets and to provide a basis for investigating theories of their origin. A very important concomitant result was a nearly complete survey of all minor planet positions, which proved to be a very valuable standard of reference whenever doubtful cases occurred in the improvement of orbits. If the computations were based on actual observations it should be possible to locate the doubtful planet on the survey plates from its computed position and, thereby, provide still more observational data, unless the planet was below the magnitude limit of the plate. On the other hand, if the supposed observations were spurious it would be impossible to locate an object at the computed position on the survey plates. The value of such a survey is so great that it should be repeated at least once every decade. For the ordinary minor planet orbits, with sufficient observations in the past and with good perturbation computations, this should be sufficient to assure accurate ephemerides; and it may have the effect of displacing at least half of the ordinary minor planet observing that now goes on.

There is room for a special type of observing program which could be undertaken by someone who has a sufficiently large telescope, who likes to sleep through the night, and who is willing to work low on the horizon. The purpose would be to increase the length of the observed arc of newly discovered minor planets, both at the end of the first opposition in which they are discovered and at the beginning of the next following opposition. A moderately large telescope, something like a 24-inch reflector, would be needed because the magnitudes will be unusually faint because of the atmospheric extinction at low altitudes and the disadvantageous phase relationship nearer to superior conjunction. Also, many of the newly discovered faint planets will be in the region of perihelion during the first

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opposition and, due to their eccentricity, will be at a greater heliocentric distance in the second opposition.

Recent work at the Naval Observatory and by Kuiper has disclosed new problems related to the physical constitution and history of the minor planets. Their solution requires concurrent photoelectric observations of individual minor planets, including changes in color, magnitude, and polarization, and extending over a wide range of phase angles. Some evidence already exists that two classes of minor planets can be recognized from polarization observations. Laboratory work of a similar nature with known materials and conditions should offer some clues to these problems. Theoretical studies are also desirable.

The Minor Planet Center has experimented with all available types of computing machines in recent years, and it has now concluded that the perturbations of all ordinary minor planets may be most readily handled either by the method of variation of vectorial constants or by Hansen's method. The computations required are no longer a formidable problem. Similarly, the problems of preliminary orbits and differential corrections have been reduced to a matter of minutes. The same results could easily be attained for all comet computations.

The routine aspects of minor planet computations are so well in hand that it is now possible to turn to new and more interesting problems, the solution of many of which will be aided by the experience gained in the work described above. An accurately computed dynamical orbit of Pallas from the time of its discovery up to the present will permit an independent and highly reliable determination of the value of the constant of precession. G. W. Hill prepared a list of 13 planets that are especially suitable for determining the mass of Jupiter, provided the observations and accurate perturbations extend over a period of about a century; work on this problem has begun. Another program, already well underway, will use the first four minor planets for determining the position of the equinox instead of observations of the sun and the major planets. This project also requires accurate computations of their orbits. More penetrating researches may now be made upon the families of minor planets originally recognized by Hirayama.

Electronic machines have not yet been used as effectively for the calculation of general perturbations as for that of special perturbations, but the problem has been attacked and will undoubtedly result in progress in the near future. The availability of electronic computing machines now makes the vistas in all these fields more attractive than at any previous time in history.

Planets, Satellites, and Comets

By Gerard P. Kuiper [1]

The planets and the satellites must be studied from distances ($\simeq$1 astronomical unit) that are intermediate between that of the stars ($>10^5$ a. u.) and that of the bulk of the earth ($\leq 10^{-5}$ a. u.). Likewise, some of the problems they present are intermediate—related both to astrophysics and geophysics—but this situation is rather recent.

The following paragraphs, part of a preface to a book now in preparation, may serve as a backdrop on which to view some of the 20th century problems of planetary astronomy.

> Until the introduction of photography with large telescopes and the birth of astrophysics, both toward the close of the 19th century, planetary astronomy—with some exceptions—*was* astronomy. The system of the "fixed" stars was of profound interest philosophically; but to the practicing astronomer it was largely a convenient frame to which the complex motions of the planets could be referred. The great discoveries in astronomy were made in efforts to interpret the planetary motions. Copernicus, Kepler, Newton, Euler, Lagrange, Laplace, Gauss, and Poincaré, to name but the greatest, created the concept of modern natural science while studying the planets.
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> The phenomenal growth of astrophysics, and the exciting explorations of the galaxy and the observable universe, led almost to an abandonment of planetary studies. The number of astronomers has always been small and for better or for worse has not followed the enormous increases of physicists and chemists. Celestial mechanics began to look like a nearly finished discipline in which further progress was hopelessly difficult. Physical observations of planetary surfaces, particularly of Mars, led to controversies and speculations. More and more this branch of planetary work, including the study of the moon, became the topic *par excellence* of amateurs—who did remarkably well with it. The Memoirs of the British Astronomical Association became the chief record for the development of planetary surface markings. Astronomers with large telescopes were so occupied with the engaging problems of stars, nebulae, binaries, clusters, the galaxy and the universe, that astronomy almost entirely became the science of the stars.

In some respects the science of planetary astronomy has greatly changed from its distinguished predecessor. Eight- or ten-decimal accuracy and a formidable theoretical apparatus have often given way to one-decimal accuracy and order-of-magnitude arguments. Observing programs, which occupied the major observatories for decades, have been replaced by isolated observations by single astronomers who build new apparatus and use it once or twice under optimum conditions. "Astronomical accuracy" is a compliment born in an age different from ours.

Nevertheless, there has been no breakdown of standards. What has happened is that a new branch of science was born, an offshoot of young and vigorous astrophysics, which was added to classical planetary astronomy but was not immediately integrated with it. And so it happened that 10-decimal accuracy and 1-decimal accuracy existed side by side, in a field now occupied by scientists of very different interests and training. The study of planetary motions and the great problem of the stability of the solar system rose slowly and laboriously on foundations laid by the great masters. New computational techniques proved increasingly valuable in the solution of special problems. Dr. Clemence reviews this basic part of planetary astronomy elsewhere in this series.

The program of this 20th century addition consists of a great variety of things that at first sight may seem to lack coherence. A geophysicist, considering the task of a planetary astronomer, might well be skeptical. He could reason that, since the objects of study are some 10^5 times more distant than the earth, the obtainable information might be 10^{10} times smaller, and furthermore, that the absence of material contact or near-contact with the planets deprives the astronomer of several sources of information: seismic studies, heat

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flux measurements from the interior, gravity surveys, magnetic surveys, study of magnetic variations, volcanism, chemical and crystallographic analyses of the crust, oceanographic studies, detailed atmospheric studies, etc. One might wonder what there is left for the astronomer to do.

Classical or gravitational astronomy, however, has put the planets on a coequal basis with the earth in some aspects. The mass of the earth in absolute units is known no better than the masses of Venus, Mars, Jupiter, Saturn, Uranus, and the Moon, with Mercury and Neptune closely following. Nor do we know the planetary orbits with an accuracy greatly different from that of the earth's orbit. Hence, the radiation received from the sun is known equally well for all. The albedos of the planets can be determined with considerable precision; hence the equilibrium temperatures can be computed quite well, even if with somewhat higher precision for some of the planets than for the earth, whose albedo is difficult to determine accurately. The periods of rotation of the planets can be found (Venus is still an exception), often with considerable precision, as well as the planetary obliquities. With the radiation intensity and the obliquity known, theoretical climatology may be applied to the planets provided something can be said about planetary composition. This, too, is within the range of possibilities. It is immaterial whether the source is 10^9 miles away or just in front of the slit of the spectrograph, provided enough light is available to make a spectrogram of the desired dispersion during, say, one night's exposure.

There are, however, serious handicaps, not resulting from distance but imposed by Nature itself. In the first place, some of the most abundant atmospheric constituents are homonuclear molecules (H_2, N_2, O_2), and because of their symmetry the vibration-rotation spectra are forbidden. Since the electronic absorption spectra H_2 and N_2 are in the ultraviolet part of the spectrum that is cut off by our atmosphere ($\lambda < 0.3\mu$), we cannot discover these gases on other planets unless such enormous quantities are present that pressure effects destroy the symmetry of the molecules and make their infrared spectrum faintly visible (as on Uranus and Neptune for H_2). Nitrogen in our atmosphere is a good example of invisibility; even at sunset, when the sun's rays pass through 320 km atm., four-fifths of which is N_2, it does not add telluric lines to the solar spectrum, even at high dispersion. A second handicap affects the inert or noble gases, He, Ne, A, Kr, Xe. They are of great interest for the study of the origin of the planets because they will not have combined with other elements during geologic time and must therefore always have been part of the planetary atmospheres. (This statement does not apply, of course, to radiogenic He^4, He^3, and A^{40}.) Because these gases range in atomic weight from 4 to 130, we can use them—in the case of the earth, where they can be observed—to determine empirically how the fraction of atmospheric constituents lost by evaporation during the process of planet formation depends on molecular weight. Since the original composition of the protoplanets, from which the planets condensed, was very probably the cosmic composition (essentially the composition of the solar atmosphere), and since the abundance of heavy elements, like Fe, Mg, Si, etc., may be estimated, we may compare the terrestrial abundance table with the cosmic abundance table to obtain the desired ratio, assuming that no appreciable fraction of the heavy elements was lost. Now it would be exciting if one could apply this approach to other planets. But the very property which makes the noble gases so interesting in tracing the early history of the earth (i. e., their stability in the atomic state due to the completeness of their outermost electronic shell) makes them at present undiscoverable on other planets. Such high energies are needed to excite these atoms that their absorption spectra are far in the inaccessible ultraviolet.

It is clear, then, that two important advances may have to await the development of an extraterrestrial observing station. If planetary spectra could be taken from 200- or 300-km elevation, entirely new and vital information could be gotten on the composition of planetary atmospheres. One would then get an undistorted picture of atmospheric composition. The handicaps imposed by Nature would have been overcome.

Some of this much-desired information can probably be obtained with a large telescope at a ground observatory. By introducing compensation methods, Hiltner has succeeded in measuring polarizations down to a few units in the fourth place. It should be possible, in principle, to do the same in spectrophotometry. This would allow one to observe the Raman spectra of H_2 in the Jovian planets and to make a rough determination of the H_2/CH_4 ratio. Conceivably even the He abundance might thus be found. Similarly for the terrestrial planets, N_2 and possibly other gases might become observable, at least if they are more abundant than the strongly scattering CO_2. It even seems possible, in principle, that the solar lines Mg II at $\lambda\lambda$2795.5 and 2802.7 A, including their variable emission components, could be observed regularly from the ground from the Raman lines in the spectrum of Jupiter, at $\lambda\lambda$3163 and 3172 A. The problem is probably largely a question of instrumental development.

Related to the problem of atmospheric composition are at least four others capable of empirical pursuit. They are the problems of atmospheric clouds, the planetary albedo and its wavelength dependence, planetary polarization as a function of the phase angle and as a function of wavelength, and the spectrum of the infrared emission of the planet to space, which at least for the terrestrial planets must balance the absorbed solar radiation. For the Jovian planets a finite fraction of the radiation emitted probably still derives from gravitational contraction and from cooling off of the planetary interior.

The atmospheric clouds on Jupiter and Saturn are almost certainly atmospheric condensation products, as is true for most of the clouds and haze on Mars. Occasionally Mars has yellow dust clouds also, while the nature of the cloud cover on Venus is still in doubt. Uranus and Neptune probably have no visible clouds, although markings have been reported on Neptune. The reality of these markings is not confirmed by observation with large telescopes, or by the model required for the atmospheres of Uranus and Neptune to account for the enormous quantities of CH_4 and H_2 observed. Saturn has a general haze cover which forms the bottom of the visible atmosphere. It usually is divided into a number of distinct belts, parallel to the equator, of slightly different reflectivity and, sometimes, color. In addition, separate clouds are occasionally seen, perhaps one per decade on the average; they must, of course, be huge to be visible, with diameters about as large as the entire earth. They seem to be caused by major eruptions from the interior and, because of the very pronounced differential rotation within the planetary atmosphere, they are soon stretched out into belts parallel to the equator, merging with the belts already present. It is quite interesting how the belt system of Saturn has changed with time. Jupiter, likewise, shows major upheavals in its cloud cover, every decade or so, not at all related to its position in its eccentric orbit, and therefore not caused by solar heating. These two planets apparently do *not* have a sun-induced meteorology, as do terrestrial planets, but one largely governed by released internal heat. It has been pointed out by meteorologists that internal heating is much more efficient in stirring an atmosphere than solar heating from the outside.

Fascinating and unsolved problems are posed by these observations. Do these occasional bursts come from the deep interior? Then how do they get through the mantle of solid hydrogen usually assumed to surround the denser core? Or is contraction of the mantle itself the cause? What is the explanation of the brightly colored clouds—brick red, chocolate brown, blue, amber, white, etc.—observed especially during these upheavals? Is the Red Spot a cloud cap over a floating island, and if so, what floats in what? Or is it merely a long-lived vortex in the Jupiter envelope? (It is not attached to the core because its rotational speed is variable.) These questions, in turn, are related to the unsolved problem of the depth of the gaseous envelope and the hydrodynamics of the differential rotation on both Jupiter and Saturn. Of the greatest interest and promise is the recent discovery of a whitish cloud on Jupiter emitting radio bursts at irregular intervals; the power of the bursts measured at 22 Mc is 10^9 times that of a terrestrial lightning discharge, but the spectrum is quite different.

The cloud problem for Mars is simple by comparison, and has been largely clarified by a combination of the brightness at different wavelengths, polarization measures, and studies of general behavior. By contrast, the identity of the Venus cover is not at all obvious. Different suggestions have been made: water droplets, dust, and salt particles, but none of these fit all the observational data on polarization, in visual and infrared light, on the brightness variations with phase, on the planet's color, and on the appearance of the cloud belts. In conversations with Professors W. E. Grath of Bonn and P. Harteck of Rensselaer Polytechnic Institute, the possibility was discussed that the particles are polymerized C_3O_2, formed as a result of the impact of solar ultraviolet radiations on an atmosphere largely composed of CO_2. This possibility will be checked by laboratory experiments. Here is an exciting problem that, once it is solved, will also deepen our understanding of the history of the earth, so similar to Venus in dimensions and mass.

A curious problem is that of the planetary radiation to space. For a planet or a satellite without an atmosphere, there is no difficulty. Black-body radiation will be a good approximation for such an object, covered as it probably is with fine powder or debris after its long exposure to a vacuum, to solar radiation varying with the rotation, to cosmic rays, and to interplanetary debris. But how does a planet like Uranus or Neptune establish its temperature balance with the absorbed solar radiation? What atmospheric constituent radiates effectively between 20μ and 100μ, where the maximum of the emission should occur? With H_2 a homonuclear molecule and CH_4 a symmetrical molecule, and NH_3 and H_2O frozen out, a situation arises which is not unlike that in the upper layers of the earth's atmosphere. There, too, appreciable quantities of (in this case ultraviolet) solar radiation are absorbed, but the atoms cannot dispose of this energy by radiating in extensive infrared bands. The result is that the atmosphere has a hot upper fringe at nearly 10 times the mean equilibrium-radiation temperature of the earth ($\simeq 250°$ K).

The thermal radiations in the radio-frequency range will be of special interest since they will presumably arise from the solid surfaces, and therefore give a measure of the depths of the atmospheres. Thermal radio emission of Mars will determine the mean daily temperature and, by implication, the surface temperature at night.

Enough has probably been said to illustrate the wide variety of planetary problems, many of them unsolved. One could mention others: precise diameter determinations and resulting planetary densities; their interpretation in terms of models based on the physics of matter under very high compression; determination of the moments of inertia and the resulting refinements of the planetary models; the related problem of planetary composition; and relation of the interior to the envelope for the Jovian planets. In a separate class is the problem of the dark Martian features and their variations, and the question as to whether they are organic or inorganic.

Satellites present a host of problems of their own. Needless to say, the moon is foremost among them, but they are all different and interesting. Titan, with its orange color and its atmosphere of methane; Triton, with its slightly yellowish color and its probable atmosphere, of unidentified composition; Io, with its bright orange color, but lack of atmosphere; the snow satellites of Saturn; the greatly different mean densities and, hence, compositions of the satellites; the great variety of albedos, from near unity for the inner satellites of Saturn to 0.07 for the moon; the differences in albedo sometimes found for different hemispheres of the same body, exceptionally large for Iapetus; the spots on the Jupiter satellites and on the moon; etc. The Rings of Saturn are unique and of unrivaled beauty in a large telescope; their snowy composition seems reasonably well established. One can understand why Jupiter does not have such a ring. The high density of Io indicates that the surroundings of Jupiter were quite hot at the time Io formed; and, even if some snow later condensed within the Roche limit of Jupiter, it would almost certainly have evaporated subsequently by solar radiation. Saturn's ring appears to be just safe from such destruction. But why don't Uranus and Neptune have rings? That is very puzzling and further work must be done to lower the thresholds set by present observations.

Comets are much stranger objects than planets or satellites. Their ephemeral nature shows that they "do not belong" near the earth; that they were not formed there. The exposure to strong solar heat and corpuscular radiation causes the comets to disintegrate rapidly, and show heads and long tails that are among the weirdest structures seen in Nature. No wonder pamphlets were written in past ages on whether the appearance of a comet might mean the death of a king. Comets are unadjusted to their surroundings, as we observe them near the earth; for this very reason they demonstrate, by their violent reactions, certain properties of these surroundings, as the old and adjusted planets and satellites no longer do. Comets have thus become of the greatest interest in the study of the properties of solar radiations and interplanetary magnetic fields, as well as for their own sake. The unpredictability of the occurrence of a "new" comet and the irregularity of the stimulating solar beams add to the excitement when a bright comet appears, which has not been very often in recent years. A good bright comet, like that of 1882, would be a major scientific event.

Problems of evolution and origin are as compelling in solar-system studies as they are in studies of stars and galaxies. It seems as if some of these are being solved. On the other hand, a good look at the problems in geophysics will temper any excess optimism. Much of what we would like to know about planets, satellites, and comets is hidden from our view; and even if we could see it, explanations would not follow automatically, as geophysics shows. Clearly, one must be satisfied with limited objectives and with explanations and theories of a general kind. But because of the many repercussions these problems have on geophysics and related sciences, any advance will also have a general interest. The limits imposed by telescopic equipment and other practical considerations have by no means been reached.

Airglow and Aurora

By A. B. Meinel[1]

The fact that the background of the moonless night sky is not entirely dark has been known for centuries, while references to the aurorae extend back into the dim recesses of Nordic antiquity. Yet only since the turn of the 20th century have these phenomena been the subject of systematic study. The presence of an emission spectrum for the aurora was recognized as early as 1867 when Angstrom observed and measured the wave length of the green auroral line. The presence of an emission spectrum from the light of the night sky was noted as early as 1895 by W. W. Campbell, who used a new visual spectrograph at Lick Observatory many years before the spectrum was rediscovered photographically by V. M. Slipher at Lowell Observatory. The light of the night sky as a detached phenomenon of physical interest was recognized by the pioneering investigations of Fabry in 1910, V. M. Slipher in 1919, Lord Rayleigh in 1920, and Dufay in 1923. For a historical account of early night sky and auroral research, the reader is referred to the articles by Dufay (1928), Fabry, Dufay, and Cojan (1934), Dejardin (1936), Elvey (1942), Dufay (1938), and Swings (1949).

Many young scientists may wonder why airglow and aurorae are included in a report on new horizons in astronomy. Historically, both phenomena are noteworthy because of their astronomical consequences, although both arise solely within the gaseous envelope of the earth. To most astronomers the light of the night sky is a nuisance to be tolerated by necessity, since little can be done about it. However, in spite of the unpleasant problems they make for the observer, the light of the night sky and the aurorae are phenomena of wide astronomical and astrophysical interest.

The term "light of the night sky" is used to describe a complex flux of radiation composed of both terrestrial and extraterrestrial sources. The extraterrestrial component arises from: (a) interplanetary scattering of sunlight (zodiacal light), (b) interstellar scattering and emission excited by stars, and (c) the integrated radiation of individual unresolved stars. The atmospheric component of the light of the night sky arises from: (a) scattering of starlight and extraterrestrial radiation in our atmosphere, (b) atomic emissions in the form of monochromatic emission lines, (c) molecular emissions in the form of emission bands and possibly continua, and (d) Cerenkov radiation and N_2^+ emission from cosmic rays. Assigning to each source a percentage of the total light of the night sky can only be done with uncertainty since it is difficult to separate clearly some effects. In the visible region the ratio of extraterrestrial to terrestrial must be approximately unity.

Upon certain occasions aurorae are superimposed on the night sky. The auroral radiations are caused by two basic mechanisms: (a) heavy-particle excited atomic and molecular emissions (in the homogeneous arc phase), and (b) electrical-discharge excited atomic and molecular emissions (in the rayed-structure phase). However, most of the light may be produced by secondary electrons in both cases.

To describe the appearance of the light of the night sky on the spectrum of a faint astronomical object, such as a distant nebula, it is best to portray each spectral region separately. In the region sensitive to the 103*a*–O emulsion, the λλ4800–3100 spectrum is characterized by many bandlike features superimposed upon a continuum which is strong in the blue and rapidly disappears shorter than λ3900. As a consequence of this spectrum it is difficult to detect weak astronomical features such as the broad, but shallow, H and K lines in the spectrum of faint galaxies.

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The region $<\lambda3500$ is composed of groupings of bands of increasing intensity and contrast down to the atmospheric cutoff. These bands appear distinct and shaded toward the red, in contrast to the diffuse X_1 and X_2 bands in the $\lambda4500$ region. No emission lines of atomic origin occur in this region except during auroral activity.

The visible region of the airglow spectrum, $\lambda\lambda6500$–4200, is dominated by four sharp emission lines with relatively weak bands and a continuum near the blue end. The lines, in order of intensity, are the famous auroral line at $\lambda5577$, two red nebular lines at $\lambda6300$–6364 (all three due to forbidden OI emission), and the sodium doublet at $\lambda5893$. The latter is generally so weak that it is only recorded on low-dispersion spectrograms and as a single line. The other features are weak OH bands and an unidentified continuum that must be heavily contaminated by starlight, etc. Whether this "continuum" is real and of atmospheric origin is still unknown. On spectrograms sensitive to the deep red (i. e., 103*a*–F emulsions) the OH bands near $\lambda6560$ and $\lambda6800$ become prominent features.

Spectrograms of astronomical sources in the visible often show additional lines that could puzzle the new observer. These lines are due to scattering by the atmosphere of neon and mercury radiations from adjacent cities. The relative intensities generally appear anomalous, especially for neon in the red because of the "sunset" reddening over long air paths due to rapid changes in the absorption coefficient.

In the infrared, the airglow becomes intense as a result of a strong band system due to the OH radical. The most intense bands of this system are 4.5μ, but the bands at $\lambda10{,}000$ and in the I–N emulsion photographic region ($\lambda\lambda8900$–6500) are strong enough to cause difficulty in some astronomical observations.

The auroral spectrum shows the same atomic line features as the airglow, with the addition of a rich assortment of strong molecular bands in the red and infrared and violet regions. The absolute intensity level can reach a factor of 10^4 times that of the airglow. Weak aurorae often make themselves evident on astronomical spectrograms only by enhancement of the $\lambda6300$ [OI] lines and the appearance of the $\lambda3914$ N_2^+ band, which appears as a line owing to the occurrence of the band head in the red branch.

Both the airglow and aurorae are phenomena that are potentially important to the understanding of the physical and chemical properties of the upper atmosphere. Our atmosphere provides us with a nearby astrophysical laboratory where we can observe a gaseous atmosphere over a wide pressure range under the influence of electromagnetic and particle radiation from a star. Unfortunately, the interpretation of these phenomena has proved so complex that we are still in doubt with regard to many of the questions that investigators have struggled with. To begin with, both phenomena, airglow and aurora, are difficult to study with resolution sufficient for detailed analysis. The airglow is very weak, necessitating the use of the fastest possible spectrographs. Even so, a single exposure sufficient to resolve molecular bands may require all the dark hours for several months. Although the aurora is much brighter (up to 10^4), it is transient in both time and space, sometimes lasting for the entire night but more frequently only a few minutes. Quite often the lifetimes of interesting features are measured in tenths of a second. Newly developed photoelectric techniques may offer hope in attacking such problems.

For some years, the major airglow problem has been the *identification* of the emissions. This problem is approaching what is thought to be a solution, although X_1 and X_2 bands of Lord Rayleigh in the blue are still completely unidentified since no one has yet resolved their rotation structure, if they possess any. Among other interesting problems are the *heights* of the emissions of the night glow and the *excitation mechanisms* of both.

In the case of heights, very ingenious instruments have been devised to measure the patchiness and motions of the airglow patches. Estimates of the heights based upon the dependence of brightness on zenith distance and made by averaging many nights of observations with careful accounting for absorption and scattering have been disappointingly at variance. The reason may lie in the fundamental assumptions of a statistically uniform, thin, emitting layer.

In the case of excitation mechanisms, some emissions have been thoroughly explained, while others present unanswered questions. The aurora is in particular interesting since the spectrograph has demonstrated the influx of energetic protons, presumed to be of solar origin. The precise role of the protons in direct excitation of the atmospheric gases taxes the present capacity of quantum mechanics, since accurate wave-function descriptions of the molecular energy states are still meager. Laboratory experiments stimulate the imagination, and when such experiments have been carefully devised the results have not been disappointing.

In the immediate future, the program for the International Geophysical Year will attempt to gather data on a world-wide scale with the best means uncovered in individual research studies. The reason is that one-point observations, even in great detail, leave phases of the problem presented by the aurora unanswerable. The synoptic observations that will be obtained should open a new door to the interpretation of solar-terrestrial relations; however, as in the past, the unlocking of these secrets will be a challenging but rewarding task for names not yet on the pages of the record.

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Solar-Terrestrial Relationships: Weather and Communications

By Walter Orr Roberts[1]

Relatively few of the many branches of astronomy can be said to have applications of direct practical importance. The field of solar-terrestrial relationships is an exception. Two decades of practice have shown the radio operator that solar variations can make the difference between success and failure in getting a message through. Today, we may look for improvements in practical weather forecasting because of new discoveries made on the common border between meteorology and astronomy. Just how far away these advances are will depend, at least in part, on the magnitude and the quality of the effort made in this field.

The effects of the sun on radio communications are well known, even if poorly understood. The influence of solar activity on weather is less apparent, and the reality and nature of the effects are still somewhat controversial. Enough clues exist, however, to convince a substantial group of research workers that changes in the sun's shortwave emanations and in its corpuscular radiation are reflected in worldwide weather patterns, and that practical gains in both long- and short-term rainfall forecasting and temperature forecasting for large areas of the earth can be expected when these connections are better understood. The fact that the sun exhibits rather stable long-term trends improves the prospects for season-in-advance weather forecasts based on variations in solar activity.

The sun's effects on weather obviously must be on a large scale. Several factors in the so-called "general circulation" of the earth's atmosphere give evidence of such solar influences. The results of these large-scale changes, in terms of surface rainfall and temperature, depend very much on local elements such as topography and latitude; a worldwide circulation change that produces rain at one spot may produce drought in another. The ties of sun to local weather are therefore most complex.

The mechanism responsible for responses of weather to solar activity clearly does *not* involve substantial changes of the sun's total energy; rather, it involves changes in selected spectral ranges where only a relatively small portion of the sun's total energy output is concentrated. It is also clear that the most pronounced weather responses are likely to be found at the upper levels of the earth's atmosphere, where the sun's variable energy is principally absorbed. However, meteorological observations at such levels are still rather sporadic. Improvements in all types of weather forecasting are likely to come from research on the nature and causes of persistence and sudden changes in the dynamics of the general circulation of the atmosphere. The motions of the upper levels and the possible nature of the mechanisms that start disruptions in the patterns of momentum and mass transport in the earth's atmosphere require particular attention. Dynamic meteorology is still in its infancy, but the solar astrophysicist has much to contribute. Ten years ago there seemed no real prospect that major advances in long-term weather forecasting would result from solar observations; today they promise advances of incalculably vast practical significance.

Without much exaggeration it can be stated that modern solar-terrestrial research began when R. C. Carrington of the Royal Observatory in England made his classic observation of a great solar flare visible in integrated light at

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[1] High Altitude Observatory, Boulder, Colo.

11 a. m. on September 1, 1859. At the instant of the flare, a fluctuation occurred in the strength of the earth's magnetic field. On the 2 days following, a violent magnetic storm was recorded by magnetometers at the Kew Observatory. Balfour Stewart, the director at Kew, concluded that the terrestrial magnetic disturbances were related to the flare; however, the idea was so unbelievable that most research workers dismissed the sequence of events as a coincidence.

The connection between flares and magnetic storms is now amply demonstrated, although the problem remains of explaining just how a solar flare produces these effects and the even more spectacular phenomena in the aurora and ionosphere. In the years since Carrington's great flare, a whole new science has developed to solve the problems common to solar physics and to terrestrial atmospheric physics.

Both sides of this joint attack have greatly enriched our observational knowledge. The spectroheliograph, the coronagraph, and the solar radio telescope have been the astronomical milestones. Geophysically, the night sky spectrophotometers and ionospheric sounding devices have competed in importance with earth-based, airborne, and rocket-borne cosmic-ray counters, with photometers, and with magnetometers operated with ever-increasing regularity from an ever-increasing diversity of stations. Great advances, particularly in meteorology, have come from the simple fact that we now can prepare daily or twice daily hemisphere-wide charts of airflow and temperature distribution at a wide range of altitudes from which large-scale dynamical studies can be made.

In every facet of terrestrial atmospheric physics, tantalizing connections between sun and earth have been found. But many pieces of the jigsaw puzzle remain to be put in place. Advances of great importance in ionospheric radio communications and in meteorology will undoubtedly appear when we have a satisfactory theoretical explanation that fits together the many known solar-terrestrial relationships.

A specific example may help to illustrate the expected course of progress. We now know that world weather patterns sometimes respond in a rather clear-cut way to changes in the character and level of solar activity as measured, for instance, by the average intensity of the emission of the sun's green coronal line. Although our understanding of the solar physics of the situation is very imperfect, we infer that the observed large changes in the coronal emission probably signify large changes in the total ultraviolet or X-ray emission of the sun. Nonetheless, the total changes of energy of the sun's emission must be very small, probably measured in thousandths or millionths of the solar constant. Not only do the world weather changes require vastly greater energy than the sun's variations can supply but terrestrial physics suggests that the level at which the X-ray or ultraviolet energy is absorbed must be so high that it is difficult to imagine that it could exert a significant influence all the way down into the weather sphere, far below. Yet the problem stands, a challenge and a mystery. No one can doubt that real progress in forecasting will come when we have a satisfactory physical explanation of the link, whether it be a trigger mechanism for amplifying infinitesimal solar changes or some yet unknown cause.

The multitude of phenomena of the ionosphere and the many variations of the effects with latitude and longitude are equally enigmatic problems. Few astronomers or geophysicists today doubt that the earth is subject to highly irregular and unpredictable "showers" of solar corpuscles, or that these corpuscles control important effects in aurorae, the ionosphere, and earth magnetism. Yet, in spite of the brilliant victories of the Chapman-Ferraro theory of such effects, we know that the theory is only a crude beginning, and that it is grossly inadequate to account for major phenomena that are well observed. We particularly need new research to improve our predictions for communications in polar latitudes.

Many simple, but major, questions of solar-terrestrial relationships are yet unanswered. For example, do cosmic rays come from the sun? A few short years ago it was hard to find a working cosmic-ray physicist who would admit that the sun as much as gently modulated the cosmic rays that were believed to come in all directions from outer space. Astronomers generally assumed, without any serious doubts, that perhaps well over half of the energy of the universe was bound up in these mysterious high-speed particle emissions. Now the view prevails that a major part of the low-energy cosmic rays come from, or are at least strongly controlled by, the sun; and how many of the more energetic cosmic rays also come from nearby, rather than from the farthest reaches of space, is an open question.

The observational-theoretical picture of solar activity needs integration. The vast complex of sunspots, solar magnetic fields, flares, plages, prominences, and the corona needs to be welded into a consistent and understandable unit. From such a unified picture of solar activity, and of the quiet sun as well, will come better understanding of the sun's radiational and corpuscular emissions, particularly those emissions stopped high in the earth's atmosphere. At the moment, it is hard to say whether the solar physicist or the rocket and satellite launchers will be first to specify the nature of the sun's variable emissions as seen from an altitude, let us say, of 250 kms. In any event, the advances in the decades immediately ahead will be spectacular, and the practical stakes in long- and short-range weather forecasting may well surpass the very important gains that can reliably be expected in the field of communications forecasting.

Solar Physics

By Leo Goldberg[1] and Donald H. Menzel[2]

At the present time, astronomy is in a remarkable period of rapid growth wherein the rate of accumulation of knowledge is higher than at any time in the past. In such a dynamic situation, existing facilities rapidly become obsolete and the new instruments required for continued development of the science are generally larger and more expensive than their predecessors. Unfortunately, the traditional sources of financial support of large astronomical facilities have been seriously diminished. Few private donors are in a position to contribute gifts of the magnitude necessary for modern research installations, and the larger foundations appear to be concentrating their primary efforts in other areas. Thus, apart from occasional gifts or contracts from industrial concerns, the burden of support must fall upon Government agencies, which can function wisely only if they are guided by the collective, considered judgment of responsible scientists. This means that astronomers as a group must assume the responsibility for deciding which large-scale facilities are urgently needed for the continued development of their science, and they must also solve the organizational problems concerned with the cooperative use of these facilities.

We do not imply that all future astronomical research should be directed by planning committees. On the contrary, we strongly believe that the best new ideas and the initiation of new fields of investigation will come from individuals or small groups of investigators who must continue to receive the strongest possible financial support from the National Science Foundation, the Office of Naval Research, and other Government agencies. The regular program of grants and contracts by such agencies supports a wide variety of studies and is frequently responsible for so-called "seed" research, in which the expenditure of relatively few thousands of dollars may lead to the germination of a whole new field of study. The next step in the nurturing of the seedling may well require the construction of equipment costing hundreds of thousands or even millions of dollars. It is at this point that planning on the national level must enter to evaluate the potentiality of the study with reference to astronomy as a whole. It would be unfortunate indeed if the question of cost should be a major factor in any decision against embarking in some new, exciting, and otherwise worthwhile project. This country is capable of extending far greater financial support than it has in the past to provide an enormously expanded effort in basic research. The really serious bottleneck in astronomy is the current shortage of topflight astronomers. We must therefore guard against wasting precious scientific manpower in large but relatively unproductive projects, especially those financed by public funds. The shortage of astronomers is a national problem which should be a major concern of the National Science Foundation.

No branch of astronomy has progressed more rapidly since 1940 than has solar physics. We do not except radio astronomy, which, as a special technique of tremendous power rather than a separate branch of astronomy, has supplemented optical methods in contributing importantly to virtually every field of solar research.

Following a period of phenomenal growth at the beginning of the century, sparked by the invention of the spectroheliograph and the solar tower and by improvements in spectroscopic gratings, solar research progressed rather slowly through the 1920's and early 1930's. Largely

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through the efforts of George Ellery Hale, observational solar physics had advanced much more rapidly than the theoretical interpretation of the data. This gap, however, began to close in the late twenties, with the development of theories of ionization equilibrium and of atomic structure.

Although by 1930 a certain number of successes had been achieved from the application of the new physical theories to the observations, they were far outnumbered by many conspicuous failures. In 1930, numerous roadblocks filled almost every avenue of solar physics. It is useful to survey these barriers from the vantage point of 1956, both to note those that have already been removed, or are in the process of being eliminated, and to assess how far we may now expect to move down the road before new obstacles appear.

The photosphere

One of the most fundamental problems in solar physics concerns the structure and circulation of the gaseous layers comprising the photosphere, the region in which the continuous spectrum is formed and in which most of the Fraunhofer absorption takes place. The solution of this problem calls for the construction of a model photosphere in which the chemical composition and the distribution of temperatures, pressures, gas velocities, and magnetic fields are completely specified everywhere in the photosphere. In theory, we can derive all of this information from observations of the continuous spectrum and the Fraunhofer lines. Practically, however, the problem is frightfully complicated. For example, measurements of solar limb darkening and spectral energy distribution will yield the distribution of temperature with depth *if* we know what processes produce the continuous spectrum. We can then calculate the pressure distribution *if* the atmosphere is in hydrostatic equilibrium. This assumption is certainly wrong if the atmospheric gases are in violent, turbulent motion caused by convective instability or electromagnetic forces. To construct an accurate model we must evaluate the relative contributions of radiation and convection in the transport of energy through the atmosphere.

Stability depends on the temperature gradient and the chemical nature of the atmosphere. The temperature gradient, in turn, must be sufficient to drive the solar radiation through the semiopaque gas. In an idealized atmosphere, where the atmospheric gases are artificially stirred and where no heat is transferred from or into the moving volume, the temperature gradient must follow the so-called adiabatic law. Such an atmosphere is in neutral equilibrium. Exchanging equal masses of gas at different atmospheric levels produces no effect on the temperature distribution. As the mass from the lower level rises and expands, it assumes the same volume, pressure, and temperature as that of the mass it replaces.

As long as the temperature decreases upward at a rate slower than that specified by the adiabatic condition, the atmosphere will be stable. Radiative transfer will predominate and the flux of energy will be essentially constant over the entire solar disk. However, if the natural gradient is steeper than the adiabatic, a mass of gas displaced upward becomes warmer than its surroundings. It will continue to rise, like a hot-air balloon. Analogously, a mass displaced downward becomes cooler than its surroundings and thus descends. An atmosphere, so constituted, becomes unstable and convection sets in.

When convection is mild, the energy conveyed upwards will essentially equal that conveyed downwards. Transfer by radiation may still predominate. However, as convection increases, nonlinear effects enter so that we no longer have a precise balance. We shall then have a net outward transport of energy by moving airmasses. The convective and radiation fields may be said to "couple" together. The radiative flux at the outer boundary will vary from point to point over the solar disk in such a way as to maintain a constant average. The convective field will carry momentum as well as energy and thus will produce either diminution or increase of the effective gravity, with consequent distention or compression of the atmospheric gases.

Unsöld has shown that convective instability tends to exist in two separate levels of the solar atmosphere, one below the photosphere and the other near the top of the reversing layer. The lower one arises from ionization effects of hydrogen, the dominant chemical constituent of the solar atmosphere. If a volume consisting largely of ionized gas is displaced upward, it expands and cools. The cooling effects lead to electron capture. The released energy raises the temperature above the value prescribed by the adiabatic relation, and thus we find a hydrogen convective zone. The second zone is associated with the region where the atmosphere is transparent except in the absorption lines. The "blanketing effect" of the absorbing atoms again changes the temperature gradient in such a way as to induce convective instability.

When we turn to the Fraunhofer spectrum for information on chemical composition and gas motions, we encounter even more difficult problems. The shape and intensity of a solar absorption line depend in a very complicated manner on a variety of factors, of which the abundance of the responsible element is only one. The "f-value," "line strength," or absorptive power of an atom for a given radiation is also significant. The population of atoms in the two levels responsible for the line formation is also extremely important. The Boltzmann equation fixes these populations if the medium is in thermodynamic equilibrium. The temperature is the determining parameter. Likewise, the Saha equation, under similar conditions, fixes the amount of dissociation. However, the very fact that energy is flowing through the medium requires departures from this equilibrium condition. An exact determination of the significant populations theoretically requires advance knowledge of all the atomic constants, such as areas for absorption of radiation or collisional excitation, and the appropriate transition probabilities. The equations of statistical equilibrium are most cumbersome and difficult to solve. Further progress would seem to depend on the development of new techniques for the obtaining of approximate solutions near thermodynamic equilibrium.

We need to know the mechanism that the atoms employ for removing energy from the line. The process may involve pure absorption, coherent scattering, or noncoherent scattering, and it is usually not obvious which mechanism or combination of mechanisms operates for a given line at a given height in the atmosphere. The character of the line depends critically on the assumed atmospheric model. Third, we must know or determine what processes cause the broadening of the spectral lines. The most important broadening mechanisms include random Doppler effects caused by thermal agitation or by macro- or micro-turbulence, collisions, Stark effect, and radiation damping. Widening from hyperfine structure and Zeeman effect may not always be negligible. The parameters necessary for calculating the Stark and collisional broadening are very difficult to come by, theoretically or experimentally.

Twenty-five years ago only a rough beginning had been made towards the quantitative interpretation of the solar spectrum. Virtually all analyses of the Fraunhofer spectrum were based on the idealized assumption that the continuous spectrum originated in a sharply bounded radiating surface, the photosphere, and that the lines were produced in a cooler superimposed layer, the reversing layer, which was supposed to be at constant temperature and pressure. Only very crude guesses were available for most f-values and line-broadening parameters, and accurate intensity measurements had been made for but a mere handful of solar lines. Nevertheless, H. N. Russell (1929) accomplished a remarkable feat in achieving what he has called the "zero-th approximation" to the chemical composition of the sun, especially in view of the fact that only recently have astrophysicists displayed any general agreement that the "first approximation" has finally been reached.

No one doubted the existence of large temperature and pressure gradients in the solar photosphere, but attempts to construct a model solar atmosphere were frustrated by a total lack of knowledge concerning the origin of the continuous spectrum. Calculations by Menzel and Pekeris (1935) gave too low a figure for the absorption by transitions involving the negative hydrogen ion. In 1938 Wildt (1939) noted the existence of a bound state of H—, and suggested that photoelectric ionizations and free-free transitions of this negative ion were the major causes of the sun's continuous opacity. Wildt's suggestion was confirmed by the work of Chandrasekhar and associates (Chandrasekhar and Breen, 1946) and Chalonge and Kourganoff (1946).

Numerous calculations of model solar photospheres followed. Even now, we must admit that the photospheric model is known only in the first approximation. Although most workers agree on the temperature distribution in the intermediate layers, the structure of the deepest and uppermost layers remains uncertain. Since most of the radiation from these regions is absorbed by the overlying gases, we must use theory rather than direct observation for the analysis. In consequence, the location and extent of the convective zone are not precisely known. Indeed, the magnitude of what appear to be convective processes in the outer atmosphere suggests that even the intermediate layer may not be free from effects of the hydrogen zone. Radiation from the upper layers can best be observed at the extreme limb of the sun, where terrestrial atmospheric seeing hampers observation. The blanketing effect of the absorption lines and possible departures from thermodynamic equilibrium further complicate the problem.

Additional difficulties of even more basic character stand in the way of a definitive model of the photosphere. Just a few years ago it seemed possible that a straightforward analysis of measurements of solar limb darkening and absolute spectral energy distribution would determine an accurate solar model. It was hoped that the model could be tested and further refined by calculation of absorption-line profiles in terms of a specific chemical composition of the atmosphere. For several reasons, this hope now seems to have been optimistic. First, no existing model has succeeded in reproducing in detail the profiles of strong absorption lines. In particular, the observed central intensity has always been greater than the calculated, but the discrepancy has usually been attributed to imperfections in the theory of line formation. Various devices such as fluorescence effects and noncoherent scattering have been employed to fill in the line center, but none has proved quite satisfactory. Second, the empirical dependence of the continuous opacity upon wavelength, derived from Pierce's (in press) latest measures of limb darkening, differs significantly from the values calculated in terms of currently accepted electron pressure distributions and the theory of continuous absorption by neutral hydrogen atoms and negative hydrogen ions. Errors evidently exist either in the model or in the theory of the continuous absorption, or perhaps in both. Third, no spherically symmetrical model of the photosphere appears capable of representing the center-to-limb variation in the intensities of both low and high excitation lines of Fe I (Böhm, 1954). Nor can the center-limb variation in the CO line intensities be accounted for on such a model (Newkirk, 1953). Similar results have been obtained by Elste (1955) at Göttingen and by others.

The evidence is accumulating that the line-intensity observations can be reconciled with theory only when account is taken of temperature and velocity fluctuations in the photosphere and chromosphere. The recognition of temperature fluctuations is not new, since they are reflected in the brightness fluctuations of the granules, but their influence on the Fraunhofer spectrum represents a second-order effect which could not be detected before the advent of modern techniques of observation and analysis. It is now generally agreed that the phenomenon of the granules is a consequence of turbulent convection in the photosphere and that, on the average, the bright and presumably hot granules are ascending and the cooler, intergranular regions are descending in the photosphere. If the convection is sufficiently violent, however, coupling of the mechanical and radiative fields may occur, with nonlinear effects. The optical thickness of the atmosphere might vary significantly between the bright and dark areas, with an appreciable change of line intensity.

Another consequence of the turbulence is the excessive broadening of the centers of the Fraunhofer lines as compared with that to be expected from thermal Doppler effect at a temperature of 6,000° K. The root-mean-square turbulent velocity derived from individual line profiles and from the curve of growth is about 2 km/sec. Richardson and Schwarzschild (1950) supposed that the radial velocities of individual granules could be obtained from the measurement of minute Doppler shifts from point to point along the length of Fraunhofer lines, under conditions of high spectroscopic resolution and exceptional seeing. Careful measurement of selected Mount Wilson plates did indeed reveal irregularities in the lines, which, upon measurement, yielded a root-mean-square velocity of about 0.4 km/sec. This effect was interpreted as arising from the macroturbulence of relatively large elements, the higher velocity of 2 km/sec being attributed to the microturbulence of elements smaller than the thickness of the "reversing layer."

It had been supposed that the observation of the random Doppler shifts was limited by the resolution of the solar image; i. e., by the external seeing. Recent work by McMath (1956) and McMath, Mohler, and Pierce (1955) at the McMath-Hulbert Observatory has revealed, however, that limitations in spectroscopic resolution are at least of equal importance and that air turbulence within the spectrograph may "wash out" the small Doppler effects. On McMath-Hulbert photographs made with the vacuum spectrograph, all photospheric lines show a characteristic "zigzag" appearance even when the seeing quality is less than average. Further, when the seeing is good, the lines fluctuate in intensity from point to point along the solar disk. Thus the temperature and velocity fluctuations in the solar atmosphere may now be directly observed in the Fraunhofer spectrum, at least for elements about 2 seconds of arc in diameter or larger.

Several inferences may be drawn from these results, the most general of which is that the interpretation of photospheric and chromospheric observations on the basis of spherical symmetry should now be abandoned, and the observational emphasis directed towards determining the nature of the velocity and temperature fluctuations in the solar atmosphere. The impact of this new development upon the National Science Foundation is likely to be very great. First, important funds will be required both to modernize existing solar spectrographs and to construct new ones. Second, an enormous quantity of new and valuable data will become available for analysis, which will necessitate funds for assistance in reduction and analysis. Third, new impetus will be provided for the development and refinement of image-tube techniques. At present photographic exposure times are not less than 10–20 seconds, whereas the image tube may be expected to reduce exposures to a small fraction of a second. Such a reduction would greatly reduce the effects of atmospheric scintillation and improve our determinations of the lifetimes of small-scale solar phenomena. Finally, it is already apparent that spectroscopic resolution has far exceeded the image resolution and that limitations in external seeing quality will seriously hinder the discovery of the details of solar atmospheric structure.

Poor external seeing is caused both by disturbances inherent in the atmosphere and by local disturbances of the air produced by solar heating of the telescope and mirrors. The National Science Foundation panel for a national astronomical observatory, under the chairmanship of R. R. McMath, has recently considered this problem and has concluded that two courses of action should be taken. First, the present site survey for the national observatory should be extended to include observations of daytime as well as nighttime seeing. Second, an investigation of instrumental seeing should be undertaken at the earliest possible moment with the goal of designing a solar telescope in which heating effects would be minimized. It is probable that the solution of the problem of telescopic seeing is now the most important instrumental challenge in the field of solar physics.

The vacuum spectrograph or other spectrographs that may be designed to eliminate instrumental turbulence will initiate a new phase of research in solar spectroscopy that will take many years to run its course. The end result should be a much finer elucidation of the structure of the solar atmosphere, including its composition and circulation, than is possible at present. As a valuable byproduct we may also expect a better understanding of the mechanisms of absorption-line formation. As previously mentioned, the fact that the observed central intensity of a very strong line is always greater than that calculated from theory has been a major difficulty. However, it is already obvious from the vacuum spectrograms that some if not all of the discrepancy between theory and observation will vanish when we allow for fluctuations in observed central intensity, which have generally been blurred by poor seeing inside the spectrograph. In addition, theorists will have to include effects of mechanical as well as radiational transfer of energy.

Finally, it may not be out of place to point out that if temperature fluctuations are present in the solar photosphere they undoubtedly occur also in stellar atmospheres, especially in the highly turbulent atmospheres of the supergiant stars.

Chromosphere and corona

By definition, the beginning of the chromosphere is the upper boundary of the photosphere. It is also the transition region, perhaps 20,000 km thick, in which the electron temperature increases from its photospheric boundary value of 4,000°–4,500° K to 1,000,000° K or higher, in the inner corona. It is therefore of strategic importance, since within its confines probably occur the processes that maintain the corona at its high temperature. More than 20 years ago Menzel (1931) called attention to the anomaly posed by the coexistence in the flash spectrum of emission lines of both neutral metals and ionized helium. Menzel pointed out that the observed intensity of He+λ4686 could not be explained by a temperature of 6,000° K even if the chromosphere were composed of pure helium, and suggested that the required ionizing radiation might come from a hypothetical ultraviolet excess in the solar spectrum.

The problem posed by Menzel is still paramount for theories of chromospheric structure, even though the solution in terms of an ultraviolet excess has been ruled out. Since the 1930's, at least three important developments have paved the way for a renewed attack on the chromospheric problem. First, the discovery of the high-temperature corona inevitably requires the existence of large temperature gradients somewhere in the chromosphere. Second, the observation from rockets of the far ultraviolet solar spectrum has shown that the hypothetical ultraviolet excess does not exist. Third, the observations clearly show that the chromosphere is not a static phenomenon and that hydrodynamic or aerodynamic processes play an important role in fixing its physical state.

Evidence bearing on the structure of the chromosphere comes from observation of the optical spectrum during eclipses, from motion pictures in Hα obtained with large coronagraphs, from observation of the radio emission at high frequencies, from observation of the central intensities of certain strong Fraunhofer lines and of the λ10830 absorption line of He I, from observation of emission lines in the rocket ultraviolet, and from observations of the earth's ionosphere. Interpretation of the observations from the conventional point of view of spherically symmetrical chromospheric models leads to serious discrepancies. In particular, one set of observations has seemed to require a temperature for the low chromosphere in the neighborhood of 5,000°–6,000° K, whereas another set seems to demand much higher temperatures of about 20,000° K or greater.

A possible path out of the dilemma was pointed out in 1949 by Giovanelli (1949), who suggested that the chromosphere is nonuniform and that it consists of alternate "hot" and "cold" columns. Hagen's (1954) measurements of the center-limb variation of the radio emission also point to a model of this general type. Strong support for the nonuniform model has recently been provided by the detailed analysis of flash spectra by the Harvard-High Altitude Observatory group (Athay, Evans, and Roberts, 1953; Athay, Billings, Evans, and Roberts, 1954; Athay and Roberts, 1955; Pecker and Athay, 1955; Matsushima, 1955; Athay, Menzel, Pecker, and Thomas, 1955; Athay and Thomas, 1955, 1956a, 1956b; Athay and Menzel, 1956; Billings, Cooper, Evans, and Lee, 1954) and by studies of the structures of Fraunhofer lines at the McMath-Hulbert Observatory (McMath, Mohler, Pierce, and Goldberg, 1956; Mohler and Goldberg, 1956). Although the exact geometry and physical properties of the hot and cold regions have not yet been clearly established, interesting working hypotheses have been suggested which clearly indicate the lines along which future researches should be planned. Observations of the flash spectrum at future eclipses will continue to play a leading role in the investigations of the chromospheric structure, but they may now be supplemented by additional new techniques which have recently been developed. Of great importance are observations of microwave radio emission, which should be carried out with large antennae of the highest possible resolving power. The accurate measurement of emission profiles of solar lines in the rocket ultraviolet will also be crucial for the testing of chromospheric models. Finally, the Fraunhofer spectrum itself constitutes a rich but largely neglected source of chromospheric information. The interpretation of the limb spectrum is complicated by the two-dimensional integration, both radial and tangential, of the chromospheric emission. On the disk, the line of sight integration is only one dimensional. Indeed, the complex structures of the $\lambda 10830$ helium line and of the cores of the hydrogen and ionized calcium lines, as revealed by the vacuum spectrograph, are undoubtedly a consequence of the temperature fluctuations in the chromosphere and should be analyzed from this point of view.

The dynamic nature of the chromosphere is graphically portrayed by the $H\alpha$ motion pictures recently obtained by R. B. Dunn of Harvard and the Upper Air Research Observatory with the 15-inch Sacramento Peak coronagraph. These remarkable photographs record the rapid changes that occur in the irregular structure of the outer chromosphere. Since the chromosphere is basically a dynamic phenomenon, with kinetic transport of both energy and momentum, a true model of this region of the solar atmosphere should depict and account for the internal motions. One may question whether any static solution of the fundamental equations exists. Small perturbations about such a hypothetical static solution, for example in terms of a linear combination of normal modes, seems out of keeping with the actual observations. Instead, we suspect that the mean energy transport, determined by the solar energy generation, can never be fulfilled in a purely radiative atmosphere.

The solution will depend on the magnetohydrodynamic equations of motion in their nonlinearized form. The Bhatnagar-Gross-Krook (1954) equation appears to be a useful substitute for the much more complex Boltzmann transport equation. The simplification represents a new approach to problems of gas dynamics in which the distribution of velocities no longer follows Maxwell's law. Instead, the equation represents the velocities as lying between the two extremes of isotropic scattering without change of velocity, or of reemission under thermodynamic equilibrium at the temperature described by the root-mean-square velocity. The equation bears a close resemblance to the Milne-Eddington equation of radiative transfer, with solution between the extremes of monochromatic radiative equilibrium and local thermodynamic equilibrium.

The solution of the transfer problem, especially when electric currents and magnetic fields are present in the medium, can rarely be expressed in terms of known functions. Instead we shall have to determine families of solutions, with ranges of boundary values and initial conditions. In general, these calculations will require the use of high-speed computing machines. The National Science Foundation may well be called on to furnish funds for the development of models of the dynamic chromosphere.

Closely associated with structural problems of the solar atmosphere is the question of origin of the solar radio emission. It is well known that an ionized gas, with specified electron density, possesses the so-called "plasma" oscillation frequency equal to the "critical frequency" at which the phase-velocity becomes equal to zero. Many persons have supposed that natural oscillations of such a medium will lead to the emission of radio waves on the plasma frequency. A detailed analysis indicates, however, that the plasma oscillations, which resemble sound waves in their longitudinal character, cannot be converted into transverse waves by means of boundary conditions alone. In short, plasma oscillations cannot produce transverse radio waves. When the medium contains a magnetic field, however, the rigidity of the medium associated with magnetism resolves any longitudinal wave into vibrations having one transverse component. A disturbance propagated from regions of high into regions of low density tends to have its vibrations amplified. In this way, as Krook and Menzel have shown, a magnetohydrodynamic wave at low density will eventually escape from the sun's outer boundary as a true electromagnetic wave, with polarization determined by the orientation of the internal magnetic field.

Low-frequency radiation tends to be trapped or attenuated in an atmosphere containing ions and electrons. Thus, only higher frequencies are able to penetrate from the chromosphere through the overlying coronal regions. Similarly, a given disturbance rising through the solar corona permits lower and lower radio frequencies to escape. Study of the changing spectrum of solar radio noise, especially in combination with optical data, should give valuable information about the solar atmosphere. J. P. Wild's (1953) dynamic spectrum analyzer presents the observational facts in graphic form. The Cornell measures of solar radio noise, as analyzed by H. W. Dodson (1953), have already yielded significant correlations with flare and other solar activity.

The corona itself poses many difficult problems. There is little doubt that the streamers, domes, and arches owe their basic structure to general and local magnetic fields. Magnetic focusing must be important in certain of these phenomena. The forces associated with electric currents undoubtedly play a significant role in determining the motions of prominences and the general condensations that occur from the solar corona. The detailed theory of fluid gas dynamics necessary to account for these phenomena will undoubtedly be very complicated.

Solar activity

The term "solar activity" includes all types of phenomena of a transient nature except the small-scale fluctuations in velocity and temperature associated with granulation. Typical of these phenomena are sunspots, faculae, plage regions, flares, filaments, prominences, and coronal disturbances. Solar activity occurs throughout the solar atmosphere; e. g., the sunspots and faculae in the photosphere, the flares in the chromosphere and corona, and the prominences largely in the corona. No attempt will be made in this brief survey to summarize the problems related to solar activity in any systematic way. The entire subject is still in a highly chaotic state, hardly less so at present than in the 1930's. One reason for this state of affairs is the aforementioned inherent diversity and complexity of solar phenomena. A second reason is that only in rare cases have the most modern spectroscopic techniques been applied to the study of solar details. The changes on the solar surface are so gross and easy to observe that solar observers have been tempted to make large numbers of observations with instruments of relatively low resolving power, either visually or on uncalibrated plates.

The rapid acceleration of observing programs during the International Geophysical Year gives to those participating in the program the responsibility of maintaining high standards for their records. It is to be hoped that the need for large masses of data will not distract the attention of solar physicists from the really basic problems of solar activity, which pertain to the origin and physical nature of solar phenomena. In the end, a complete understanding of the effects of solar radiation on the earth is more likely to come from the solution of these basic problems than from correlations developed between one or two observed solar quantities and various geophysical data.

Knowledge of the physical state of the various kinds of solar phenomena must precede correct theories of their origin. In the light of recent technical developments—which include the perfection of gratings and the magnetograph by the Babcocks, the construction of the vacuum spectograph by McMath, and the development of a large coronagraph by the Harvard-Air Force group on Sacramento Peak—we can look forward to a fruitful period of quantitative analysis of the spectra of solar details during the forthcoming sunspot maximum.

An understanding of the detailed structure of sunspots, including the three-dimensional distribution of temperatures, pressures, gas velocities, and magnetic fields, should be a primary target during this period. There also seems to be no reason why high-dispersion studies of flare spectra should not lead to knowledge of the vertical temperature and pressure distributions in the flare-emitting layers, which can provide insight into the mechanisms of origin both of the flares themselves and of the ultraviolet radiation responsible for ionospheric disturbances. In this connection we consider that the physical investigation of faculae and the associated "plages faculaire" has been grossly neglected. It is well established that flares break out only in regions occupied by the plages. The latter, which are also regions of abnormal magnetic activity, are generally located above the photospheric faculae. There must exist, then, certain physical properties associated with faculae and plages that favor the outbreak of flares; yet the properties of these regions have hardly been studied.

Our understanding of the physics of prominences is equally weak. The development of the motion-picture technique by McMath and by Lyot in the early 1930's has been followed by large numbers of reasonably accurate measurements of prominence motions, chiefly in Hα radiation. Some of the observed motions have been explained plausibly, but nevertheless only qualitatively, on the basis of the combined laws of hydrodynamics and electrodynamics by Alfvén and by Menzel, but a detailed quantitative description of prominence behavior is still somewhere in the future. Here again, the development of a successful theory is retarded by uncertain knowledge of the temperatures, pressures, turbulent motions, and magnetic fields within the prominences. The first three of these quantities are readily within the reach of modern instruments and theory. But one must avoid the temptation to tackle these important problems with equipment yielding marginal data that can be interpreted only on the basis of doubtful assumptions or even wishful thinking.

Finally, although we have devoted major attention to observational trends in solar physics, we have not wished to minimize the importance of support by the National Science Foundation and other Government agencies for theoretical research of varying shades of purity. The so-called theoretical projects that are most likely to receive support today are those that involve detailed computations—usually by high-speed calculators—based on theories already in existence. In short, practical results are guaranteed, but such projects are no more theoretical than those that involve the measurement of stellar magnitudes or of spectral line intensities. We do not question the value of accurate computations to astronomy and solar physics. However, the National Science Foundation should also consider how its support might stimulate the birth of new theories as well as foster applications of existing ones.

For example, the solution of many problems of solar structure or solar activity waits upon further developments in the field of generalized gas dynamics concerning the motions of high-temperature gases in the presence of various types of force fields. Indeed, the United States appears to be lagging in this important field, which has applications to physics, geophysics, and industry as well as to astrophysics.

Several symposia on this general subject have already been held and have been useful both in terms of summarizing what little knowledge exists in this area and in stimulating new thinking. If a really top-notch group of investigators could be assembled to work together for a relatively long period—for months, or even years, instead of a few days—to study the problem in its broadest aspects, we could expect significant new advances. For a problem of this magnitude, support would be necessary for a number of years, during which headquarters of the project would be maintained at a particular university with some rotation of personnel. A center of this sort devoted to theoretical problems of fluid gas dynamics could be as important to astronomy and to other branches of science as a cooperative observing facility.

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Stars and the Galaxy

Spectral Classification

By W. W. Morgan[1]

In a classical review titled "Some Problems of Sidereal Astronomy" prepared by H. N. Russell in 1917, the main object of astronomy is stated as being

> . . . the development, on the basis of collected facts, of satisfactory theories regarding the nature, mutual relations, and probable history and evolution of the objects of study.

Russell suggests that before the stage of formation of a general theory is reached, two courses may be followed:

> (1) to collect masses of information, as accurate and extensive as possible, by well tested routine methods, and leave it to the insight of some fortunate and future investigator to derive from the accumulated facts the information which they contain regarding the general problems of the science; (2) to keep these greater problems continually in mind, and to plan the program of observations in such a way as to secure as soon as practicable data which bear directly upon definite phases of these problems.

The present survey gives an approximate picture of the research situation in spectral classification in 1956, a comparison with Russell's survey, and some suggestions of the probable directions for future work.

The Henry Draper Catalogue, which was published between 1918–1924, remains the most important fundamental body of data in Russell's first category. Russell's conclusions are, to a large extent, based on the Harvard work.

The interval 1917–1955

Two fundamental conclusions were drawn by Russell from the study of the lines of stellar spectra: (a) that almost all of the observed lines are identifiable with known elements; and (b) that the vast majority of stellar spectra fall into a single, continuous linear sequence. Later work has confirmed fully Russell's first conclusion; the second requires some qualification.

As early as 1897, Miss Antonia Maury had reached the conclusion that—

> . . . a single series was inadequate to represent the peculiarities which presented themselves in certain cases, and that it would be more satisfactory to assume the existence of collateral series.

She devised a system of 22 "groups" which formed a sequence; most of the "groups" were then divided into "divisions," which, in turn, introduced a second dimension. It was from this pioneering work of Miss Maury that the field of spectroscopic parallaxes derives, through the later work of Hertzsprung, Russell, Adams, and Kohlschutter.

The situation in 1920 was, therefore, approximately as follows: spectral classification was considered to be primarily a one-dimensional problem; in addition, differences in luminosity were observable by means of certain sensitive line-ratios. The early work of Miss Maury had not been adopted as standard, nor was it continued on any appreciable scale.

If a single development could be considered of primary importance in spectral classification since 1920, it would be the realization of the fundamental two-dimensional nature of the problem. The critical work here was that of Bertil Lindblad, who developed criteria for the separation of stars of differing luminosity by use of plates of low dispersion; this last property permitted the extension of the spectroscopic parallax method to great numbers of stars too faint to be observed with higher dispersion.

Another fundamental development was the formalizing of the earlier work (in particular, that of Lindblad) in the two-dimensional Yerkes system of Morgan and Keenan. As far as the actual criteria of classification are concerned, there was little new in the latters' system; the principal development lay in the recognition that spectral classification *per se*

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is a two-dimensional process and that the designation of the "luminosity class" should be by means of an empirical notation similar in nature to the ordinary "temperature type."

The process of determining spectroscopic absolute magnitudes was thus divided into two stages: (1) the determination of a spectral type and luminosity class; and (2) the calibration of the empirical luminosity classes in terms of absolute magnitude. The first of these operations is purely a description of the spectra. This description is a fundamental property of the latter, and there are no compelling reasons why it would have to be revised with the passing of time. In this respect the second operation can be improved with the passing of time, due to more and more accurate calibration data becoming available.

Another development in the intervening years has been the devising of methods for segregating certain kinds of stars by means of spectra of exceedingly low dispersion. The most important applications of these methods have been to the use of objective-prism spectrograms.

In 1950 attention was called to the possibility of classifying members of certain "natural groups" on objective prism spectra. For example, a single criterion is sufficient for the segregation of a well-defined group of early A main-sequence stars; this is carried out by means of the Balmer series of hydrogen. If a group of stars is selected having the characteristic of maximum intensity for the Balmer lines, it is found that the stars in this group possess the characteristics of closely similar absolute magnitude and spectral type. Among the most interesting of the groups identifiable on objective-prism plates is that of the blue giants. Nassau and collaborators at Cleveland have prepared such a catalog of northern blue giants, and this work has been extended to southern declinations and fainter northern stars by Haro and associates at the National Astrophysical Observatory in Mexico.

Of comparable importance has been the development of a method of classification of late M giants in the infrared spectral region by Nassau and collaborators. A catalog of the brightest of these objects has been published recently, but a beginning has scarcely been made on this most promising field for future galactic studies.

A most important development has been in the field of classification of the faint inhabitants of dust clouds—the T Tauri stars—by Joy (Mount Wilson), Herbig (Lick), and Haro (Tonantzintla). The work on these strange systems of stars is also in its infancy.

Present and future problems

This topic will be considered under three general heads: (1) astrophysical interpretation; (2) spectral classification as applied to problems of galactic structure and stellar evolution; and (3) instrumental needs.

(1) *Astrophysical interpretation.*—Very promising beginnings have been made in the past few years in devising semiquantitative methods of classification for stars in certain restricted areas of the HR diagram. Some of these have made use of measures of line depths and equivalent widths to furnish more objective data for classification. Of especial importance is the work of Greaves, Baker, and Wilson at Edinburgh, of Chalonge and associates in Paris, and of Hossack at Toronto. Accidental accuracy of a high order has been achieved. The principal difficulty here is probably in devising a frame of reference sufficiently precise to make full use of the extremely accurate individual results obtained by these investigators.

It is from investigations such as these that we will be able to decide how uniquely the stars can be classified in a two-dimensional array, and what the relationship is between the "normal" and the "peculiar" stars. The practical limit attainable in the accuracy of spectroscopic parallaxes will also be determined from high-dispersion investigations.

(2) *Spectral classification as applied to problems of galactic structure and stellar evolution.*—The application of the spectroscopic parallax method to large numbers of fainter stars is now quite feasible. The only thing needed for a great increase in our knowledge of the arrangement of the stars in space in the neighborhood of the sun is more investigators; the method and equipment are now quite adequate for the work. New programs will probably be of two kinds: (1) work on the O-associations, galactic clusters, and other objects associated with spiral struc-

ture; and (2) investigations of the amorphous disk and halo population.

An interesting group for further investigation in the second category is that of the late M giants, which are most important for the determination of the kinematical properties of the disk population. However, for their observation at great distances it will be necessary to devise infrared techniques for measurement of radial velocity and absolute magnitude.

Some of the most dramatic developments of the 30-odd years since Russell's survey have been in the field of stellar evolution. The theoretical work in this field, up to 1951, has been well summarized by Stromgren (1952). This work, together with later developments, now makes possible the application of Russell's second criterion quoted at the beginning of this summary. It is now possible to formulate precise observational experiments concerned with various aspects of the great general problem of stellar evolution.

One of the most inviting practical problems of the future is the invention of a system of spectral classification according to stellar age, or relative evolutionary state.

(3) *Instrumental needs.*—The principal instrumental need for present and projected observational problems in this field is probably not for new or larger telescopes but for more efficient spectrographic equipment for use with existing instruments.

The requirements for such "maximum efficiency" spectrographs have been outlined clearly by Bowen (1947, 1952), who has also designed and supervised the construction of instruments of this type which are now in use with the Mount Wilson-Palomar reflectors. Special attention should be called to the new 60-inch Cassegrain spectrograph designed by Bowen which has recently been put into operation. The faint limiting magnitude obtainable with this instrument illustrates how great a gain in efficiency is possible with reflectors in the second category of size. Special mention should also be made of the exceedingly efficient nebular spectrograph designed and constructed under the direction of Mayall for the 36-inch Crossley reflector of the Lick Observatory.

There are now several large and most useful objective prism Schmidt cameras in operation. Especially important new instruments of this type have been put into operation recently at Hamburg-Bergedorf, the University of Michigan, and Vanderbilt University. Exceedingly efficient slitless spectrographs have been designed and constructed recently by Herbig (Lick) and Meinel (University of Chicago).

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Stellar Atmospheres

By Marshal H. Wrubel[1]

The outer region of a star in which the optical spectrum is formed is referred to as the atmosphere. This definition delimits a shell lying between the deeper regions, which cannot be directly observed, and the higher regions, which contribute very little energy to the optical spectrum (but which may be all-important in the radio spectrum). Although it is convenient to treat this shell separately, it is certainly not independent of the layers lying below and above it.

Any discussion of stellar atmospheres logically begins with the sun. Here is a star on our doorstep; and the variety and accuracy of the solar data we can accumulate far surpasses that for any other star. We may examine the radiation received from every point on the sun's disk and for every wavelength that penetrates the earth's atmosphere.

In spite of centuries of solar observation, new techniques continue to introduce new phenomena. To mention only two of the most interesting: the Babcocks' magnetograph, which gives a tracing of the atmosphere's magnetic field point by point; and the McMath-Hulbert vacuum spectrograph, which has revealed a remarkable complexity of line structure. Both of these innovations are triumphs of observational technique and will create challenges to the theoretician.

The theoretical models that have been explored until recently may be characterized as being in "hydrostatic and radiative equilibrium"; that is, the atmosphere is supported by hydrostatic pressure and radiation is the sole means of energy transport. The logical chain is this: the temperature distribution is found either theoretically or by limb darkening measurements, and it depends on the broad continuous absorption characteristics of the gas. A complete physical description of the atmosphere follows from the temperature distribution by using the hydrostatic equation, the absorption coefficient, the ionization equation, etc. The resulting "model atmosphere" combined with the theory of the formation of absorption lines is used to predict the observed spectrum. The only adjustable parameters of such a solar model are the abundances of the elements which are determined by a comparison with observations.

Although the reasoning is straightforward, many problems arise even in the static model. To list only a few:

(1) The temperature distribution of the upper layers is uncertain because of the difficulty of observation close to the limb of the sun.

(2) The abundance of the second most abundant element, helium, cannot be determined directly since it is effectively "dead weight" in a low-temperature atmosphere.

(3) The fundamental data of transition probabilities for many lines are still missing. The great emphasis on nuclear and molecular physics in recent years has attracted physicists away from research in atomic spectra. A possible solution is for some young astronomers to learn the laboratory techniques and to do the work themselves.

(4) The theories of the shape of the line-absorption coefficient, i. e., broadening, absorption versus scattering and noncoherent processes, are not in satisfactory form. Of particular interest in this connection is the recent use of a shock tube at the University of Michigan to obtain laboratory data on broadening.

(5) The problem of predicting the profile of an absorption line formed when radiation passes through many layers of different physical characteristics has been solved only for very special cases.

(6) The cumulative effect of many absorp-

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tion lines (blanketing effect) is difficult to evaluate.

However, overshadowing all these difficulties today is the problem of describing a dynamic atmosphere. The theoretician no longer can avoid including large-scale motions in his solar models but the kinematical description is far from clear. One important source of information is the "granulation"; but the details are obscured by "seeing" in the earth's atmosphere. It is to be hoped that Schwarzschild's unorthodox plan to photograph the sun from above the "seeing" will be successfully carried out in the near future.

Although simple models (such as those used by de Jager) involving temperature inhomogeneities in adjacent columns of the atmosphere may prove serviceable for a while, eventually we must have a model obeying the hydrodynamical laws (better still the *hydromagnetic* laws) and including the transport of energy by a combination of convection and radiation.

Increasing use will undoubtedly be made of high-speed electronic computers to obtain numerical solutions to these difficult problems. Computers can certainly not create ideas, but they can explore the consequences of various assumptions to an extent previously impossible. It is a challenge to find efficient machine procedures for calculating model atmospheres and line profiles under a variety of physical conditions. Computer techniques will probably be second nature to astrophysicists a few academic generations hence; at the moment, however, theoreticians have been very conservative in adopting these new methods.

As if the existing observations do not provide sufficient problems, astronomers have watched with great interest as rocket spectrographs and radio telescopes have broadened the limits of the observable spectrum. Lyman α has at last been photographed and even soft X-rays have been detected. Observations such as these will have a profound effect on future models of the sun.

There is very little generally accepted theory concerning the spectacular transient solar phenomena. Many solar observatories are involved in the accumulation and classification of data from which theories will eventually arise, and a highly coordinated effort in this direction is being planned for the forthcoming International Geophysical Year. Many problems in this particular field are treated individually in other articles of this volume.

The techniques developed to describe the solar atmosphere have been applied with some success to "normal" atmospheres of other spectral types. In some cases it is possible to obtain information that the sun will not provide directly: for example, the abundance of hydrogen relative to helium can be found in principle from the spectra of hot stars. Unfortunately, no conclusive value can as yet be given.

Problems immediately arise because of observational limitations. There is just not enough light to work with. Photoelectric techniques for the absolute spectrophotometry of stars are currently being developed by several observers and should yield important astrophysical data. Nevertheless we have only indirect measurements of limb darkening, and these for only a few eclipsing binaries.

As the available light goes down, so does the possible dispersion, and observations become less reliable. Some objects are out of reach of all except the largest reflectors.

Surveys can be carried through by using rough curve-of-growth methods based on idealized models, but eventually we need detailed model atmospheres for a wide variety of spectral types. These are constructed by using theoretical temperature distributions and are tested by requiring the flux to be constant at every depth. However, it is difficult to apply this criterion in early-type stars where the flux is jagged due to the absorption edges of hydrogen and helium.

As we go toward the cool stars, the importance of the blanketing effect grows and a premise upon which other models are founded breaks down—it is not possible to separate the lines from the continuum. Entirely new theoretical techniques will have to be combined with laboratory data on the absorption of molecules before we will have as detailed an interpretation of the atmospheres of stars of late spectral type as we have for the sun.

Nature has provided a unique tool for studying the outer regions of late-type giants. Binary systems like 31 Cygni, in which a small hot component is gradually eclipsed by the extended atmosphere of its giant companion, provide a wealth of detailed information. The observations indicate a "network of prominences" far more extensive than that of the sun; and if an understanding of a dynamic atmosphere is important in the sun, it is vital here.

As the spectroscopic peculiarities become more unusual, the extrapolation of normal techniques becomes less successful. Thus, our present understanding of the atmospheres of pulsating variables, magnetic stars, Wolf-Rayet stars, etc., is rudimentary at best. Nevertheless, the tendency is to make quantitative measurements whenever possible and not to be satisfied with visual estimates.

It is obviously impossible to cover all aspects of such a varied subject in a short survey. Fortunately several detailed discussions of solar and stellar atmospheres have recently appeared, and references to individual papers will be found there.

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Aerodynamic Problems in Stellar Atmospheres

By Richard N. Thomas[1]

The term "cross-field research" occurs with increasing frequency in astronomical studies. This new emphasis does not imply that astronomy, in the past, failed to utilize advances in other sciences; rather, it indicates our growing awareness that the physical problems of matter studied by the observational astronomer are not far removed from those studied by the laboratory scientist. Classically, astrophysics has dealt with matter under conditions that were strange and abnormal, compared to those in the terrestrial laboratory. Astronomy has been an observational science. The objects of its inquiry have been obscured by the earth's atmosphere and situated at great distances; and the phenomena studied were incapable of reproduction in the laboratory. Of all the "cross-field" liaisons that exemplify our changing views, none is more interesting than that between modern aerodynamics and astrophysics.

Modern astrophysics not only concerns itself with the common problems in the two sciences but also recognizes that the data required to support a theory or an anticipated future development in one field may already exist in the other. Also, the analytic methods that are gradually being developed for a specific problem in one field may already be common knowledge in the other. For example, the advent of high-altitude rockets, satellites, and the possibility of extraterrestrial manned objects will break the barriers imposed by the terrestrial atmosphere and the astronomical distance scale. Yet a satisfactory development of ultraspeed aerodynamics requires careful attention to the problems of ablation from a solid moving through a gas, of radiative energy loss from a gas compressed rapidly to a high degree, of the attendant ionization and chemical reactions in the gaseous atmosphere, and of the methods of description of a gas under conditions departing drastically from local thermodynamic equilibrium.

These problems are all of vital interest to astrophysics because our observations show that such configurations occur in astronomical objects. Several of these problems, those connected with the ablation from a rapidly moving solid object, form the fundamental basis of meteor astronomy and have led to the creation of astroballistics, a new field comprising both astronomy and aerodynamics, which is described elsewhere in this series of articles. Others of these problems seem to occur with increasing frequency as we acquire more and better data on stellar atmospheres and are thus faced with the need to construct a theory sufficiently precise to explain the data. In this review, we want to elaborate on certain aspects of stellar atmospheres and to emphasize the continued interplay of astrophysical theory and observation with aerodynamic theory and experimentation, in a kind of checkerboard pattern. The exciting aspect concerns the common physical conditions occurring in the stellar atmosphere and the aerodynamic experiment. The frustrating aspect is the lack of facilities for experimental astrophysics, as it becomes more and more evident that we can actually duplicate in the laboratory physical situations of direct astronomical interest.

Ten years ago, theorists concerned with stellar atmospheres were completely preoccupied with the notion of a gaseous atmosphere whose properties were fixed by the three assumptions: radiative transfer of energy, local thermodynamic equilibrium, and the absence of any velocity fields large enough to affect the structure of the atmosphere. The discovery by Schwarzschild, 50 years ago, of the overwhelming efficiency of radiative energy transport, relative to convective, completely dom-

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inated all thinking in subsequent years. The later recognition of atmospheric convective zones in stars where hydrogen was not mainly ionized was of minor consequence; even in these zones radiation dominates the energy transfer. There were, however, three "types" of atmosphere where "contrary" evidence was becoming difficult to rationalize away: the atmospheres of the variable stars, where the notion of a velocity field had long existed but where the exploration of the physical consequence of its existence had been rudimentary; the atmospheres of certain supergiants, where the evidence for large velocity fields had existed for 10 years but nothing had been done in the way of incorporating them into an atmospheric model; and the solar chromosphere, where considerable evidence of velocity fields and of nonequilibrium phenomena caused the breakdown of virtually all our classical notions of a stellar atmosphere.

There are two ways in which a velocity field can perturb an atmosphere: through a transfer of momentum or a transfer of energy. What little thinking on the influence of velocity fields that did take place in these earlier days was concerned largely with the momentum effect. Velocity fields were simply imposed as an added pressure term, and the thermal and radiative properties of the atmosphere were supposed to remain invariant. Unfortunately, the velocity fields discussed are often of such size that, if the temperature of those atmospheric regions where the velocity fields exist are *not* higher than we would infer from our customary theories, the motions must be supersonic. Such a situation made it difficult to introduce the experience of the aerodynamicist in describing velocity fields in a compressible gas because such supersonic motion, particularly of the quasirandom sort required by the astronomical data, is in aerodynamics always accompanied by shockwaves and by the rapid conversion of mass motion into thermal. Thus we had the unhappy situation of an empirical fact (large velocities) forced into an artificial framework (no dissipation of mechanical energy) because astronomers were reluctant to abandon the atmospheric models which had hitherto worked so well. Moreover, there were absent many of the features one would expect to occur in a rapid production of thermal energy—emission lines, excesses of ultraviolet radiation, etc. The situation, therefore, was far from clear cut.

(If the reader expects the above history to be climaxed by a happy solution in this review, he will be disappointed. If these problems had been solved there would be little point in recording their apparently illogical history. We dwell on the above pattern of thinking because, unhappily, much of it is today's pattern of thinking also. At present we can report only on efforts to resolve these difficulties, not on their success.)

On the other hand, when the thermal dissipation of the mechanical energy of the velocity field was included, the effect on the atmospheric model was, and is, likewise far from clear. This energy transfer represents the most serious and the most fascinating problem of all. First, any such energy transfer establishes a cyclic process, a mechanical energy source and a radiative sink. Such a situation is ideal for setting up a departure from the conditions of local thermodynamic equilibrium. Second, such energy transfer introduces the possibility of a perturbation on the radiation field produced by the star. Consequently, the obvious subject for investigation is the problem of the energy transfer associated with velocity fields in stellar atmospheres.

The solar chromosphere offers the most natural starting point for an investigation of this sort. First, from a general point of view, there is one strong boundary condition on this investigation of aerodynamic effects in stellar atmospheres: the "classical" stellar atmosphere models have been remarkably successful in reproducing the features of the continuous spectrum in the visual region. How can we introduce such things as shockwaves without affecting the continuous spectrum? In the sun, the large velocity fields seem confined to the outer atmosphere, where the total mass is too small to make appreciable contribution to the continuum. We may, however, determine how far down toward the photosphere the effect of the chromospheric velocity fields extends by looking at weaker and weaker lines and the wings of the strong lines. With this information, we may be able to answer the question of what observable consequence would result from an increase by some factor in the energy of the velocity field.

Or, alternatively, what would we have to do to turn the solar atmosphere into that of a Wolf-Rayet star, where the *whole* atmosphere seems a composite of aerodynamic motions?

Second, with a view to finding the origin of these velocity fields, the closeness of the sun and our ability to resolve its disk are of enormous value. Many astronomers believe that the chromospheric velocity fields simply reflect the motion of the solar spicules, which are supposed to arise from the granulation, whose origin lies in the hydrogen convection zone. Some of these astronomers regard magnetohydrodynamic effects as essential in the production of spicules from granules; others believe the transition can be effected from the aerodynamic behavior of a compressible gas in a gravitational field alone; and still others believe that the connection between spicules and granules has yet to be established. Yet in all these points of view several experimental and theoretical aerodynamic problems stand out—problems which we can investigate jointly in astronomy and in aerodynamics: (1) What is the behavior of a supersonic jet when radiation processes form a major dissipative mechanism? Recent solar work on the stability of an ionized gas against radiative cooling suggests that these stability considerations may fix, to a major degree, the permitted kinetic temperature of the gas in the jet. (2) How does a supersonic jet composed of an ionized gas behave in a magnetic field, with the field (a) parallel to the jet axis, and (b) perpendicular? (3) Suppose we have a velocity field, with time-dependent terms, in a gaseous atmosphere in a gravitational field. How rapidly do the acoustic waves, produced by this field and propagated upward, die out? What is the interference pattern? (4) If we superpose a fluctuating magnetic field on this velocity field with time-dependent terms in an ionized medium, can induction effects accelerate a nontrivial amount of gas? (5) Last but hardly least in our incomplete list of problems, How do we specify the spectroscopic state of the gas under the environment of these four problems, and others in the same physical sequence?

Let us return for a moment to the suggestion that spicules are the source of the mechanical energy which causes the chromosphere and that spicules arise from granulation. In this case, all stars with atmospheric convection zones should have chromospheres, that is, all main-sequence stars of spectral class later than $\sim A_0$. But what of the earlier spectral classes? Should we expect no extended atmospheres here, no velocity fields? Yet the existence of differential velocities between emission and absorption lines in stars of classes O and B is well known. In a more extreme case, we refer again to the Wolf-Rayet stars, where the whole atmosphere seems composed of a system of jet-ejections, or streams of outgoing and ingoing material. Whence arises this motion? Aside from the possibilities of the hydrogen convection zone (and possibly a helium convection zone in the hotter stars?) and induction effects in time-dependent magnetic fields, we have two other sources of mechanical energy: stellar rotation and stellar pulsation.

It is interesting to note that the first suggestion that aerodynamic turbulence might arise in stellar atmospheres arose from the observation of the high Reynolds numbers associated with stellar rotations. Furthermore, we note that "shell" stars are most often those having a rapidly rotating nucleus. What is the aerodynamic state of such a rapidly rotating gaseous atmosphere? Does the star set up a system of aerodynamic turbulence, anisotropic for the largest scale motion, with the greatest velocities along the direction of rotation? This would conform to laboratory experience. Or, is the rotation velocity so high (greater than our laboratory experience) that rings of matter are ejected? This problem has hardly been touched, astronomically or otherwise.

The concept of stellar pulsation is relatively old; the implications of stellar pulsation, relatively new. Given a gaseous atmosphere of arbitrary temperature and density distribution, and an impressed oscillation of some thermodynamic variable at some level in the atmosphere, what happens? Remember, we are not dealing with the terrestrial atmosphere, with temperature ~ zero so far as activation of internal degrees of freedom are concerned. We need a terrestrial disturbance of ~ Mach 10 to cause any but the most trivial luminosity. In the star, the ambient temperature ranges upward from ~ 4,000°, and even for Mach 2 one expects to find an observable change in ionization and excitation. A literal interpretation of velocity-curves would suggest $M>2$ in a wide class of variable stars. Indeed, in some stars emission lines appear over some portions of the cycle, and we might interpret their occurrence as implying the existence of localized regions of high kinetic temperature. On the other hand, some stars, whose velocity variations imply compression waves of sufficient amplitude to be shock-waves, do not show these emission lines. Should we interpret these differing results as suggesting that the compression wave just does not have a sufficiently long path to develop into a shock before it is out of the visible atmosphere?

Actually, two physical parameters seem to play a major role in aerodynamic phenomena in the atmospheres of variable stars: the extent of the hydrogen convection zone and the extent of the atmosphere. The convection zone appears to determine the phase relation between the luminous flux and pressure at the "origin" of the disturbance; the extent of the atmosphere determines the character of the disturbance, and, in a sense, has a self-amplifying aspect. The more the dissipation of energy in the atmosphere, the more extended the atmosphere, hence the greater the chance for a shock to develop and dissipate energy.

All these problems are tantalizing. Few have been investigated, none solved. Our greatest progress has been in our finally recognizing what the problems actually are. Our greatest challenge is the need to develop some physical insight to the solution of these problems which lie on the most advanced frontiers of both astrophysics and aerodynamics.

Emission Nebulae

By Lawrence H. Aller [1]

Galactic nebulae that show an emission line spectrum are of two types. Those associated with the type I population are the so-called diffuse nebulae; those associated with the type II population are the planetaries. The diffuse nebulae are normally irregular in form, often of low density and surface brightness, and sometimes of considerable size (e. g., Orion, 30 Doradus in the Large Magellanic Cloud, and NGC 604 in the Triangulum Spiral). The planetaries are often symmetrical in form and smaller than the diffuse nebulae. Many have a higher surface brightness and higher density than the better known diffuse nebulae.

Types of observations

Because of their different characteristics, the kind of equipment and technique best suited for the one type of emission nebulae is not necessarily best for the others. In studies of diffuse nebulae, wide-angle cameras of high speed and detectors sensitive to low surface brightnesses are desirable. For studies of the planetaries a large scale (and therefore a large telescope) is essential, since the angular diameters of all but the largest of these objects amount to only a few seconds of arc. The principal types of observation that can be made are the following:

(a) Direct photographs with the aid of narrow band-pass filters to isolate monochromatic nebular radiations. In particular, interference filters have proved very useful in picking up faint Hα emission regions throughout the Milky Way. When most of the nebular radiation is concentrated in a few strong, well-separated lines, the filter technique is extremely valuable for studying problems of stratification and structure.

(b) Photographs with the aid of Fabry-Perot etalons and suitable plate-filter combinations are extremely valuable for studying the internal motions in extended diffuse nebulae. This technique, introduced by Fabry and Buisson more than 40 years ago and further developed by Baade, Goos, Koch, and Minkowski, has been applied with great success by Georges Courtes at Haute-Provence. Studies may be made with relatively small wide-angle telescopes that will yield considerable information on the mass motions and internal turbulence. It is important that such investigations be carried out not only in Hα but also in the forbidden radiations of [O II] and [O III] whenever possible.

(c) Spectrographic studies fall essentially into three categories. First are slit spectrographic studies of the line and continuous spectra to obtain line identifications and intensities from which the physical state in the nebula or nebular filament may be inferred. For this type of problem a so-called nebular spectrograph with high speed and low dispersion is necessary for all but the brightest objects. Planetary nebulae have been studied rather intensively, particularly by Bowen and his coworkers, but the spectra of diffuse nebulae (except Orion and a few special objects) have not been adequately investigated. Spectrographs of high dispersion may be used for studies of the internal motions in small, bright planetaries. Olin Wilson's multislit has proved particularly valuable in such studies. Finally, slitless spectrograms are essential for the study of monochromatic images of small nebulae when radiations that fall close to one another are to be separated; e. g., the [N II] λ6548, 6584 and Hα 6563 lines.

(d) Polarization measurements are important in these objects where scattering by small solid

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particles occurs and in radio sources. Electron scattering is rarely a factor in the continuous spectra of diffuse nebulae.

(e) Radio-frequency observations of the free-free emission from diffuse nebulae have been made by Haddock and his coworkers. Eventually, with the development of larger antennae, it should be possible to measure the emission from the brighter planetaries as well. These objects have high surface brightnesses but small areas so that their total flux is small. The 21-cm data supply information on those regions of space where hydrogen is neutral.

Observable parameters

The following data can be obtained for typical emission nebulae:

(a) The apparent size, form, and structure can be measured in each of the stronger monochromatic radiations.

(b) The surface brightness and isophotic contours can be measured for each of the stronger monochromatic emissions.

(c) The wavelengths, identifications, and intensities of the lines and the energy distribution in the continuous spectra can be measured for typical nebulae.

(d) The distances of diffuse nebulae may be found from the apparent magnitudes, color excesses, and luminosity classes of their illuminating stars. The distances of the planetaries cannot be established so easily, and for the moment we shall have to be content with statistical distances based on the association of these objects with the central bulge of our galaxy and external galaxies.

(e) The relationship between the structure and internal motions can be established from a comparison of isophotes of slitless spectrograms or monochromatic photographs and radial velocity measurements. It is possible to establish whether the motions are orderly expansions or turbulent streaming, and to correlate the motion with the appearance of the object. O. C. Wilson has given a rather complete picture for the planetaries. Similar studies for the diffuse nebulae should prove worthwhile.

Interpretation of the observational data in terms of physical parameters

The densities and temperatures of the radiating gases may be established from the surface brightness and from spectroscopic data. If the nebula is smooth and unobscured and an estimate of the electron temperature is available, a measurement of the surface brightness in Hα or preferably in the Balmer continuum will provide an estimate of the electron density. Both diffuse nebulae and planetaries are frequently highly obscured. If a measurement of the Balmer decrement is available, an estimate of the space absorption can be found readily. Albert Boggess III has shown how one may combine optical measurements of surface brightness in Hα with radio-frequency measurements to get the space absorption and densities for certain diffuse nebulae for which Balmer decrements have not been measured.

The forbidden lines provide estimates of the electron density N_ϵ and give us our best guesses concerning the electron temperatures T_ϵ. If all the radiations originate in the same strata one may obtain N_ϵ and T_ϵ from a comparison of the forbidden line intensities of [O III] and [N II], for example. Often, however, the [N II] and [O III] lines are predominantly produced in different regions of the nebula. Hence, some other method is needed. A number of years ago, Ufford, Van Vleck, and I called attention to the fact that the intensity ratio of the 3726 and 3729 [O II] lines varied from one nebula to another, apparently depending on the density. Seaton calculated improved target areas for the collisional excitation of the [O II] lines so that quantitative estimates of the density could be made from the observed line intensities. Osterbrock has recently derived densities in the filaments of the Network Nebula, in the Orion Nebula, and in other objects from the λ3726/λ3729 data.

Some outstanding problems

At the moment, the physical nature of the excitation of the bright line spectra of the gaseous nebulae appears to be well understood. The continuous spectra of normal, purely gaseous nebulae are less well understood, but seem to be interpretable in terms of recombination of hydrogen and helium ions with electrons and the double-photon emission. Further quantitative measurements of the nebular continua are needed to test various theoretical suggestions.

Further calculations of transition probabilities for forbidden lines, especially those of iron in various stages of ionization, are needed. Continuous absorption coefficients should be calculated for abundant ions, and further target areas for the collisional excitation of metastable levels should be computed. The accuracy of the available theoretical target areas ought to be improved.

Numerous theoretical problems connected with the structure and especially the kinematics of gaseous nebulae remain to be formulated and solved. For example, what holds together the thin filaments in such an object as the Network Nebula? It is generally assumed that magnetic fields are responsible, but the character and particularly the origins of these fields remain obscure. Any real understanding of the forms of diffuse nebulae must await some fundamental progress in the aerodynamics of compressible ionized gases moving at supersonic velocities in the presence of magnetic fields. Classical hydrodynamics and turbulence theories will require much amplification and extension before they can be applied to the diffuse nebulae and planetaries.

The relation between the diffuse gaseous nebulae and the solid particles of the interstellar medium requires further theoretical and observational study.

Perhaps the most exciting problems are those posed by the gaseous nebulae that are strong radio sources. Oort and Walraven recently interpreted the continuous spectrum of the Crab Nebula as "synchrotron" radiation from fast electrons moving in a magnetic field. Possibly such radiation is always or nearly always associated with strong radio-frequency emission, although powerful radio sources do not necessarily emit a strong optical continuum. The origin of the magnetic fields and the source of the energy of the particles is not explained. It is not sufficient to blame it on the supernova process; the detailed mechanism must be worked out.

New equipment and observational techniques have expanded and are continuing to expand our empirical knowledge of emission nebulae. Theoretical interpretations of the forms and kinematics are lagging behind. The problems posed are among the most difficult in theoretical astrophysics, a fact which makes the subject of bright-line nebulae all the more challenging.

Some suggested references

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Double and Multiple Stars

By Otto Struve[1]

The emphasis at the present time is upon problems connected with the origin and evolution of double stars. G. P. Kuiper's discussion in three articles in the Publications of the Astronomical Society of the Pacific[2] in 1935 and 1955 forms a sound basis for future work. He attributes the origin of double stars to the formation of separate condensations in a primordial interstellar cloud which possessed too much angular momentum, or too much mass, for the formation of a single star. In this respect the origin of a multiple system does not differ significantly from that of a star cluster. But the later evolution of a binary differs from the evolution of a loose cluster. A visual double star is a very stable formation and is not likely to change very greatly during many hundreds of millions of years, while a galactic star cluster *may* be dispersed in the Milky Way in an interval of ten or a hundred million years (though at least one cluster, NGC 67, is believed by H. Johnson and A. Sandage to have an age of 5×10^9 years).

Since we have good reasons for believing that some galactic clusters are very young (the associations of Orion and ζ Persei, the double cluster in Perseus, NGC 6231, etc.) while others are much older (Pleiades, Hyades, Praesepe, NGC 725 and NGC 67), it would be of great interest to know whether any binaries in these clusters show differences in their properties that might be related to the differences in their ages. As yet, our information concerning all types of binaries in galactic clusters is too fragmentary for us to draw any conclusions.

Of special interest is the question of the evolution of *close* binary systems. From Kuiper's work on β Lyrae, we know that two types of instability may occur, with matter escaping from one or both components either through the bottleneck near the inner Lagrangian point, L_1, of the critical zero-velocity surface (instability of type A), or through an opening at the first outer Lagrangian point, L_2 (instability of type B). Kuiper thought that the instability of β Lyrae is a combination of types A and B, but more recent work seems to indicate that both components are unstable and lose matter in the form of two streams moving in opposite directions through the bottleneck near L_1. There can be little doubt that this phenomenon produces the secular change in the period of β Lyrae. The loss of matter in β Lyrae, if the streams are ultimately expelled into space, must amount to about 5×10^{22} gr/sec in order to explain the increase of the period. Since the mass of the star is of the order of 10^{35} grams, the life expectancy of β Lyrae should be of the order of 100,000 years.

No other star is known that *closely* resembles β Lyrae (in itself a good indicator of the short duration of its particular stage of evolution). However, many other systems have gaseous rings or streams and many of them, according to F. B. Wood, have changing periods, especially when at least one component is a large subgiant whose volume fills its loop of the critical zero-velocity surface.

One of the most pressing needs in this field is a systematic, prolonged study of the periods of all suitable eclipsing and spectroscopic binaries. The photometric observations would be relatively simple, but should be made with photoelectric means. Results of great value would become available in a few years; but even more important would be a list of accurate periods during the next 10 years which could later be compared with similar lists at intervals of about 25 years. We cannot start too soon with such a program!

The spectroscopic observations could, for many systems, be carried out with telescopes

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[2] Vol. 47, pp. 15, 121, 1935; vol. 67, p. 387, 1955

of moderate size. We need periodic determinations of the velocity curves of all the brighter spectroscopic binaries. Here again results may be expected immediately, not only with regard to the periods but also with regard to changes in the orbital elements. Algol, Spica, δ Orionis, and many more should be reobserved at least once every 10 years.

One of the most puzzling questions in the field of double-lined spectroscopic binaries is the interpretation of the tendency of many systems to show a strengthening of the violet-displaced absorption lines relative to the red-displaced components, irrespective of which of the two stars happens to be approaching. This phenomenon was discovered by Miss Maury at Harvard in the spectra of μ Scorpii and V Puppis. But later observations at McDonald Observatory failed to show this variation. Yet, independently, we found that it was conspicuous in Spica and in several other short-period spectroscopic binaries of early class B or O. A recent study of π Scorpii by S. J. Inglis shows that it is present in the helium lines but that it may be reversed in sign in the hydrogen lines. I had previously assumed that there is more gas in front of the advancing hemispheres of each component than in front of the receding hemispheres. However Inglis' result suggests that it may be caused by a difference in ionization and excitation. As far as I know, there are no photoelectric measurements that would help us in explaining this phenomenon. Since it occurs only in close systems (it is also conspicuous in many W Ursae Majoris systems) I suspect that it is in some way related to the existence of gaseous streams.

S. S. Huang has recently asked whether there might not be accumulations of gaseous material at those two Lagrangian points which correspond to the equilateral triangle solutions of the restricted three-body problem. Unless the mass ratio of the binary is very different from one, these solutions are not stable, but there could still be regions of increased density in the gaseous ring at L_3 and L_4. It is possible that a more careful study of the eclipses of the emission features in the hydrogen lines of RW Tauri, RW Persei, SX Cassiopeiae, U Sagittae, and many more would enable us to locate the regions in which these emission lines are produced. Joy's original interpretation of RW Tauri in terms of a ring around the brighter component of the binary, or my later interpretation in terms of a ring of gas surrounding the entire system, may have to be modified in the light of Huang's idea.

During the interval 1940–1950 several McDonald astronomers made a superficial survey of the velocity curves and spectroscopic features of about 100 eclipsing variables. Most of the systems presented no peculiarities and the results were sufficient for statistical studies, but a considerable number yielded results of exceptional interest. A few of these stars have since been investigated more exhaustively (U Cephei, U Sagittae, SX Cassiopeiae, RX Cassiopeiae, RZ Scuti), but quite a number have not yet been scrutinized. I can mention here only a few of them. WX Cephei (J. Sahade and C. U. Cesco) shows amazing changes in the intensities of the two Ca II absorption components. They are unlike the changes discussed above. DN Orionis has an exceptionally small range of velocity and, therefore, a very small mass function. It is one of the most peculiar binaries in this respect, resembling XZ Sagittarii (J. Sahade). Both must possess subgiant components of very small mass (about 0.1 or 0.2⊙) but of large diameter. These components violate the conventional mass-luminosity relation. AW Pegasi and V 377 Centauri (Sahade) are even more peculiar, and we have been unable to interpret their spectra. Details about these and other systems may be found in the Astrophysical Journal or in the Contributions from the W. J. McDonald Observatory.

The famous visual double star γ Virginis has been suspected by Lick astronomers to vary in light. Since both stars can be observed spectroscopically with high dispersion, a test of each component (or of the integrated light of both) for variability would be of interest. Any visual binary whose orbit is known should be investigated at least in integrated light for variability. The discovery of an RR Lyrae or another pulsating component in a double star, whose masses are known, would be a major triumph. It might even be possible from the colors (or spectra) and magnitudes to pick out promising pairs, but the chances for success can hardly be estimated. I recommend this important search only to those who have other problems that are *certain* to give significant results.

A few eclipsing binaries must be observed as nearly continuously as is possible, both photoelectrically and spectroscopically. Among these I should list ε Aurigae, VV Cephei, β Lyrae, UX Monocerotis (R. Lynds suspects that the small, bright, and hot component of this system is a short-period pulsating variable, while the other component is a large and cool subgiant). No spectrographic equipment is now available for such continuing observations. I therefore endorse Th. Dunham's project for the construction of a new spectrographic telescope.

I hope that someone will have observed the light curve of ε Aurigae over a wide range of wavelengths. It is important to know whether the depth of the eclipse (a totality began Dec. 15, 1955, ending 330 days later) is really the same in all wavelengths.

What is the dispersion of the mass-luminosity relation, expecially at the upper end? If nuclear evolution proceeds without appreciable change in mass, we should expect some scatter among the O- and B-type stars. Most of our present information comes from the velocity curves of double-lined binaries, and this problem is looked after by the astronomers at Victoria. Special attention should, however, be devoted to such stars as J. S. Plaskett's massive binary, in which the more massive component has the weaker absorption lines; the profiles of the lines of this component show irregular changes.

It is not yet clear whether the yellow and red giants in Population I obey the conventional mass-luminosity relation. K. O. Wright's work on Capella seems to indicate that it does, and my own earlier measurements suggested only a relatively small departure. D. M. Popper's work on ζ Aurigae and other similar systems may soon solve this problem. It may help us in constructing the evolutionary tracks of massive stars, but here again we must be prepared to find that the giants lose mass by expansion. A. J. Deutsch's work on the expanding shell of the system of α Herculis supports this hypothesis.

What is the nature of the so-called Trumpler stars? Some of them occur in binary systems but we have as yet no firm knowledge of their masses. As Trumpler has shown, their lines have large red shifts which, if interpreted by the theory of general relativity, would give very large masses (or very small radii). There are some reasons for believing that their masses are not more than about 75⊙. But how do we then explain the red shifts?

Are all post-novae and all SS Cygni stars close binaries? And why are there so many Wolf-Rayet stars which are components of close binary systems? Are all of these objects the products of the evolution of binaries (as Huang suggests in a recent article in the Astronomical Journal[3]) and are the RR Lyrae stars the products of nuclear evolution of single stars (or of wide visual binaries) uncomplicated by the loss of mass resulting from the instability of a close binary? It is not yet clear why loss of mass into space (as distinguished from the formation of streams within a binary, or the exchange of mass between the components of a binary) should be significantly different. We must assume that once a stream of gas is generated in a binary it is somehow expelled from the entire system, and that the absence of such streams in single, slowly rotating stars impedes their loss of mass by "corpuscular radiation."

It would be unreasonable to conclude this report without stressing the importance of continuing routine observations of all classes of double and multiple stars. In preparing his program, an investigator should not be concerned solely with the solution of immediate problems but should devote a part of his time to the accumulation of accurate observations which will bear fruit long after his death. The most important astronomical problems—those of evolution of stars, of perturbations in double star orbits, of slow periodic or irregular variations, and many more—require tens or hundreds of years of persistent effort. It is

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[3] Vol. 61, p. 49, 1956.

especially difficult to sustain an enthusiastic attitude on the part of a scientist if he does not expect to gather the harvest resulting from his labor. Nevertheless, we must all follow the dictum of Ejnar Hertzsprung: every astronomer has profited from the observations of his predecessors; he should therefore be willing to pass on to his successors a store of good observations to make up for what he has inherited from former generations.

Stellar Dynamics

By U. Van Wijk[1]

Although stellar dynamics is largely a theoretical field, anyone working in it has a strong interest in observational results concerning the motions of the stars—their radial velocities and proper motions.

One of the more active areas of stellar dynamics has been the study of the interaction between stars and interstellar clouds insofar as it affects the motions of the stars. In papers by Spitzer and Schwarzschild (1953) and by Osterbrock (1952), the effect of randomly distributed interstellar clouds has been considered. One may hope that the 21-centimeter band observations will ultimately lead to a more specific idea about the distribution of interstellar clouds and that the effect of nonrandom distributions, such as a spiral arm, may then be considered.

A field which is basically quite fruitful but which has been lying fallow recently is that of spherical clusters and, particularly, the escape of cluster stars. The papers of Spitzer (1940) and Chandrasekhar (1943) are still the basic references, and it may well be that further progress will strongly depend on the ready availability of electronic calculators.

An interesting recent development is the attempt to interpret the present kinetic properties of the stars in terms of the conditions under which they were formed. Examples of this approach are the papers by Belzer, Gamow, and Keller (1951) and van Wijk (1956). Here we approach the border line between stellar dynamics and the study of galactic structure. But two subjects which are just beyond this border line may still be mentioned here because of their intimate connection with our present subject: the work on pseudointegrals of motion by Lindblad and the study by Blaauw (1952) of the dissolution of very loose galactic clusters.

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Variable Stars

By C. Payne-Gaposchkin [1]

Variable stars play a dual role in astronomy. First, they furnish standards of luminosity and distance. Second, their own physical properties throw light on energy sources, the processes of pulsation and explosion, and the circumstances of stellar formation.

Standards of luminosity

The RR Lyrae stars, Cepheids, novae, and supernovae have been the most important indicators of distance. Their average luminosities (mean for the pulsating stars, maximum for the explosive ones) are known with an uncertainty of a few 10ths of a magnitude. We are now concerned with determining the dispersion of luminosity for stars of these groups.

The absolute magnitudes of RR Lyrae stars will emerge from critical comparisons of the color-magnitude arrays of globular clusters. Probably they will be found to be related to the metal richness of the cluster stars. The striking differences between the noncluster RR Lyrae stars of our neighborhood and those near the galactic center, when interpreted in the light of the data from globular clusters, will furnish a new approach to the dimensions of our galaxy. These studies, which require spectroscopic analysis and photoelectric accuracy, can be made only with the largest telescopes. The extension of this work to the nearby, bright globular clusters of the Southern Hemisphere would be most important.

The dispersion in the absolute magnitudes of Cepheid variables and its relation to color and spectrum is likewise an investigation to be carried out in the Southern Hemisphere. The Cepheids in the Magellanic Clouds furnish perhaps the most urgent and profitable problem in applied variable star astronomy; the study should be made concurrently with photoelectric and spectroscopic equipment. It should be borne in mind, however, that the Magellanic Cepheids may differ in detail from galactic Cepheids of like period. The study of color and spectral variation of galactic Cepheids should therefore be pressed, with especial attention to the effects of selective absorption. Here, again, material from the Southern Hemisphere is of particular urgency; the rich Carina region seems comparatively free of absorption, and radial velocities of Cepheids in this area will fill out our information on the relation of the Cepheids to galactic rotation, and thus on the dimensions of the galactic system.

The absolute magnitudes of novae have recently been placed on a firm basis by the light curves of the novae in Messier 31. Probably the novae in other nearby galaxies will be the most valuable means of extending this information.

The absolute magnitudes of supernovae, the distinction between the two types, and their relationship to ordinary novae must again rest on studies made with the largest telescopes.

Physical problems

Detailed study of the brighter variable stars is continually revealing new types of variation. Future progress in variable star astronomy calls for understanding the relationships of these types to one another and of the physical processes involved in them. While the discovery of variable stars should certainly continue, it seems probable that systematic study of chosen typical specimens is more important than indiscriminate search for faint variables. However, it should not be assumed that all undiscovered variable stars are faint; even among the naked-eye stars there may still be a number of important examples hitherto undetected. Means for tracing the variations of brightness of stars that are spectroscopically

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interesting, such as shell stars and Of stars, should not fall into abeyance; in this regard the maintenance of adequate sky patrols (not necessarily with powerful instruments, as the profitable stars are likely to be brighter than the tenth magnitude) is a project worthy of continued support in both hemispheres.

It is important that the variable stars chosen for systematic investigation be studied with the greatest available precision. Brightness and color should be measured photoelectrically. Spectra should be photometrically analyzed, and all spectra should be suitably standardized for this purpose. *Estimates* of the intensities of absorption and emission lines are not good enough for modern purposes. It should be emphasized that the red and near infrared are now as accessible as the photographic region, and often provide data that are equally or more significant.

Lastly, a star that is varying should be studied *concurrently* by photometric and spectroscopic methods; this is of especial importance when the variation is not strictly periodic.

Eclipsing stars.—Of unique importance because of their contribution to our knowledge of stellar masses and dimensions, eclipsing stars have entered a new era with the coming of photoelectric photometry. *Any* eclipsing star that gives a two-spectrum velocity curve and a good light curve adds to our fundamental knowledge of stars.

Several groups of eclipsing stars give unusual promise. The combinations of a blue star and a red giant with an extensive atmosphere are important in the study of stellar envelopes; in addition to the well-known specimens now being actively studied, others are undoubtedly to be be found in lists of "composite spectra."

The remarkable analogies between the short-period UX Ursae Majoris, the system of Nova Herculis, and the pair that constitutes AE Aquarii invite a search for such stars, which will throw light on the processes of stellar explosions.

Periodic variables.—The classical Cepheids and the parallel sequence of Population II variables are rich in possibilities. Concurrent studies of brightness, color, spectrum, and radial velocity will be needed before the interrelationships of these groups are clarified. Careful spectrophotometry will probably reveal differences of composition. Equally important is the development of the physical theory that bears on the propagation of waves through the envelopes of these groups of stars.

The long-period and other red variables involve similar theoretical problems. Their spectra also invite quantitative observational work: the identification and intensities of bright lines are of obvious importance, and quantitative study of the absorption spectra (admittedly beset with grave observational difficulties) is also a problem of the first importance.

Explosive variables.—The most difficult problem, which can be attacked only with the largest telescopes, involves the physical processes of the supernovae, and especially the unsolved problem of their spectroscopic changes.

The study of the novae proper has always been hampered by the unexpectedness of the outbursts. Too often, alas, a nova has been studied from a sense of duty, and each contribution thus tends to be isolated from related studies. Every suitably equipped observatory should have a nova program prepared in advance, and the supplies necessary to put it into action. The program should from the first include the red and near infrared, and especial attention should be paid to photometric standardization.

The U Geminorum stars are so faint that the necessary spectroscopic studies require powerful equipment. The likelihood that all are double stars and the possibility that many are spectroscopic binaries of short period make them of exceptional interest. Photometric studies might reveal that some of them are eclipsing stars; in addition, it would be important to learn whether the recently observed rapid changes of SS Cygni are a common feature in the rest of the class.

Irregular variables.—The faint irregular variable stars in nebulosity are destined to play an important role in ideas of the origin and development of stars. The discovery of these "T associations" and the concurrent spectroscopic and photometric study of their behavior are extremely important provinces of variable star astronomy.

Interstellar Matter

By Lyman Spitzer, Jr.[1]

The study of interstellar matter may be divided into two main parts. Firstly, there is the measurement of the interaction between interstellar material and electromagnetic radiation. The objective of this research is to determine, from the observed radiation reaching the earth, the properties of the material between the stars. While this study is primarily observational, the interpretation of the observations in terms of the number of absorbing atoms or of the properties of the absorbing solid particles may involve much theoretical analysis.

Secondly, there is the physical analysis of those processes that occur in interstellar space. In this study the density, composition, and spatial distribution of interstellar material are obtained from the observational research described above, and the various physical processes that occur are deduced from the laws of nature, as determined in terrestrial laboratories. Thus, for example, the internal temperature of the small solid particles or grains is computed theoretically, the interactions between atoms and grains are analyzed, and the methods by which interstellar material can condense into a new star are deduced.

At present our information on material in space is seriously limited both by observational inaccuracies and by a lack of information on the relevant laws of nature. During the next few decades significant advances in both these respects may be anticipated.

New experimental techniques promise a great increase in observational accuracy. Of particular importance is the imminent development of photoelectric spectrophotometry. The combination of a photoelectric cell and a spectrograph will have many important advantages in interstellar research. One possibility, which is already being explored by Strömgren at the Yerkes Observatory, is the accurate color measurement for stars of all spectral types. Accurate measures of absorption lines yield very precise determinations of spectral type, and hence of the intrinsic stellar color. The color excess, or deviation between the actual color and the intrinsic color, may then be found for any star. With this development we should be able to determine the density of small solid particles at points in the sky very close together, and thus obtain a more detailed picture than is now possible of the distribution of interstellar material.

Another suitable program for photoelectric spectrophotometry is the precise measure of interstellar line profiles. With this technique it is possible to determine both the number of absorbing sodium and calcium atoms in the line of sight to each star and the precise velocity distribution of the atoms. Still another possibility is the measurement of much fainter interstellar lines than are customarily observed. Thus, detailed information can be obtained on the spatial distribution of such interstellar atoms as neutral Ca and ionized Fe and Ti. At present the interstellar lines produced by these atoms can only barely be detected in a very few stars.

Radio astronomy is another very important observational development in this field. As the size of radio telescopes increases more and more, the information about the distribution of neutral hydrogen will become more and more detailed. Information about other types of atoms may also be obtained, perhaps, with radio techniques. Evidently our exploration of interstellar clouds will become much more precise and much more extensive in the years to come.

This increasing detail of information, and this very great increase in the accuracy of interstellar maps that can be drawn, will naturally lead to an expanded effort on the analytical and

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theoretical front. For example, data are gradually accumulating on what might be called interstellar meteorology—the great problem of the motions and transformations of the interstellar clouds. As in terrestrial meteorology, this subject must include not only ordinary dynamics but also the effects of radiation, both emitted and absorbed. Changes of state, involving the combination and dissociation of molecules and atoms, must also be considered. These phenomena are probably influenced profoundly by the presence of both large-scale magnetic fields and cosmic rays, which have no counterpart in terrestrial meteorology. Evidently the comprehensive analysis of the many simultaneous processes will be a vast and challenging adventure.

Another theoretical problem concerns the physical chemistry of grains. The boundary conditions in this problem are simple. We know approximately the conditions under which atoms in interstellar space gather together to form solid particles. However, the nature of these particles is completely unknown. In particular, the detailed structure of the grains, the forces holding them together, and, in fact, all except the grossest properties of these small solid particles are completely uncertain. A precise, elaborate, and ingenious laboratory approach, together with a considerable amount of theory, is probably required to shed light on the situation. The interactions of grains with atoms, including the rate at which the grains grow and are destroyed and the various selective ways in which they interact with different types of elements, are of particular interest astronomically. Another important problem concerns the magnetic properties of such grains, the solution of which also probably demands a combination of observation and theory.

A central theoretical problem is, of course, the one of evolution. How do clouds evolve over a period of a billion years or more, and, in particular, how are new stars formed from the interstellar medium? The detailed answer to these questions is perhaps the most difficult part of the entire field, and from a logical standpoint should perhaps be postponed until the rest of the subject is fully developed. In view of the very great interest in this particular problem, however, it appears certain that during the next few decades much new work will be done. While no final results may be expected in this area for some time, it seems very likely that ingenuity and hard work will produce many glittering and intriguing hypotheses.

21-Centimeter Research

By Bart J. Bok [1]

The discovery of the 21-centimeter line of neutral hydrogen by Ewen and Purcell (1951) and the subsequent confirmation of this discovery by Dutch and Australian groups (Muller and Oort, 1951; Pawsey, 1951) marked the birth of a new era in the study of our Milky Way system and of the universe of galaxies. That radio radiation with a wavelength of 21 cm emanating from neutral atomic interstellar hydrogen might be sufficiently strong to be recorded was first suggested by van de Hulst (1945) and was predicted independently by Shklovsky (1949). But not until the actual discovery of the line did astronomers begin to realize how powerful a tool for future research had become available.

Research in the 21-cm field may at present be divided roughly into three broad areas. The first concerns the spiral structure of our galaxy, and has yielded spectacular first results. Really detailed analysis, however, has only begun, and will undoubtedly be fruitful in future studies of spiral structure. The second category is that of related optical and radio studies of the fine structure of the interstellar gaseous medium in our galaxy. We shall list below some of the topics of research most important here, but it is already clear that the "21-cm astrophysicist" has waiting for him a multitude of specific research problems. The third category is that of extragalactic 21-cm research, one in which the work has barely started but which obviously will attain increasing importance as the reach of our equipment increases.

One should bear in mind that up to the present all but one of the five principal radio telescopes that are active in the 21-cm field are paraboloids with apertures of the order of 25 to 30 feet, the one exception being the 50-foot paraboloid at the Naval Research Laboratory in Washington. Also, most of the work until now has been done with electronic equipment with bandwidths of 40 and 15 kc/sec (equivalent to resolutions in radial velocity of 8 and 3 km/sec) and very few observations have been made with bandwidths between 5 and 10 kc/sec (equivalent to radial velocity resolutions of 1 to 2 km/sec). Within a year or so there should be in operation at least a half dozen radio telescopes with apertures of 60 to 100 feet, all of them steerable and with surface tolerances sufficiently strict to permit full use at the 21-cm wavelength. Research at 21 centimeters has just been started with two large radio telescopes—the 83-foot instrument at Dwingelo in Holland and the 60-foot George R. Agassiz radio telescope of Harvard Observatory (see the recent article by Heeschen, in press). Several of these instruments apparently will have electronic equipment capable of recording 21-cm profiles with a bandwidth of 5 kc/sec (equivalent to a resolution in radial velocity of 1 km/sec). The group at the California Institute of Technology is planning to use two 90-foot antennas as an interferometer with variable separation of the two component antennas. Moreover, three very much larger paraboloids intended in part for use in 21-cm research are now either under construction or on the drawing board: the 250-foot paraboloid for Jodrell Bank, the 140-foot paraboloid for the Inter-University Radio Observatory now under consideration by the National Science Foundation, and the large instrument planned for Australia.

Spiral structure of our galaxy

The Leiden group has contributed most effectively to the study of the spiral structure of our galaxy. The early work by the Leiden group culminated in the famous joint paper by van de Hulst, Muller, and Oort (1954) which

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contains the picture of the spiral structure of our galaxy in its broad features as observable from a Northern Hemisphere radio observatory. For the Southern Hemisphere a preliminary survey has been completed by Christiansen and Hindman (1952), and the most recent results were presented by Carpenter (1955) at the Troy meeting of the American Astronomical Society. Since the original Dutch survey was completed, there has been considerable activity in the study of the spiral structure for the part of our galaxy between galactic longitudes 40° and 200°; that is, from Cygnus to well beyond Sirius. The most extensive research has been done by Westerhout (in press), who has derived and analyzed 21-cm profiles for the entire section between galactic latitudes −10° and +10°. To supplement the work of Westerhout, we have the published and unpublished results of Matthews (1955) and of Davis at Harvard and of Helfer and Tatel (1955) at the Carnegie Institution. All these researches indicate that the simplified descriptions of three primary spiral arms in this section, the Orion Arm, the Perseus Arm, and the Distant Arm, are only very rough first approximations. The available evidence suggests major branching of the principal spiral features; it is evident, furthermore, that all of the spiral features are definitely not precisely in the same plane. Comparable detailed studies for the Southern Hemisphere are still lacking, but the first results by the Australian groups suggest that here, also, complexity rather than simplicity are to be found.

The study of the spiral structure in the part of our galaxy interior to our sun offers a variety of complex problems. The principal source of difficulty is that, even on the simple assumption of purely circular galactic rotation, a feature with a given radial velocity may be produced by hydrogen clouds at either one or another distance; or, more generally, that a particular feature may well be the blurred combined impression produced by features at two different distances from the sun. The early results obtained by the Leiden group have been summarized in a paper by Kwee, Muller, and Westerhout (1954); and, more recently, Schmidt (in press) has obtained useful new evidence. At Harvard, Heeschen and Howard (1956) have begun a study rather similar in scope to that of Schmidt. It seems established that one Inner Arm is present which presumably is identical with the optically discovered Sagittarius Arm, but further evidence exists for the presence of some structure in the internal neutral-hydrogen conglomerate, close to the center of our galaxy.

Two major problems arise in any analysis of spiral features from 21-cm profiles. First, a large group of problems relates to the probable shape of the curve that gives circular velocity of rotation as a function of distance from the galactic center. In 21-cm research we have no direct way of obtaining distances, and we can only assign to a given observed feature a distance based on its observed radial velocity of approach or recession. If our assumed form for the curve relating distance from the galactic center to circular velocity of rotation is in error, then all of our derived distances obviously will be in error also. A second and related cause for difficulties lies in the fact that, on the basis of 21-cm observations alone, we have no way of disentangling effects of peculiar motions from those caused by purely circular galactic rotation.

We should be able to outline on a fairly homogeneous basis the general features of the spiral structure of our galaxy once the southern Milky Way observations are completed and analyzed as have been the profiles for the northern Milky Way by the Leiden observers. Great interest attaches to the future clarification of the details of spiral structure, but here progress will be slow at best, and, initially at least, somewhat uncertain. We have already indicated that the dynamical study of the law of circular galactic rotation is imperative if we wish to derive meaningful distances for the features found through our 21-cm observations. To deal conclusively with problems of the branching of spiral arms and with fine structure phenomena, our only hopeful approach appears to be through coordinated optical and radio studies of sections of the Milky Way, one by one. For proper analysis of 21-cm features, we shall need extensive and precise optical data—for example, for OB stars and associations in the area of the sky covered by a particular 21-cm study. For proper interpretation of the 21-cm features, we should at all times attempt to obtain radio profiles for a fairly wide range of galactic latitudes and for points in the area of investigation spaced as close together as appears to be reasonable for a particular radio telescope. Preliminary work in this field by Matthews (1955) has already demonstrated that the results of closely spaced surveys will be well worth the effort, and that correlated radio and optical studies will provide insight into the fine details of spiral structure. Furthermore, a great deal of new information should be obtainable regarding the fine structure of the interstellar medium and the association between interstellar hydrogen and certain classes of stars. A related problem of great interest is the relative distribution of neutral hydrogen and cosmic dust inside a spiral arm, or branch of an arm.

Astrophysical studies

The 21-cm astrophysicist is essentially a spectroscopist who has for study only one single spectrum line. Fortunately, the microwave spectrographs presently in use are really high-dispersion instruments and thus much can be learned from a single 21-cm profile. The 21-cm astrophysicist realizes that he is the fortunate fellow who has first achieved access to the all-pervading medium of neutral hydrogen of our galactic system, which means probably as much as 95 percent of all the interstellar hydrogen. In this section, we shall describe first some astrophysical problems that have proved practicable for paraboloid antennas with apertures of 20 to 30 feet, then turn to problems whose solution is aided by antennas with apertures of 50 to 80 feet, and conclude with some astrophysical problems that we may attempt to study with antennas of 100-foot and larger apertures.

The work of Lilley (1955) and of Heeschen (1955) at Agassiz Station illustrates the first group—astrophysical problems that may be studied with antennas of relatively small aperture. For the Taurus Complex of dark nebulosity, Lilley found generally far stronger signals for fields well inside the dark complex than for relatively unobscured fields bordering upon the complex. It thus became evident that the large dust complexes have excess neutral hydrogen gas associated with them. Lilley found the ratio between the average densities of gas and of dust to be close to 100:1 inside the Taurus Complex. Lawrence, Menon, and I (Bok et al., 1955) used the 24-foot paraboloid to study some very densely obscured spots inside the Ophiuchus and Taurus Complexes. We found no marked differences in 21-cm signal strength when we compared intensities for the highly obscured fields with those found for neighboring fields still inside the complexes but definitely less obscured. We deduced from our observations that the large dust complexes are regions of markedly high concentration of interstellar atomic neutral hydrogen, but that the distribution of the atomic hydrogen inside the complex does not mirror precisely that of the cosmic dust. Existing 21-cm observations suggest that the neutral hydrogen is more evenly distributed than the cosmic dust, but no really significant conclusions can be drawn until the really large paraboloids become available for studies of this nature. A careful search for neutral hydrogen concentrations by 21-cm interferometer techniques should prove of great interest in connection with this problem; a negative result would be fully as important as a positive one. When the necessary observations have been made, their interpretation will still present a good many difficulties. Our lack of information regarding the presence of molecular hydrogen complicates analysis considerably, and as yet the possible effects of variations in temperature inside the large dust complexes are by no means understood. The assumption that the interstellar medium of neutral atomic hydrogen possesses one single characteristic temperature is at best a very crude one, and in future research temperature variations undoubtedly will have to be considered along with density variations.

A second area in which 21-cm studies have already made important contributions is that of the study—by combined optical and radio techniques—of regions of special interest, such as the Orion region. The recent work by Menon (in press) illustrates how much we can learn through detailed 21-cm studies. Optically, the Orion region is known by its separate features: the Great Nebula in Orion, with a total estimated mass not in excess of

1,000 solar masses; the Trapezium Cluster and various OB associations and aggregates; Barnard's Luminous Arc of very great dimensions; and, finally, the large dust complex that is evidently obscuring much of the region. The 21-cm observations by Menon show that all of these features are imbedded in a large "bowl of neutral hydrogen jelly," with a total mass probably of the order of 60 to 100 thousand solar masses. Menon's observations suggest that this entire mass is in slow rotation and that it is, very likely, expanding at the rate of 8 to 10 km/sec. Here the 21-cm approach has already added a dimension to our earlier unrelated optical studies. The astrophysical and cosmogonical importance of the new approach is obvious.

The third group of problems that are proving amenable to study by 21-cm techniques deals with the fine structure of the interstellar hydrogen medium. The studies by Lawrence (in press) and by Heeschen and Drake (1956) serve to illustrate two different approaches. Lawrence, working in close collaboration with Munch, has studied at the Agassiz Station 21-cm profiles for fields centered upon stars for which Munch, at Mount Wilson and Palomar, had found multiple optical interstellar lines. Two established coincidences between radial velocities of 21-cm features and strong interstellar absorption lines indicate that the same interstellar gas clouds may be responsible. Further study of these phenomena should prove exceedingly rewarding, but we can hope to arrive at a clear understanding through 21-cm studies only with radio telescopes of large apertures with associated electronic equipment of very narrow bandwidth. The research of Heeschen and Drake refers to the general direction of the Pleiades Cluster. They find a double-peaked 21-cm profile—the radial velocity of one peak coinciding almost precisely with that of the Pleiades stars, and that of the other peak being very nearly equal to the mean radial velocity for the strongest components of the interstellar lines. In all these investigations of the fine structure of the interstellar medium, one must insist on high angular resolution accompanied by narrow bandwidth; without narrow bandwidth, the whole study of the distribution of individual gas-cloud velocities becomes impracticable. Once we have perfected our equipment, success in breaking down the interstellar medium into its basic components should be within our grasp.

The greatest contribution so far to 21-cm research by the 50-foot paraboloid of the Naval Research Laboratory has been in the study of absorption features observed in distant discrete radio sources. Hagen, Haddock, McClain and Lilley (Hagen, et al., 1955; Lilley, 1955) have studied 21-cm profiles and related phenomena in the continuum at wavelengths of 21 cm and less for a number of discrete sources, some of thermal origin, others not. The first relevant 21-cm profiles have exhibited certain amazing absorption features which tend to confirm the cloud or turbulent nature of the interstellar gaseous medium. For the future study of these profiles it will prove profitable to insist on the highest attainable angular resolution accompanied by very narrow bandwidth of the recording equipment. Almost every one of these sources studied has presented us with a different type of problem. The neatest absorption features are probably shown by the Cassiopeia source, and it seems difficult to escape the conclusion from the 21-cm observations by the Naval Research group and by Davies (in press) and his associates at Jodrell Bank that the source is in the Perseus Arm rather than within 1,000 parsecs of the sun. The study of the source at or near the galactic center—or at least in the direction between our sun and the galactic center—offers a host of possibilities for future research and here very much greater angular resolution than is attainable to date is urgently required. We shall return in the next section to the Cygnus source, which exhibits absorption features that originate far beyond the bounds of our own galaxy. But the brief references that we have given above indicate that 21-cm techniques offer great opportunities for future research. The contemplated interferometer for 21-cm research, with 2-component 90-foot steerable paraboloids, should make possible an entirely new approach to the study of discrete sources and their absorption features. Large paraboloid antennas with apertures in excess of 100 feet also promise very significant contributions. In cases where the 24-foot antenna is useless, the

50-foot antenna begins to suggest; but the 100-foot antenna should be able to show the way and the larger antennas should really be able to solve some of the critical galactic astrophysical problems of 21-cm research that are ahead of us.

Extragalactic research

To the Australian group at Sydney (Kerr, Hindman, and Robinson, 1954) and their associates (Kerr and de Vaucouleurs, 1956) goes the credit for having detected and studied the first 21-cm radiation from beyond our own Milky Way system. Their studies of the Magellanic Clouds, which have been blended skillfully with the optical researches carried on at Canberra (Buscombe, Gascoigne, and de Vaucouleurs, 1954), have demonstrated conclusively that the 21-cm technique offers entirely new possibilities for the study of galaxies beyond our own Milky Way system. These studies have already made important contributions both to the dynamics of the Magellanic Clouds and to our knowledge of population distributions. Until it was found that the 21-cm signals from the Small and from the Large Magellanic Clouds are comparable in strength, many had doubted that the Small Cloud had anywhere nearly as much neutral hydrogen as the Large Cloud. Through the 21-cm study we are learning a great deal about the dynamics of the two Clouds. Their rotation seems well established, and the masses derived from rotational velocities are in good agreement with those estimated in other ways. Studies of the distribution of random velocities promise to add materially to our knowledge of the dynamics of the gaseous interstellar medium in these two galaxies.

The second big contribution to date to the study of radiation from outside our galaxy was made by Lilley and McClain (1955) in their work on the principal absorption feature in the discrete source in Cygnus. They have established that an absorption feature in the spectrum of the Cygnus source is present at precisely the frequency predicted from the optically known velocity of recession, produced by the red-shift. The absorption feature obviously originates in the galaxy inside which the Cygnus source itself is imbedded. Not only is the work of Lilley and McClain important in establishing the presence of a 21-cm neutral hydrogen medium surrounding the Cygnus discrete source, but the agreement between the optically predicted red-shift velocity and the radial velocity determined by radio techniques has important consequences for cosmogonical theory.

The 21-cm radiation from the Andromeda Nebula and other nearby galaxies remains as yet undiscovered. Special equipment to aid in its detection and measurement is now under construction in Holland and elsewhere. The importance of 21-cm studies for individual galaxies of the Local Group can hardly be overrated. If we can attain angular resolution sufficient to separate areas inside spiral arms from those between the arms, very significant contributions can be made to the solution of the whole group of problems related to the dynamics of galactic rotation and of spiral structure. We shall then have also wholly new evidence on the distribution of neutral atomic hydrogen in spiral and other galaxies and new light will be thrown on the problems of stellar birth and evolution. For the future, 21-cm research of nearby galaxies, notably those with spiral structure, has a high priority.

Quite recently Heeschen (in press) has succeeded in detecting 21-cm radiation associated with a cluster of galaxies. At a frequency near 1387 mc/sec, corresponding to a recessional radial velocity of close to 7000 km/sec, he found evidence for a weak but consistently present signal ($\Delta T = 2°K \pm 0.°2$) from the direction of the Coma cluster of galaxies. The specifically determined radial velocity of recession for the same cluster is 6680 km/sec, which appears to indicate satisfactory agreement. The dispersion in radial velocity derived from the 21-cm observations appears to be of the order of 500 km/sec, somewhat smaller than the optical value of about 800 km/sec. The total estimated mass of neutral atomic hydrogen is a little less than 10^{14} solar masses. Heeschen's result was obtained with the 24-foot radio telescope at Agassiz Station. Information regarding the distribution of neutral hydrogen inside the cluster can be obtained only with instruments of greater aperture, which afford higher angular resolution.

A potentially very profitable approach to the problems of intergalactic hydrogen is through the study of absorption features. Field and Heeschen have recently attempted to observe in the spectrum of the Cygnus source absorption features produced by the general medium of intergalactic hydrogen between the Cygnus source and our sun. The results with present equipment are inconclusive, but the analysis of the available data shows that very rarefied absorption features might be detectable, even for the low densities that presumably prevail in the intergalactic medium.

We should at this point refer again to the interferometer array now under construction by Bolton and his associates at the California Institute of Technology. A variable-spacing interferometer, with two basic components of 90-foot aperture each, should make accessible for study a number of discrete sources running literally into the hundreds. From the absorption features, much information should be obtainable—information relating not only to the clouds between our sun and these discrete sources but also concerning the distances of individual discrete sources.

Concluding remarks

It is now just about 5 years since Purcell and Ewen first succeeded in detecting the 21-cm line of neutral hydrogen. In the intervening years much progress has been made, and I doubt if many would have dared to predict in 1951 that by 1956 equipment equaling in excellence present-day radio telescopes and electronic recording equipment would have become available at several institutions. But although we may look with some satisfaction upon our accomplishments to date, in reality 21-cm research has only just begun.

I have purposely confined my remarks to 21-cm research in a most limited sense. I have studiously avoided referring to the importance of studies in the continuum at wavelengths of 50 cm and less, which must become an integral part of all 21-cm studies. I have also omitted all reference to other spectrum lines in the microwave range, notably to the line of deuterium, the discovery of which would open up an entirely new field for research of the interstellar medium by radio techniques. It would be very helpful if, instead of having to confine ourselves to the single 21-cm line, we could have available additional lines, preferably those that might give clues to the presence of atoms other than hydrogen, and components of bands that would permit the study of molecules, such as OH and H2. The field of galactic and extragalactic microwave spectroscopy is indeed a fruitful one for future exploration.

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Some Observational Problems in Galactic Structure

By Harold Weaver[1]

The past decade has brought many new insights into the problems of galactic structure. New observational techniques—optical and radio—have produced results that were thought far beyond reach only a few years ago. We now realize the importance of the various structural units of the galaxy (clusters, associations, arms, etc.) as groups of evolving stars of different ages. Data on the structure and the kinematic properties of the galaxy provide basic information for studies of stellar evolution; clusters and associations provide tests of stellar-model evolutionary calculations. It is clear that we must relate our galactic studies to those of other nearby resolved galaxies. Knowledge will advance most rapidly if we understand how the structural details of our galaxy relate to those of the sequence of galaxies.

New approaches

Several recent observations, to a considerable degree, have reoriented the whole trend of thinking about galactic structure and have forcefully indicated the need for new approaches to the problems. Among these observations are the following:

1. Baade's (1944) decisive demonstration that the space and physical-specification variables in the space-density function $D(M, S; R, \theta, z)$ are strongly correlated.

The stellar space-density function $D(M, S; R, \theta, z)dMdSdV$ will play an important part in the discussion that follows; it indicates symbolically the space density of stars in absolute magnitude range M to $M+dM$, spectral-type interval S to $S+dS$, and volume element dV, centered at galactocentric position R, θ, z. Other or additional variables can be used for physical specification; color is frequently substituted for spectral type. If we fix the space variables and represent the distribution graphically we obtain the Hess (1924) diagram.

The space distribution of nonstellar material may be represented by $D_i(R, \theta, z)$, which refers to particles of kind i.

For R small or z large in $D(M, S; R, \theta, z)$ one finds pure or essentially pure Population II. If to M, S are assigned ranges encompassing intrinsically bright O and early B stars, Baade found that in extragalactic systems the locus of maximum of $D(M, S; R, \theta, z)$ traces out spiral arms where Population I stars and much interstellar dust is to be found. Population I, occurring in regions where z is small and R not small, appears as an addition to, and intermingled with, the general substratum of Population II stars forming the disc of the system.

2. Morgan, Sharpless, and Osterbrock's (1952a, 1952b) use of Baade's spiral tracer technique to produce the first picture of spiral structure in the galaxy.

3. Oort, van de Hulst, and Muller's (1952) observation that the 21-cm radiation of hydrogen indicates hydrogen concentration in spiral arms whose form and position confirm and extend the work of Morgan and his associates.

4. Ambarzumian's (see Kourganoff, 1951) recognition of stellar associations and of their importance in galactic and stellar evolution problems.

In the following discussion we shall concentrate attention on the problems that fall principally under 1 and 2; those that fall principally under 3 and 4 will form the subject matter of other papers. Effort will be made to avoid duplicating material included in

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Blaauw's (1955) excellent summary of the International Astronomical Union symposium, "Coordination in Galactic Research," which should be read by all investigators in this field.

In this discussion we shall critically examine the results of some recent researches in galactic structure; and, rather than stress the agreements, we shall stress the discrepancies between observation and theory and between the observations themselves. While this approach will accomplish our purpose—to expose areas where problems need to be worked on—it will show the field of galactic research in an untrue light. The reader must guard against gaining the false impression that little has been accomplished in the field. The fact is, rather, that much remains to be done.

Form of the arms

The form of the spiral arms first indicated by Morgan and his associates, using emission nebulosities, and by Oort, using hydrogen concentrations, becomes increasingly complex and less easily understood as additional observational data accumulate. Further work, both observational and theoretical, in detailed delineation of the spiral arms by stars and by gas is required. The Morgan-Meinel-Johnson (1954) technique of very short spectra provides a powerful method of discovering distant spiral tracers. Southern Hemisphere observations of the 21-cm radiation are especially needed; 21-cm observations of high resolving power in angle and in frequency are needed in both hemispheres. Such observations will, among other things, provide data for determining the forms of the gas condensations, and the degree of association between OB stars and gas.

The distance scale within the galaxy

The distance scale presently employed in tracing spiral structure by means of OB stars is correct only to the extent that (1) absolute magnitudes and colors of the MK classification system are correct, and (2) the ratio of total interstellar extinction to color excess is known.

The distances of the hydrogen condensations are correct only to the extent that (1) an accurate differential-rotation function $\Delta\omega(R)$ is available, and (2) the interstellar gas is free from large-scale peculiar motions.

Stellar distance scale.—The present scale of absolute magnitudes (Keenan and Morgan, 1951) is not entirely independent of galactic rotation constants (first order theory only). These, in turn, are dependent upon an older absolute magnitude scale and on corrections for average interstellar extinction. Work of a fundamental nature is here necessary to eliminate the possibility of a closed circuit of systematic errors that do not easily reveal themselves. Fundamental absolute-magnitude scales are required—scales derived from stellar associations, clusters, moving clusters, and stars of large parallax (with the latter two types of objects serving for establishment of zero point). The degree of agreement between main sequence magnitudes (and also luminosity class IV, III, . . ., magnitudes) derived from different associations, clusters, and so forth, will be of extreme interest; comparisons with field stars in the solar neighborhood will likewise be of importance. Several investigators are engaged in observations of this type and are producing very interesting results.

Observations of the ratio of total interstellar extinction to color excess are contradictory. On the basis of both photographic and photoelectric studies (Baade and Minkowski, 1937; Stebbins and Whitford, 1945; Sharpless, 1952), the Orion Nebula has been pointed out as possessing an extinction law appreciably different from that of other interstellar material. A photographic spectrophotometric study of O and B stars by Divan (1954) indicates precisely the same extinction law in the Orion region as in all other regions investigated. On the other hand, very accurate photoelectric observations by Johnson and Morgan (1955) indicate an "abnormal" ratio of extinction to color excess for the Cygnus region in the sense that relatively more ultraviolet extinction is present in that region than in the Cepheus-Monoceros region. Space variations of the extinction law complicate photometric distance calculations and pose difficult problems for the theoretician attempting to explain the distribution of particle size in the interstellar material. The observational determination and subsequent theoretical discussion of the wavelength dependence of interstellar extinction requires further attention.

Hydrogen distance scale.—The differential rotation function $\Delta\omega(R)$ for $R>R_0$ must be derived from stellar motions or from the mass distribution in a model galaxy; circular motion is assumed in either case. If derived from stars, $\Delta\omega(R)$ is dependent upon the accuracy of the stellar distance scale. For $R<R_0$ the hydrogen observations themselves permit, in principle, the establishment of $\Delta\omega(R)$.

A 21-cm observation in the direction of the inner part of the galaxy yields a $v_{\max}$ which, in a galaxy in pure rotation and with a monotonic $\omega(R)$ function, arises from the point that, on the given line of sight, is nearest the galactic center. Precisely,

$$\omega(R)-\omega_0\equiv\Delta\omega(R)=\frac{v_{\max}}{R_0 \sin\lambda} \qquad (1)$$

In practice, there may be observational difficulties in the measurement of the $v_{\max}$ described in equation (1) because of local peculiar motions of the gas, random motions or cosmic dispersion within the gas, and variations of gas density along the line of sight.

For $R-R_0$ small, and with the definition $A=-\frac{1}{2}R_0\omega'_0$, equation (1) may be approximated by the expression,

$$R_0=-\frac{v_{\max}}{2A(1-\sin\lambda)\sin\lambda}. \qquad (2)$$

On the basis of linear theory one can find R_0, provided $v_{\max}$ has been measured and the Oort A parameter is known.

Van de Hulst, Muller, and Oort (1954) used equation (2) to compute R_0 with an adopted value of $A=19.3$ km/sec per kiloparsec, which is a mean of various A values derived on linear theory. It is likely that A is overestimated. (Weaver, 1955a, 1955b, 1955c.) From four $v_{\max}$ values they found $R_0=8.26$ kpc; they employed the value $R_0=8.2$ in further calculations of $\Delta\omega(R)$ from equation (1). The scale of $\Delta\omega(R)$ is fixed by R_0; systematically, the $\Delta\omega(R)$ or $\omega(R)$ curve found from the $v_{\max}$ observations is, then, no more precise than the R_0 or, if we look back one step in the reasoning, than the A value and the linear theory on which it was based.

Van de Hulst, Muller, and Oort checked R_0 against Baade's (1954) value for the same parameter, 8.16 kpc, derived from the distribution of RR Lyrae variables in the region of the galactic nucleus. The excellent agreement of the two values does not necessarily confirm their correctness. Baade's estimate could be appreciably changed by a small revision of the interstellar extinction correction employed. A change of 0.25 mag in the extinction would alter R_0 by a kiloparsec.

The crucial need of an accurate R_0 is apparent; further investigation is imperative.

The uncertainty in the galactic distance scale is also indicated by inconsistency in the currently quoted values of R_0, ω_0, and V_0. Van de Hulst, Muller, and Oort (1954) found $\omega_0=26.4 \pm 2.5$ (m. e.) km/sec per kiloparsec, a value derived by differencing A and B. Weaver and Morgan (1956) employed proper motions of 79 Cepheids in mathematically unbiased equations to find $\omega_0=23.2 \pm 5.0$ (m. e.) km/sec per kiloparsec. These values combined with $R_0=8.2$ kpc yield, respectively, $V_0=216$ km/sec and 190 km/sec. These are not fundamental determinations since they represent the product of two independently derived quantities.

Mayall (1946) found $V_0=200$ km/sec from radial velocities of 50 globular clusters. This is a fundamental determination, though it probably does not represent the true value of V_0, being smaller than that value by the difference between the circular velocity of the galaxy at R_0 and the corresponding value for the system of globular clusters. A direct observational determination of this difference does not exist. Mayall (1946) attempted to evaluate it by determining the solar motion with respect to the extragalactic nebulae. From several solutions he concluded $V_0=300$ km/sec. Humason and Wahlquist (1955) have derived an essentially identical value. Any peculiar motion of the galaxy is included in this result, which therefore does not permit a strong conclusion that V_0 is as great as 300 km/sec, but strongly indicates that $V_0>200$ km/sec. Fricke's (1949a, 1949b) value of V_0 from high velocity stars, also a fundamental determination, likewise indicates $V_0>200$ km/sec. Drawing an analogy between our galaxy and the Andromeda Nebula, we reach a similar conclusion from Mayall's (1951) velocity measurements in Andromeda. An inconsistency thus appears.

The product $R_0\omega_0$ is smaller than the V_0 value derived by independent fundamental methods. Examination of R_0 and ω_0 is required. Of the two quantities, R_0 is, percentagewise, the more uncertain.

The $\omega(R)$ curve derived by Kwee, Muller, and Westerhout (1954) from 21-cm observations shows waves which, they suggest, represent departures from circular motion which are correlated with position with respect to spiral structure. The general question of systematic deviations from circular motion over sizable volumes of the galaxy merits investigation on a broad basis. Observations of both hydrogen and stars are desirable. Of particular interest will be tests for similarity of kinetic properties of stars and gas in the same volume of space and for a correlation between gas and stellar motions and spiral structure as suggested by Kwee, Muller, and Westerhout.

Study of departures from circular motion is likely to prove easier with stars than with hydrogen. For the stars, accurate photometric distances and radial velocities can be derived for objects nearer than r_0, an observationally set limit. Over the region of space thus defined (shown in fig. 1,*a*) the motion pattern can, at least in principle, be derived and regional departures from circular motion deduced. Hydrogen observations provide no distance scale independent of velocity; they permit study of departures from circularity only over the volume of the galaxy in which $v_{\max}$ occurs (shown in fig. 1,*b*) in the range $R_1 \leq R \leq R_0$. The galactocentric distance R_1 is fixed at the point at which strong turbulence in the interstellar hydrogen sets in. In the case of hydrogen, a large peculiar motion occurring in the line of sight, but not within the indicated volume, could obscure a smaller peculiar velocity within the indicated volume and thus confuse the observation. To a lesser degree, variations in the distribution of random velocities in the hydrogen also obscure the situation. Such difficulties

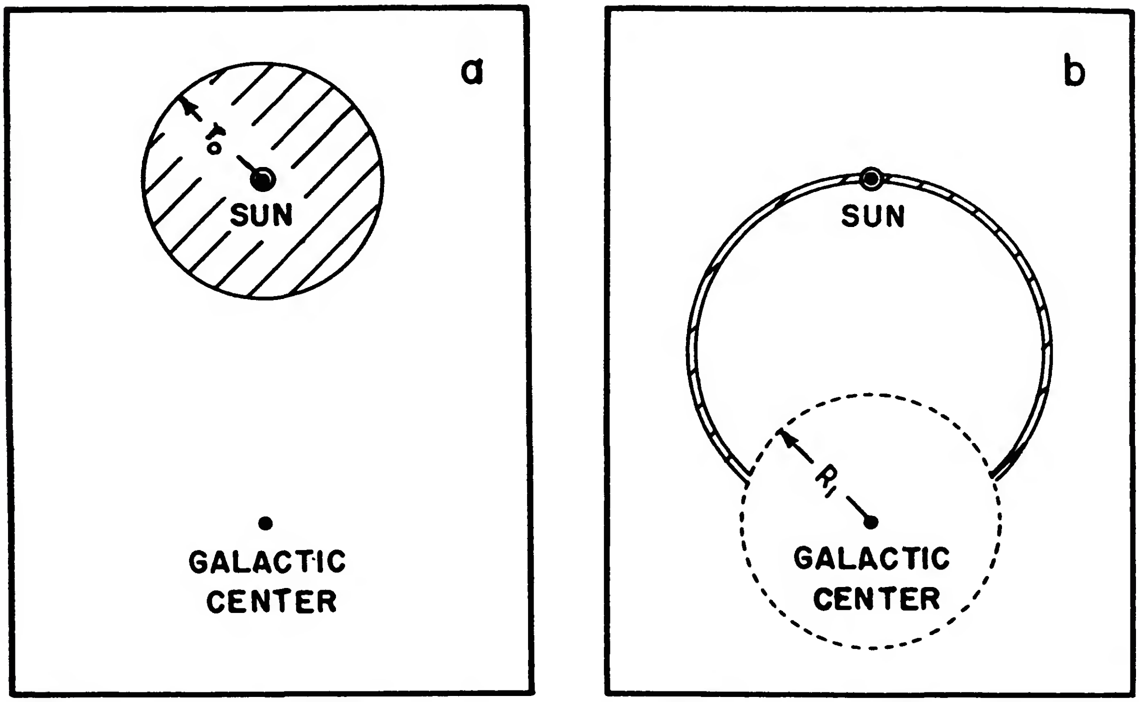

FIGURE 1.—The plane of the paper represents the plane of the galaxy. *a*, Crosshatched area indicates the region over which stars permit the study of departures from circular motion. *b*, Crosshatched area indicates the region over which 21-cm radiation of hydrogen permits study of departures from circular motion.

do not exist for the stellar observations. Hydrogen observations, on the other hand, extend to a much greater distance than do stellar ones. Comparison of v_{max} values derived at corresponding angles on either side of the galactic center will be of very great interest.

Association of spiral tracers and hydrogen

No adequate test has yet been made of the commonly accepted hypothesis that arms or structures delineated by very early type stars are coincident in space with hydrogen gas density maxima. There are indications that these may not always be coincident (Weaver, 1953; van de Hulst, Muller, and Oort, 1954). OB stars may appear where no hydrogen density maximum occurs.

Several tests of this hypothesis can be proposed. The simplest involves investigation of the simultaneous occurrence of hydrogen maxima and concentrations of early type stars over the surface of the sky. This test was independently proposed by W. W. Morgan during a colloquium given at Berkeley, Calif., in November 1955. An alternative test involves the agreement of velocity maxima of the radial velocity distributions of the OB stars (treated as particles in a star gas) and of the hydrogen gas, properly weighted to match the distribution of the stars in longitude. A third test involves the determination of the closeness of association in space of maxima in the space density functions of OB stars and of interstellar hydrogen as found from the 21-cm observations. Distances of the stars are to be derived photometrically; distances of the hydrogen maxima are to be determined from a rotation function based on the same photometric distance scale used for the stars. Different assumptions are involved in the three cases; all three tests should eventually be made.

Composition of the arms

Understanding of the physics of the spiral arms will require, among other data, knowledge of their composition. Nearby extragalactic systems will undoubtedly play an important role in composition studies. Photographs of M 51 published by Zwicky (1955) are instructive; analogous photoelectric measurements would be invaluable. Isophotes and isocolor contours, even of a rudimentary kind, for details in a few properly chosen extragalactic systems would be of great interest. A start on this problem could be made by measuring magnitude and color differences between arm and interarm regions of some of the most resolved extragalactic systems.

Spiral tracers are highly concentrated in the arms; data on the space distribution of later-type Population I stars, B 3, B 5, . . . , in and near the arms is lacking. We have no knowledge of how prominent the arms would appear if the galaxy were viewed through a series of hypothetical filters, each of which would permit us to see stars in only a small spectral-type range, B 3, B 5, ... The ordinary method of analysis of star counts does not offer much promise of producing such a picture of the galaxy. Rather, we should obtain the picture with the aid of accurate individual photometric distances derived for each member of a large sample population of stars. An empirical model of the space distribution of any one particular type of star could then be constructed. Data such as density gradient perpendicular to the galactic plane, in the galactic plane, and perpendicular to the arm, and so forth, could be inferred from the model for each stellar type.

An approach through such an empirical model avoids the concepts of a continuous space-density law and of a space-invariant luminosity function. It does not involve the solution of an integral equation for the space-density law or the correction of the apparent space-density law with the aid of an average interstellar extinction relation in a specified direction. Each star is treated individually; maximum resolution is achieved. A limit of completeness in absolute magnitude $M(r)$ can be specified at each distance; the space density of intrinsically faint stars is not inferred from a few intrinsically bright ones as when the integral equation is solved.

Extensive observations are required for such a program; a cooperative venture involving several observers and telescopes might prove advantageous. Strömgren's (1951, 1954) accurate photoelectric method of spectral classification should play an important part in any such plans. Strömgren's results indicate that the photometric probable error of one observation of a predicted absolute visual magnitude is less than 0.2 mag; in distance estimate a probable error of approximately 15 percent might be expected. With the 82-inch McDonald telescope, observations could be extended to apparent magnitude 14. Further exploratory work in the use of this important observing technique is called for. The results obtained should provide data for the establishment of an empirical space distribution as a test.

The need of an accurate and fundamental calibration of the absolute magnitudes and colors of the MK spectral types and luminosity classes as well as an accurate value of the ratio of total extinction to color excess is reemphasized by a program of this type.

Variations in the arms

Within the spiral arms are found variations in the space density of stars and in the stellar mixture. Observational data leading to a better understanding of such variations would be of considerable value.

A pronounced example of the first kind of variation is found in the longitude range 110° to 145° adjoining the rich Perseus star cloud. In this range of longitude there exists a deep minimum in the number of OB stars (Weaver, 1953); there is essentially a discontinuity in the Perseus arm as delineated by early-type stars.

Variations in the content of the arms frequently appear. The Perseus cloud contains O stars and late-type supergiants (Bidelman, 1943, 1947); classical Cepheids are found within it. The Orion association contains principally main sequence stars of type O 6 and later; it contains no supergiants of type later than B (Sharpless, 1952, 1954). The Scutum association, which has M 11 as its nucleus, contains main sequence stars of type B 9 and later, and ordinary giants (Russell, 1953). Gurzadian (1949) has pointed out many cases of this sort.

A preliminary study of variations in the arms might be made on the basis of galactic clusters and Trumpler's cluster types.

Luminosity functions and related quantities

An observing program of the type outlined in the preceding sections would provide detailed information on the space variation of $D(M, S; R, \theta, z)$ over the M-range and r-range accessible to observation. However, such a program now represents only a possible future development; information on stellar populations which will provide data for stellar evolution studies must be provided more rapidly.

Among observable quantities that provide such information with less completeness than $D(M, S; R, \theta, z)$ but that are much more easily obtained are the following:

1. The luminosity function, $L(M; R, \theta, z)$, which is the integral of D with respect to S.
2. Integrated magnitudes, colors, or spectra, which represent, essentially, integrals of the luminosity function over specific wavelength ranges and which refer to a defined volume element of the galaxy or of some extragalactic system.
3. The ratio of number of stars brighter than some fixed M and within a defined volume element to the total luminosity of all stars within the same volume element (Baum and Schwarzschild, 1955). The wavelength ranges in which M and the total luminosity are measured must be specified.
4. The ratio of mass to luminosity (measured in a specified wavelength range) of the material within a defined volume element of the galaxy or of an extragalactic system.
5. The ratio of luminosities of stars contained within some defined volume element of the galaxy or an extragalactic system measured in several different specified wavelength ranges to the luminosity of the same stars in some standard wavelength range.

Basically, the integrated quantities represent certain average properties of the stellar population in the defined volume element. The ratios compare one portion of the population with another portion of the same population. The particular ratio taken fixes the portions of the populations compared. All of these observable quantities need further investigation and application within our own galaxy and extragalactic systems.

The luminosity function of stars characterizing the solar neighborhood has been determined by van Rhijn (1936), by Luyten (1939, 1941), and others. Van Rhijn's function shows a minimum at absolute magnitude +8; Luyten's does not. The reality of this feature requires checking. The test might be made with the aid of late-type dwarfs discovered spectroscopically (Vyssotsky, 1943, and coworkers, 1946, 1952). With the present functioning of Schmidt telescopes, intrinsically faint stars discovered spectroscopically should play an increasingly important role in the determination of $L(M;\ R_0,\ 0,\ 0)$.

The van Rhijn luminosity function presumably characterizes Population I; the exactness of the characterization may bear further analysis. The method of deriving the luminosity function entails the use of volume elements of different sizes for different luminosity ranges. The very bright stars are observed over a volume element of great size, a cylinder of possibly a kiloparsec radius; the very faint stars are observed within a spherical volume element of a few parsecs radius centered on the sun. The highly luminous stars are known to be nonrandomly distributed in the galactic plane; indications are (McCuskey, 1951) that the fainter stars also vary in mixture over moderate distances from the sun. The van Rhijn luminosity function was derived when there was still belief in the universality of the function. There is no certainty that it refers to a homogeneous population of stars. The function is, for the faint stars, essentially $L(M;\ R,\ 0,\ 0)$; for the bright stars it is some average $\bar{L}(M)$, the average being taken over a large and somewhat uncertainly specified volume element.

An important step towards a clearer understanding of the Population I luminosity function could be taken by determining the luminosity functions of a number of representative Population I objects; namely, galactic clusters, star clouds, associations. Such luminosity functions could be determined with adequate accuracy by statistical means, provided an accurate magnitude sequence was available for each case. Of particular interest would be a study of variations in the form of the luminosity functions for stellar groups of different Trumpler type or different age, different size, and so forth. The possibility of forming from such a sample a mean function representative of Population I in the solar vicinity should be investigated. Variations in different groups or changes through evolution may, of course, make the establishment of such a mean function impossible on the basis of present knowledge.

Luminosity functions of typical Population II would also be of great interest. Important results for luminosity functions of globular clusters have recently been given by Sandage (1954) and by Tayler (1955); for nebulae by Baum and Schwarzschild (1955), by Baum (1955), and by Roberts (1955, and in press). For these latter cases indirect methods using integrated magnitudes and multicolor observations were employed.

Variations have been found in luminosity functions of typical Population II systems just as they have in Population I systems. An elliptical nebula appears to contain a much larger percentage of dwarfs than a globular cluster. The luminosity function of the dwarf branch of a globular cluster appears remarkably similar to that of the stars in the solar neighborhood; a typical galactic cluster contains a much smaller percentage of dwarfs than does the solar neighborhood. Comparisons of this sort based upon many more cases than are now available will be of very great interest. They may well provide the key to an understanding of the mixture of stars we find in the neighborhood of the sun, particularly if information of the space density of stars of different spectral types and luminosity classes in and between the arms can be derived.

The local system

Interpretation of space density results in the region of the sun in terms of a simple picture of spiral arms may prove difficult because of the interference of the "local system" (see Bok, 1937, for earlier references). The observations by Nassau and Morgan (1951) demonstrate that the distribution of bright OB stars follows the outline of the local system. Heeschen and Lilley (1954) have found the local system in the 21-cm radiation of hydrogen. The structure likewise appears among both the bright and dark nebulae. A thorough modern study of the local system would be of interest; it would also be of value as an aid in disentangling the local system and what one ordinarily thinks of as spiral structure.

Other aspects of the galaxy

For an understanding of the galaxy a knowledge of the interstellar material is no less important than that of the stars. Problems of some aspects of interstellar matter have been described where necessary: the degree of association of interstellar hydrogen and spiral tracers, motions of the hydrogen, and the value of the ratio of interstellar extinction to reddening. However, general problems of the interstellar medium and of the 21-cm radiation of hydrogen fall outside the scope of this review. They will be found in the reviews of those subjects. Likewise, problems of motions within the galaxy have been introduced only where necessary since they form the subject matter of a separate paper. In actual practice, the study of the distribution of stellar or interstellar material and the study of kinematics cannot be separated if a complete view of the problem is to be gained. The distribution of material and the motions of the material are component parts of one problem that must be considered as a whole.

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Galactic Clusters and Associations

By A. Blaauw[1]

Research on galactic clusters and associations can be divided into two categories: the properties of the individual objects, and the properties of the system of the objects as a whole. The first aim of these investigations is, of course, to arrive at a knowledge of the present condition of the individual clusters and associations and of their present motions and distribution in space. But the ultimate purpose is to understand these conditions as a result of the origin and evolution of the clusters and associations. This problem is immediately connected with that of the history of the galaxy and with that of stellar evolution. This double aspect makes the study of clusters and associations particularly significant.

There is no sharp division between galactic clusters and associations. This is best illustrated by the fact that certain objects, such as NGC 2244, may be classified under either of these categories. Most associations must have short lifetimes and will have dispersed among the general population of the galaxy within one or two revolutions of the galaxy (a few hundred million years). Galactic clusters are more stable objects but this need not mean that their origin is essentially different from that of the associations. They may simply be remnants of the rich central parts of some associations with very small internal motions, that had a negative energy from the outset, or have disposed of a small positive energy by the ejection of part of their stellar content. Stellar associations offer an opportunity to study the properties of the very youngest stars, and they seem to be one of the best places to look for information on the process of star formation itself. Galactic clusters offer a variety of star samples, each of which informs us about the properties of stars formed simultaneously and at the same location in the interstellar medium, under certain common circumstances. A vast amount of observational data has been collected in the past for the galactic clusters, most of which will serve as a basis of more refined work made possible by the improved present and future observational techniques. Much less has been done on the associations, whose importance has only recently become clear. However, what has been done observationally so far, especially in the field of photometry, meets the standards required for our present demands.

Having in mind that research on galactic clusters and associations can contribute to our understanding of the evolution of the galaxy and of the stars, we shall consider three major trends in this research, in the three sections following.

Individual properties of the stars

Individual properties of the stars in clusters and associations may be: the absolute magnitude, the color, the spectral type, the angular momentum, the duplicity or multiplicity, and the motion of the star with respect to the center of the cluster or association. Such studies are important because the stars in the cluster or association can be assumed to be of approximately equal ages, to have formed at the same location in the interstellar medium, and, perhaps, to have uniform chemical composition. This last assumption is uncertain since the abundance of interstellar grains may have varied within the cloud complex in which the stars were formed. In principle, knowledge of these properties of the stars in a large number of clusters and associations would provide an ideal basis for studying (1) the properties of stars of equal age but of different mass and angular momentum; (2) the changes, with age, not only of the stars' position in the HR diagram but also of their rotational and duplicity properties.

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Trumpler's extensive investigations of galactic clusters have revealed the large variety of patterns in the HR diagrams and this, combined with modern concepts of stellar evolution, shows that these objects represent a wide range of evolutionary stages. The modern equivalent of these diagrams, based on accurate photoelectrically measured colors and magnitudes, has already allowed more detailed discrimination of the properties of different stars in the same cluster, and more refined comparison of the color magnitude arrays of different clusters. It has, moreover, the great advantage of reaching considerably fainter apparent—and, hence, also absolute—magnitudes than the spectroscopic method.

While color and absolute magnitude are the most obvious quantities to choose in defining the physical properties of a star, they do not describe them completely. Initial chemical composition and angular momentum cause variations of the array in the color absolute-magnitude diagram for clusters of equal age. We should consider also the duplicity or multiplicity of the stars and their motions in the cluster. These will probably have no relation to the color-magnitude arrays, but they must have an important bearing on the process of the formation of the cluster from the interstellar medium and will have to be taken into account in subsequent studies of the evolution of the clusters. There may be other properties of the stars in addition to those listed above, which, though not yet easily accessible, may provide important clues; the magnetic fields might be among these.

There can be little doubt that the first desideratum for future work on galactic clusters is the determination of accurate color absolute-magnitude arrays for a large number of clusters. These should provide the basis for subsequent studies of the secondary effects mentioned above, which may be feasible only for a limited number of stars and a limited number of clusters. These latter could then be selected so as to represent the most useful variety of evolutionary stages.

A critical step in the determination of the color absolute-magnitude arrays is the conversion of apparent magnitudes into absolute magnitudes. There are only a few clusters for which we have geometrically determined distances: the Hyades, Ursa Major, and α Persei clusters. The use of differential galactic rotation as an indicator of distance has not produced valuable distances in the past, but it may do so in the future for the young clusters if these follow the spiral structure of interstellar hydrogen closely and if radial velocities determine uniquely to which arm the clusters belong. H. L. Johnson's approach to the problem of the absolute magnitude determination, based on the assumption of identical "zero-age main sequences," may prove to be very useful provided sufficient evidence can be produced to show that the chemical composition does not affect the position of the main sequence. One must bear in mind, however, that this approach eliminates the detection of composition differences unless these are of a more pronounced character in the rapidly evolving part of the color absolute-magnitude diagram than in the slowly evolving part; the determination of the absolute magnitude scale should be based, preferably, on the latter.

The extension of the color-magnitude arrays to faint stars may require the identification of fainter cluster members than are known at present. This holds even for the nearest clusters, the Hyades being a good example of a cluster whose faint members are still unknown. It will in general be the case for the poorer clusters observed against the rich background of the Milky Way. So far, observations of the faint stars in clusters have usually been confined to a sample considered representative as far as the magnitudes and colors are concerned, with little attention being given to the estimation of the total numbers of faint members. Yet, this is an important item if we want to consider the density of the population along the main sequence at zero age for different clusters. That differences in this respect exist follows from the comparison of NGC 752 and Praesepe. Such differences are probably related to the mass density and the state of motion in the interstellar medium from which the cluster originated. Their observation may provide interesting data on the formation process of the clusters.

Existing data on the identification of faint cluster members can in many cases be considerably increased by the measurement of new proper motions in the fields of the clusters.

The large collections of photographs of galactic clusters, taken at several observatories 30 or more years ago, are becoming more and more useful for this purpose. In many cases, work of this kind done in the years preceding World War II cannot be considered to be up to date for the future projects mentioned above. Comparison of the old epoch plates with modern ones may give proper motions of several to 10 times the weight of those available at present. It is gratifying to know that several observatories that possess fine collections of old plates have already started comparing these with modern ones, whereas others have expressed their interest in undertaking programs of this kind. International Astronomical Union Commission 37 on star clusters and associations at the Dublin Assembly has adopted a resolution to the effect that observatories which possess collections of early epoch cluster plates present lists of these to the president of Commission 37 and indicate to what extent they are in a position to collaborate on proper motion work.

Observations of the stellar rotation velocities and of the frequency of spectroscopic and visual binaries have, in the past, been given relatively little attention. Yet they would seem to offer most interesting prospects for future research. Why are there few or no spectroscopic binaries among the Pleiades although visual doubles are plentiful, whereas spectroscopic binaries are frequent in other clusters, notably in those containing many early-type stars? Are we facing here an evolutionary effect or is this difference directly related to different initial conditions in the interstellar medium at the time the clusters were born? Whatever the answer may be, it is obvious that a systematic study of the frequency of rotational velocities and of the duplicity characteristics in clusters of a variety of ages and appearances will ultimately give valuable information on the formation problem.

The foregoing remarks referred in the first place to the work on galactic clusters. Although the basic problems are very much the same for the associations, the emphasis in future work will probably be somewhat different. The associations on the whole are much younger than the clusters so that the stars have evolved very little, while the internal velocities are generally large and very likely much the same as at the time of formation of the stars; therefore, they can indicate the initial properties of the stars and may yield clues to our understanding of their process of formation. The observations made so far have been concerned mainly with the photometry (absolute magnitudes and colors), the proper motions, and radial velocities, while a beginning has been made with the systematic investigation of the duplicity properties. But all these referred only to the brightest part of the population and the stars of spectral types about B5 and earlier. Very little is known as yet of the occurrence of fainter, later-type stars. Stars down to spectral type A0 along the main sequence have been surveyed in the Orion association, in III Cep, and in the most concentrated parts of a few other objects. But in two of the nearest associations, II(ζ) Perseus and I Lacerta, we are still ignorant about the members of types B5 and later. Yet these two associations are favorably located at relatively high latitudes where the confusion by the general galactic background is less serious than in most other cases. Surveys of the late B and later-type stars in associations will suffer from a few drawbacks: the area over which the stars have to be classified is much larger than for the clusters—for the nearest associations of the order of 100 square degrees—and, since the internal velocities are large, members and field stars cannot be distinguished uniquely. The membership may have to be based on statistical evidence, like that, for instance, showing that the concentration in the sky for a particular type of star is greater in the region of the association than outside it. The size and direction of the proper motions may help when the expanding character is pronounced, but then it can be used only in the outer regions where the density of the population is small. In spite of these difficulties, knowledge of the fainter membership of the associations must be considered one of the most urgent goals of research on these objects. The first approach should, of course, be by Schmidt telescopes or large-field astrographs equipped with objective prisms.

Dynamical studies

Dynamical studies of clusters have, in the past, been mainly concerned with systems in a state of approximate equilibrium, and have dealt with the relation between internal velocity distribution and mass distribution, the times of relaxation, and the rate of escape of stars from the cluster. Investigators usually assumed that the clusters are approximately the age of the universe, several billion years. Recently acquired knowledge of the ages of clusters derived from increasing information on stellar evolution offers the possibility for a fresh approach to dynamical studies of clusters. Various questions come to our mind. We notice that the distribution of stars in the Hyades is quite irregular. We estimate its age at about 10^9 years. Can we reconcile these two observations, estimate how many stars must have escaped from the Hyades, and predict its future constitution? Suppose we indeed collect data on the ages of a large number of clusters as suggested in the preceding section, can we explain the numbers of clusters of various ages as a result of the predicted rate of disintegration?

The dynamics of associations presents problems of a somewhat different kind. Especially in the youngest objects, the forces acting on the stars are probably mainly due to the interstellar matter present in the region of the association. If we make the reasonable assumption that only a small fraction of the interstellar matter has condensed into stars, its mass may very likely exceed the total mass of the stars many times. Probably the most promising aspect of the study of the motions in associations is that it will give us direct information on the state of motion of the generating interstellar cloud complex, and it is intimately connected with the complicated problems of the dynamics of cosmic clouds. It is clear, however, that we must obtain the most precise data on the motions of individual stars. For the brightest ones ($m<6$) we will depend on continued meridian observations. For the fainter stars (around $m=9$) we must rely on photographic determinations of new positions. These will require special programs involving large numbers of plates covering the limited regions of the associations in order to attain high accuracy for the individual stars. In addition to the proper motion work we must consider radial velocity observations as one of the principal desiderata for future work. This has been mentioned also in connection with the detection of spectroscopic binaries.

The system in the galaxy

Investigations of the space distribution and the kinematical properties of clusters have shown that they occupy a flat subsystem in the galaxy with peculiar motions of the order of 10 km/sec. Only in recent years have the more accurate photometric distance determinations revealed the connection between open clusters and the spiral structure.

For future work in this field, also, the accumulation of a large number of accurate color-magnitude diagrams with the inferred knowledge of the ages of many clusters forms the basic requirement. Once this information has been obtained one can study the distributional and kinematical properties for different age groups. For the youngest clusters the evidence already obtained for the distribution along the spiral arms will be strengthened, and it will be interesting to see where, along the spiral structure of interstellar gas, the formation of clusters used to take place. Data on proper motions, already referred to, and mean radial velocities will provide information on the velocities of these objects at the time of formation.

The most intriguing of these studies may, however, well be those dealing with the somewhat older objects. Shall we be able to reconstruct from their present distribution and motions their distribution at the time of formation? This may be possible for the slow moving clusters whose ages are now of the order of one revolution of the galaxy (200 million years). If we assume their space velocities to be of the order of 5 km/sec, they have traveled during their lifetime a distance of about 1,000 parsecs from their origin. This is probably not too far to allow an approximate reconstruction of the distribution of the original locations. Thus we may be able to study the secular changes in the spiral structure of the galaxy, a problem which we otherwise could tackle only by studying the space distribution of the A-type stars. These are, of course, much more numerous, but the clusters have the advantage of being detectable over a larger area.

These studies require measurements of the proper motions and of the radial velocities of the brightest stars in the clusters, in addition to the photometric data. It may not be too optimistic to expect that present and future observational equipment may collect these data for several hundred clusters.

Studies of the space distribution of the associations are well under way at present and are of great interest because they outline the spiral structure. Also radial velocities of the association are being measured and they are essential in supplementing the studies of spiral structure based on the 21-cm hydrogen emission. Work on the proper motions, of special value for the nearer objects, will be greatly facilitated by the recently planned repetition of the AGK_2.

Globular Clusters Observed through a Crystal Ball

By W. A. Baum[1]

At the focus of a large telescope, a globular cluster is one of the most magnificent sights in the sky. One can see thousands upon thousands of stars all crammed together within a few minutes of arc. Embedded like jewels here and there in the sparkling swarm, the brighter stars run the full gamut of color; the brightest are brick red while others, slightly less bright, are distinctly blue. Toward the center of the cluster, the population becomes fantastically dense. It is amusing to consider what our sky would look like if the earth were associated with a star in the nucleus of a globular cluster.

Perhaps the best way to judge what the future has in store will be to examine the present state of our knowledge and some present lines of speculation to see the gaps which need to be filled.

Globular clusters constitute a very well defined class of objects, all pretty much alike in their general features. You could hardly mistake one for any other type of system. Out of more than a hundred observable globular clusters in our own galaxy, only two or three are still debatable cases.

The distribution of globular clusters in the galaxy is almost spherically symmetric about the galactic nucleus, whereas stars like those in the solar neighborhood, along with gas and dust, are restricted to a highly flattened disk-shaped region. This difference in distribution is associated, as one might expect, with a difference in angular momentum; globular clusters probably do not as a group share to any large degree in the rotation of the galactic disk, but they have large individual radial velocities. Except in the immediate region of the galactic nucleus, the number of globular clusters per unit volume decreases as the inverse third or fourth power of the distance from the nucleus, and there is no well-defined outer boundary to their domain. It would be very valuable to have a more complete and accurate analysis of the distances and velocities of all known globular clusters in the galaxy, but the task is a big one.

The stars in globular clusters are an entirely different breed from those with which we are familiar in the solar neighborhood. They have different chemical abundances and they consequently follow different patterns of evolution as they age. These differences can be deduced from spectra and from color-magnitude diagrams. Stars of the globular-cluster kind are sometimes referred to as Population II. They are found not only in the clusters but also as unattached vagabonds wandering through the same regions of the galaxy (nucleus and halo) frequented by the clusters. They are found similarly in the halo of M 31 and in nearby dwarf galaxies. In general they seem to favor regions which are free of dust. Since it does not necessarily follow, however, that stars inhabiting a dust-free region are always the same kind (i. e., same chemical abundances and associated patterns of evolution), one cannot say with certainty whether stars of the globular-cluster kind do or do not constitute the predominant population in elliptical galaxies; if they do, then they are probably the most numerous kind of stars in the universe. This is a fundamentally important question on which more work is needed.

Color-magnitude diagrams

One of the best ways to characterize the stars that compose a stellar system is to plot their color indices (or their spectral types) against

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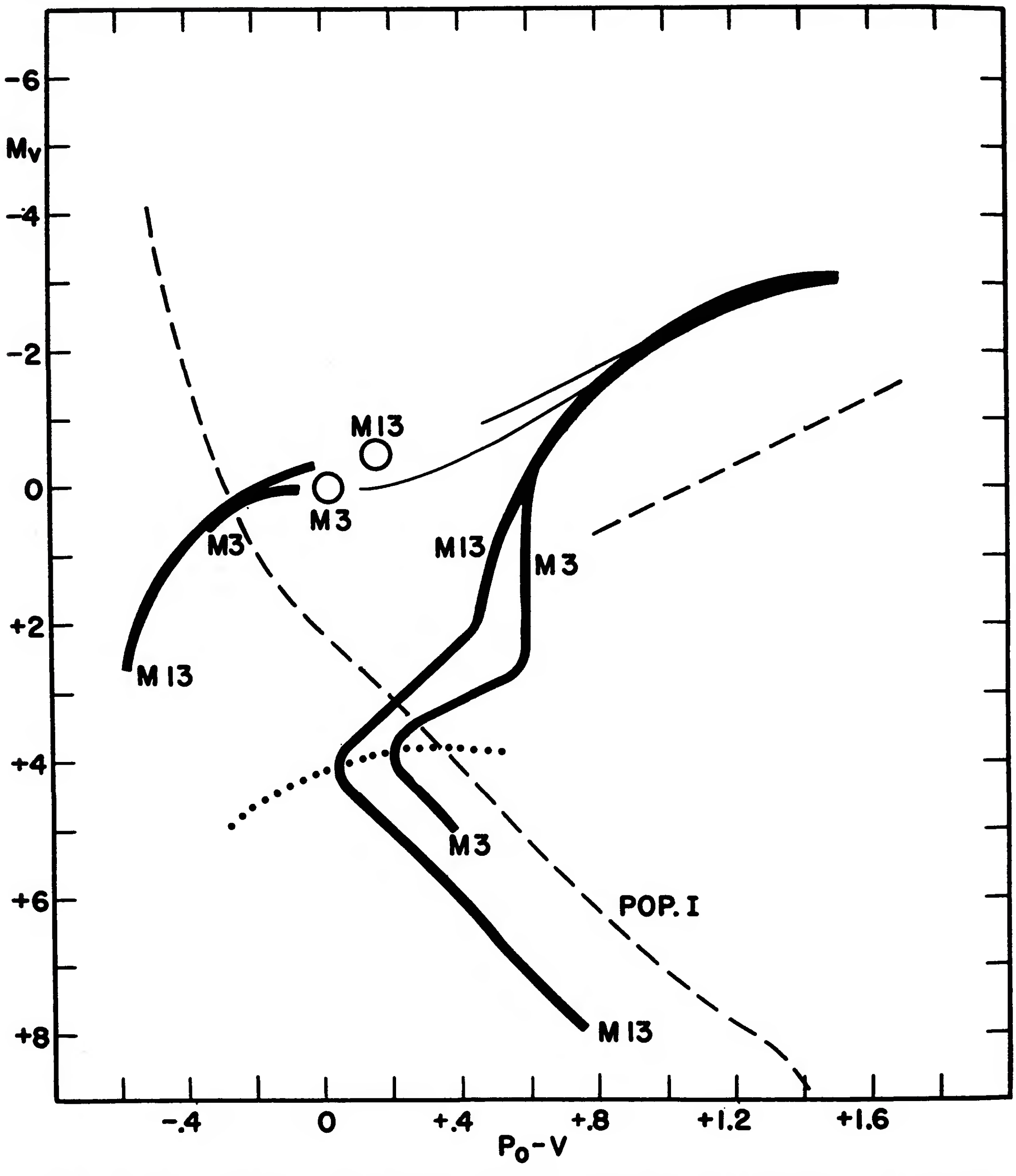

FIGURE 1.—Schematic color-magnitude diagrams for M 3 and M 13. Sequences for the solar neighborhood are sketched with dashed lines for comparison. The diagrams have been adjusted vertically so that the mean of the cluster-type variables (circle) in M 3 falls at $M_v=0$ and so that the evolutionary breaks from the main sequence fall at the same bolometric magnitude (dotted line).

their magnitudes. In contrast to the diversity of color-magnitude diagrams found among open clusters which inhabit the galactic disk, the color-magnitude diagrams of globular clusters all have basically similar features. This does not mean that they are identical. There are indeed important differences among them, but the differences mainly pertain to the positions of the sequences rather than to the existence or nonexistence of various sequences.

Color-magnitude diagrams for two well-known globular clusters, M 3 and M 13, are sketched in figure 1. The color indices span an extremely broad range; the bluest stars have indices around -0.5 on the P_0-V system while the reddest are around $+1.5$. The brightest stars in globular clusters have absolute photovisual magnitudes of about -3, while the faintest are presumably much below the present limit of observation at the bottoms of the diagrams shown here.

In the lower part of each diagram, from $M_v\sim+4$ downward, is a segment of the main sequence. Stars which formerly lay a little above $M_v\sim+4$ on the main sequence have recently evolved away from it and they presently form the upper branches of the diagram. Stars which started from somewhat brighter levels of the main sequence, say above $M_v\sim+3$, have long since completed their evolutionary sequences and passed on to the graveyard. When a star evolves away from the main sequence it evidently moves into the subgiant region at the right of the main sequence and climbs upward into the red-giant branch. Since the total ascent is about seven magnitudes, the star is consuming fuel several hundred times faster during its red-giant phase than during its childhood on the main sequence. As a result it doesn't live very long as a red giant. When it starts to run short of hydrogen, the star is believed to move toward the left along the horizontal branch and then dribble downward at the extreme left of the diagram to the graveyard. Its death throes are suspected of being occasional nova outbursts, after which it collapses into a degenerate white dwarf and cools itself into oblivion.

The time required for the color-magnitude diagram to reach its present configuration is uncertain, but it apparently is of the same general order as the age of the universe judged from the recession of galaxies, say, 5 to 10 billion years. Each star probably spends more than half of its life on or near the main sequence, where it uses up only 10 to 15 percent of its hydrogen. As it proceeds up the vertical branch, its rate of rise is roughly proportional to the luminosity, and its radius expands as the square root of the luminosity. By the time it reaches $M_v\sim 0$, the star is evolving quite fast. It requires only about 2×10^8 years to go the rest of the way to the top of the diagram and about an equal length of time to traverse the horizontal branch. The nova stage, if indeed that is the star's actual route to the graveyard, must be less than 10^6 years' duration. Beyond that, its evolutionary schedule is unknown.

Near the top of the red-giant branch, the star starts to fluctuate small fractions of a magnitude at a relatively slow rate, its amplitude increasing as the tip of the branch is approached. In the same region of the color-magnitude diagram one occasionally finds a bonafide long-period variable, which suggests that the fluctuation may build up briefly to large amplitudes as the hydrogen-spent star starts to collapse and slide back down the red-giant branch. In any case, it apparently quiets down again as it travels rapidly toward the left along the horizontal branch. Then suddenly it breaks into another fit of oscillation, this time as a cluster-type variable. Its period and light curve are relatively steady, but they are believed to undergo gradual secular changes as the star pursues its evolutionary course through this region of the diagram. Present data suggest that the period, starting initially at about one day, becomes progressively shorter, while the amplitude rises to a maximum and then falls again. This fall in amplitude is accompanied by a change in the shape of the light curve which may be associated with a change in the mode of pulsation. At the blue edge of the variable-star region the star quiets down again until it slides off the blue end of the horizontal branch. If the star then passes through a nova stage, one might count it as the third fit of instability along the evolutionary track, but it evidently differs in kind from the other two.

The foregoing paragraphs outline the general features of globular-cluster diagrams and their evolutionary interpretation as we understand them today. While certain basic facts now seem to be fairly definite, it should be emphasized that much of this information is only tentative and some of it is even speculative. Moreover, there are a few items which were omitted altogether, because we haven't the foggiest notion how to fit them into the over-all evolutionary picture. These include the long-period Cepheids (between $M_v \sim -1$ and $M_v \sim -5$) found in some of the clusters, the planetary nebula in M 15, and the occasional blue stars found above the horizontal branch in a few clusters.

Altogether, there are so many points on which more photometric material is needed that it is difficult to suggest what should be undertaken first. In some cases, the question is largely one of observing more stars or sampling more clusters. This is true, for example, if one wishes to understand the nature of red-giant fluctuation, the properties of the red long-period variables, or the role of the long-period Cepheids; it is also true of investigating the differences between cluster diagrams, which we shall discuss shortly. In other cases, the problem is rather to improve the accuracy of existing data. It has sometimes been tempting to overrate the finality of the present material and to neglect the need for further investigation.

Among the various branches of the cluster diagrams, the main sequence is observationally the most difficult. Recent developments in photoelectric photometry, however, have made it possible to measure extremely faint stars with complete freedom from the scale errors that have hampered photographic efforts. As a result of such developments, it has been found that the stars comprising the main sequence of a globular cluster do not fall on the ordinary main sequence with which we are familiar. They are subdwarfs. This result is of cosmogonic significance because it leaves little doubt that globular clusters are made from a different recipe from that of the majority of stars in the solar neighborhood; a disparity in age alone would hardly seem sufficient to account for it.

There are some fascinating differences between the color-magnitude diagrams of various globular clusters. Features which differ noticeably from cluster to cluster include: (1) the position of the main sequence, (2) the position (colorwise) of the top of the red-giant branch, (3) the shape and tilt of the red-giant branch, (4) the number of cluster-type variables, (5) the populousness of the horizontal branch at the right of the cluster-type variables, and (6) the shape and tilt of the horizontal branch. The last four of these features seem to be mutually related; if one intercompares all of the color-magnitude diagrams which have been photoelectrically calibrated on the same color system, he finds that they can be arranged into a series (call it series A) in which these last four features tend to change mutually and progressively from one diagram to the next. The number of cluster-type variables thereby becomes a handy index for categorizing globular clusters and their diagrams. It is rather puzzling to note, however, that the second feature in the list above suggests arranging the diagrams into a different series (call it series B), and that it is this latter arrangement which spectroscopic observations tend to support. Data bearing on the first feature in the list above are still too scanty to tell us which series, if either, the main sequences will favor, but a prediction can be ventured: if series A truly represents the effects of chemical abundances upon evolution, the arrangement of the main sequences ought to be in accord with it.

Actually, series B has somewhat the appearance of being series A folded in the middle, but the number of clusters investigated is too small to provide more than a hint of any such relationship. If one intercompares a group of cluster diagrams arranged in order according to series A, the tops of the red-giant branches tend to be progressively bluer until one comes to M 92, after which the red-giant branches are progressively redder. Both extremes of series A might thus be associated with the red extreme of series B, and we could then forget about series B having any independent significance. This happy unification seems to run into grief, however, if we attempt to interpret abundances from the spectra and simultaneously to invoke abundances to account for series A. If abundance differences are reserved for explaining series A, and if B cannot be associated with it, then perhaps we should seek a phenomenon which does not affect the general evolutionary pattern but which does affect the swollen atmospheres associated with the stars during their red-giant phases. The fact that all the giants of a cluster are affected to somewhat the same degree suggests the possibility of an environmental phenomenon, such as surface accretion during passage of the cluster through the galactic plane or nucleus, but such environmental effects have not been regarded with much favor. A third possibility for explaining the existence of the two series is based upon the fact that abundance differences themselves are not necessarily one-dimensional; in principle there are as many parameters as there are elements in the periodic table. We can imagine, for example, that some of the features of the color-magnitude diagram (maybe those abiding by series A) might be sensitive to the hydrogen/helium ratio, while others (maybe those abiding by series B) might be sensitive to the hydrogen/metals ratio. In any case, the problem of interpreting these series is a very challenging one.

Photometric observations of high precision are badly needed in more globular clusters if the differences between them are to be fully understood. Although many color-magnitude diagrams of various sorts exist, only a few have been calibrated photoelectrically and adjusted accurately to a standard color system. There are plenty of favorably situated clusters whose diagrams would be valuable. Table 1 is a list of clusters which lie 20° or more from the galactic plane. Twenty-four of them are in the Southern Hemisphere while only 13 are in the Northern Hemisphere; however, several of the southern clusters can be reached fairly well by northern telescopes. The modulus represents a rough estimate of the magnitude of the horizontal branch; for the upper branches to be well defined, the color-magnitude diagram should extend about two magnitudes fainter than the modulus without serious deterioration of accuracy. Since integrating techniques now enable one to obtain photoelectric observations to about the same limit that can be reached photographically, most of these clusters can be reached with telescopes of modest aperture if they are adequately equipped. The approximate number of known variables, the integrated spectral class (or alternatively the integrated color index), and the approximate distance from the galactic nucleus are all parameters by which clusters can be grouped and compared. We have already cited the number of variables as an index to the form of the color-magnitude diagram according to series A. We shall return in a moment to a discussion of the relationship of these integrated properties to the distance of the cluster from the galactic nucleus.

Among the clusters in table 1, color-magnitude diagrams suitable for intercomparing the upper branches have thus far been published for NGC 4147, M 3, M 5, M 13, M 92, M 2, M 10, and M 15. Work is now in progress on one or two others, but the majority haven't been touched. It should also be mentioned that there are several clusters which are too interesting to neglect in spite of the fact that they lie at less favorable galactic latitudes than those listed in table 1. Outstanding examples with low moduli are ω Centauri, M 4, M 22, and NGC 6397. Clusters lying close to the galactic nucleus include NGC 6304, NGC 6316, NGC 6355, NGC 6453, and NGC 6522. There are also two or three massive galactic clusters of great age, similar perhaps to M 67, whose color-magnitude diagrams may help to clarify evolutionary differences between halo and disk populations.

It is much more difficult to reach significant samples of the main sequences than similarly to reach the upper branches. It requires a large telescope and a great deal of photoelectric observing time under first-rate conditions. Thus far, M 13 is the only cluster for which the main sequence has been firmly located. Some tentative photoelectric results were used for including M 3 in figure 1, and similar material also now exists for M 15. Earlier appearances of normal main sequences in the photographically extrapolated diagrams for M 3 and M 92 have turned out to be spurious. It may be several years before a definitive amount of data on the relationships of globular-cluster main sequences can be assembled.

TABLE 1.—*Globular clusters for which* $|b| \geq 20°$

Cluster designation		*α 1950*	*δ 1950*	*Estimated modulus (pg)*	*Number of variables*	*Integrated spectrum*	*Distance from gal. nucleus*
		h m	° ′	mag			kpc
NGC 104	47 Tuc	00 21.9	−72 21	14.5	8	------------	8
288		00 50.2	−26 52	15.7	2	------------	15
362		01 00.6	−71 07	15.7	14	------------	12
1261		03 10.9	−55 25	------------	------------	------------	------------
1841		04 52.5	−84 05	------------	------------	------------	------------
1851		05 12.4	−40 05	------------	3	F5	------------
1904	M 79	05 22.2	−24 34	16.3	5	F3	20
2419		07 34.8	+39 00	19.4	36	F5	65
4147		12 07.6	+18 49	17.0	4	A5	24
4590	M 68	12 36.8	−26 29	16.1	28	A6	13
5024	M 53	13 10.5	+18 26	16.7	42	A8	19
5053		13 13.9	+17 57	16.4	10	------------	17
5272	M 3	13 39.9	+28 38	15.7	186	F2	13
5466		14 03.2	+28 46	16.4	18	------------	17
5634		14 27.0	−05 45	17.1	7	F4	19
5694		14 36.7	−26 19	17.7	0	A9	22
5824		15 00.9	−32 53	------------	------------	F5	------------
5897		15 14.5	−20 50	16.2	------------	------------	8
5904	M 5	15 16.0	+02 16	15.2	97	F7	7
6171	M107	16 29.7	−12 57	16.2	24	G2	6
6205	M 13	16 39.9	+36 33	14.8	15	F2	9
6218	M 12	16 44.6	−01 52	15.2	1	F7	4
6229		16 45.6	+47 37	17.7	21	F6	28
6254	M 10	16 54.5	−04 02	15.2	2	G0	4
6341	M 92	17 15.6	+43 12	15.2	16	A5	10
6684		18 44.1	−65 14	------------	------------	------------	------------
6752		19 06.4	−60 04	14.2	1	------------	5
6809	M 55	19 36.9	−31 03	14.5	2	------------	4
6864	M 75	20 03.2	−22 04	18.1	11	G1	25
6934		20 31.7	+07 14	16.9	51	F9	15
6981	M 72	20 50.7	−12 44	17.0	31	G2	16
7006		20 59.1	+16 00	18.8	20	F1	39
7078	M 15	21 27.6	+11 57	15.9	66	F0	12
7089	M 2	21 30.9	−01 03	16.2	17	F0	13
7099	M 30	21 37.5	−23 25	15.5	3	A7	9
NGC 7492	----------	23 05.7	−15 54	17.9	9	------------	32
IC 4499	----------	14 52.7	−82 02	------------	------------	------------	------------

The foregoing discussion of color-magnitude diagrams is presented in terms of ordinary two-color photometry. Much can be added, however, by extending observations to three or more colors. In particular, the addition of ultraviolet enables one to compare the relative strengths of the Balmer regions in various stars. This can be done for instance by plotting a diagram of *U–B* against *B–V*. Results in M 13 show that the red giants and subgiants have an ultraviolet excess of about 0.05 magnitude, while the very blue stars on the horizontal branch have very pronounced ultraviolet deficiencies. Rather oddly, there is a lonesome B 2 star lying about two magnitudes above the horizontal branch in M 13 which does not exhibit this ultraviolet deficiency. In M 3 and NGC 4147, the ultraviolet excess of the red giants and subgiants is several times greater than in M 13. Similar information for other clusters would be very valuable; it might provide an important clue to the reason for the differences between their color-magnitude diagrams.

Multicolor photometry and spectrophotometry have not yet been applied to individual stars in globular clusters, and the results of any multicolor exploration are likely to pay handsome rewards. Although the useful range of a photometer becomes limited to brighter objects when the color bands are made narrower, the bright stars in globular clusters are still within easy reach of conventional six-color observations with a telescope of modest aperture. On the other hand, narrow-band spectrophotometry will be quite difficult.

Spectra

Spectroscopically, the individual stars in globular clusters are rather difficult objects; hardly any of them are brighter than 14th magnitude in the blue region. Until recently, the spectra have consequently been of quite low dispersion. These have been suitable, however, for spectral classification and for detection of the grosser peculiarities of the cluster stars. It was already recognized a decade ago, for example, that cyanogen absorption is abnormally weak and that the hydrogen lines are a little more enhanced than in normal stars of the same absolute magnitude.

During the last few years, the fast new coudé cameras at Palomar have made it possible to reach some of the brighter cluster stars with a dispersion of 38 A/mm and, in two cases, of 18 A/mm. Because of the very large collimator-to-camera ratios for these dispersions, the slit of the Palomar spectrograph can be made wide enough to receive nearly all of a star image during good "seeing" without causing a loss of photographic resolution in the spectrum. The first four such spectra at 38 A/mm were obtained in 1952 with the idea of checking spectroscopically on the photometrically observed difference between the red-giant branches of M 3 and M 92, which at that time were the only two clusters whose color-magnitude diagrams could be intercompared on a standard system. These spectra not only confirmed the reality of an intrinsic difference between these two clusters but also showed quite dramatically that the red giants in M 92 are very extraordinary objects. They are markedly different from any other known stars. Additional spectra of the same dispersion were soon obtained in M 92 and, subsequently, in most of the globular clusters for which intercomparable color-magnitude diagrams now exist as well as in several others not yet photometrically investigated.

The most striking peculiarity of the red-giant spectra in some of the clusters is the extreme weakness of the metallic lines. Superficially, these spectra appear to be of very much earlier types than the color indices of the stars suggest. In M 92, for instance, the metallic lines seem to have roughly the strengths usually found in F-type stars, whereas the color indices would normally be associated with early K stars. This disparity largely vanishes, however, if the spectral classification is based upon the ratios of certain metallic lines instead of upon their absolute strengths. In other words, the excitation temperature is much less discordant with the color temperature if it is inferred, as it should be, from the ratios of line strengths instead of from the absolute strengths themselves.

A few particular ratios deserve mention. As the excitation temperature increases, the ratio of λ4254 to λ4250 should decrease, whereas the ratio of λ4247 to λ4250 should increase. The feature at 4254 A is a resonance line of neutral chromium (0.0 volt excitation potential), the feature at 4247 A is a blend of scandium II with a high excitation line of neutral iron (3.3 volts), and the comparison line at 4250 A arises principally from a low level of neutral iron (1.6 volts). Another useful ratio which decreases with increasing temperature is Cr I 4275 to Fe I 4271, and another ratio which increases with increasing temperature is Ti II 4394 to Fe I 4405.

M 92 is apparently an extreme case of the peculiarities cited above, although M 15 runs it a close second. In some of the other clusters, such as M 3 and M 13, these effects are relatively mild. Within any one cluster, the spectra all show roughly the same degree of peculiarity. In general, this degree of peculiarity appears to be correlated with the redness of the red-giant branch (i. e., with series B) in the sense that those clusters whose red-giant branches lie the farthest toward the right in the color-magnitude plane are the least peculiar spectroscopically.

All of the spectroscopic evidence suggests that the weakness of the metallic lines in some of the cluster spectra is a bona fide abundance phenomenon. Quantitative abundance estimates have been made on the basis of spectra obtained at 18 A/mm in M 92 and M 13, which represent opposite extremes. Equivalent widths of suitable metal lines in an M 92 spectrum are found to be about 60 percent of those in an M 13 spectrum, implying that the metals in M 92 are at least a factor 10 less abundant than in M 13. Line ratios in these same spectra assure us that the excitation temperatures in M 92 and M 13 are about the same in spite of the difference in the color indices; perhaps the color difference is due to the fact that metallic lines chop different amounts out of otherwise similar continua.

As pointed out earlier, however, the use of abundances to account for spectroscopic differences (and therefore series B) poses a dilemma, because we also feel obliged to call upon abundances to explain the various evolutionary features which behave according to series A. Possible ways around this dilemma, such as allowing more than just the hydrogen/metals ratio to vary, have already been mentioned.

Integrated properties

In addition to the classification of color-magnitude diagrams, there are several other informative parameters which pertain to each cluster as a system or as a unit. These include integrated luminosity or magnitude, integrated color index, integrated spectral-energy distribution, integrated spectral class, mass, mass-luminosity ratio, distance, reddening, position in the galaxy, motion, spatial profile, and so on.

Since the integrated luminosity and color represent the summed effects of all of the members of a cluster, one should in principle be able to subtract the contributions of the resolved stars from the total observed luminosity, and thereby deduce how much light is contributed by members which are too faint to be individually resolved by present telescopes, say, fainter than $m_{pv}=23$. In practice, however, uncertainties in the luminosity function (i. e., in the numbers of stars per magnitude interval) are much too large and the quantity sought is much too small for such a procedure to succeed. Direct measurements of this unresolved background by itself appear to show some indications of a substantial white-dwarf population, but the uncertainties are presently too large to justify much confidence.

As one might expect from the differences between color-magnitude diagrams, the fractions of the total light contributed by the various branches differ somewhat from cluster to cluster. Typically, about half of the visual light comes from the red giants above $M_v=0$, perhaps 20 percent each from the horizontal branch and from the subgiants, and the remainder from the main sequence downward. In view of the broad range of color indices in each cluster diagram, it is not surprising that the integrated color indices of globular clusters are not identical. One cannot correctly determine the reddening of an individual cluster simply by comparing its color index with an unreddened mean.

The integrated spectral-energy distribution of a stellar system such as a globular cluster is, of course, quite different from that of a single star having the same color index. This means that, regardless of data-reduction procedures, the ordinary color index of a cluster is rather sensitive to the actual color response of the photometer used.

The spectral energy distribution of a globular cluster is also very different from that of an elliptical galaxy, indicating that the color-magnitude diagrams must be fundamentally unlike unless the distribution of stars in the unevolved region of the cluster diagram is radically different from that for an elliptical. If the diagrams are assumed to be of the same form, one can show that the ratio of the number of K stars to the number of F stars on the main sequence of an elliptical galaxy would need to be literally hundreds of times greater than on the main sequence of a globular cluster in order to account for the observed disparity in their integrated spectral-energy distributions. Since the present data can be fitted equally well by assuming unlike diagrams, the identification of the predominant population in ellipticals remains an open question. The importance of further work on this problem has already been stressed.

For much the same reason that the color index is sensitive to the wavelength bands used for the observations, the estimation of the integrated spectral class of a stellar system such as a globular cluster is dependent upon the spectral region utilized. The blue stars on the horizontal branch play a bigger role at short wavelengths than at long wavelengths. Integrated spectra of 50 clusters have been obtained by throwing the clusters sufficiently far out of focus to smear a blend of many stars uniformly over the spectrograph slit. The spectral types listed in table 1 were derived from integrated spectra obtained in this manner. Some of these spectra are currently being reexamined in an effort to take better account of the peculiarities now recognized; the present tendency is to assign them later spectral types than were formerly estimated.

An attempt has been made to determine the mass of M 92 from the dispersion in radial velocities among red giants in its nucleus. This was done by applying the virial theorem to velocities measured on 23 Palomar spectrograms of 15 stars. Some of the red giants for which two spectrograms were obtained show evidence of intrinsic velocity variations, which is not surprising in view of the photometric variations already described. As a result of these variations, the uncertainty in the true velocity dispersion is disconcertingly large. Nevertheless, with some recent refinements in theory the results yield an estimated mass of 1.4×10^5 solar units, the upper limit being perhaps twice that value. The corresponding mass-luminosity ratio is of the order of unity, which is several times smaller than the average for our own galaxy as a whole and is about a hundred times smaller than that of an elliptical galaxy. The interpretation of these comparative ratios in terms of differing populations, luminosity functions, and nonluminous contents are not yet clear.

The distances of globular clusters are conventionally estimated by assigning the cluster-type variables a mean absolute magnitude of zero, or by comparing the brightest stars with those belonging to other clusters whose variables have been calibrated. It should be remembered that the assignment of zero absolute magnitude to the cluster-type variables is only a rough approximation which should not be taken too seriously when color-magnitude diagrams are intercompared. In figure 1, for example, the cluster-type variables are a half magnitude apart because the diagrams were adjusted to place the evolutionary breaks from the main sequences at the same bolometric magnitude.

Since most globular clusters inhabit regions well outside the absorbing material in the galactic disk, the photometric moduli (blue) should, on the average, be reduced by 0.25 csc *b* in order to estimate true distances. While a statistical correction of this sort is useful when one is dealing with large-scale problems involving many clusters, it does not provide a reliable estimate of absorption for individual clusters due to the probable patchiness of the absorbing blanket in which we are imbedded. Unfortunately, other criteria of reddening and absorption such as comparison of U, B, V data with the solar neighborhood or matching of colors of the cluster-type variables are also open to question. Consequently, the existence of accurate photometric data would not by itself guarantee a precise distance for a cluster even if the absolute magnitude of the cluster-type variables were exactly known.

The fact that globular clusters differ significantly from one another in their diagrams and in their over-all characteristics suggests that they probably were not all formed under identical circumstances. It is therefore of interest to consider what clues we have as to their times and places of origin during early epochs of the galaxy. When the integrated characteristics of globular clusters are examined in terms of their positions in the galaxy, some fascinating correlations stand out immediately. In particular, the number of cluster-type variables, which is an index for classification according to series A, appears to have a marked correlation with the distance from the galactic plane. If we examine all clusters which have been searched for variables, which are not badly obscured, and whose distances are fairly well known, we find that the variable-poor clusters (say, those with 0 to 3 variables) favor regions much closer to the galactic plane than the others, hinting that they may have been formed during a slightly later stage in the dynamic relaxation of the galaxy. The sample of clusters in table 1 is not well suited for illustrating this effect because of its cutoff at 20° latitude, but the effect can still be seen; the mean distance from the galactic nucleus to the variable-poor clusters listed in the table is 9 kpc, while the mean distance for the variable-rich clusters is 19 kpc.

It follows, of course, that the various characteristics which are correlated with the number of variables tend to show this same dependence on galactic distribution. For example, the integrated spectral type, which is influenced by the relative shape and populousness of the upper branches of the cluster diagram, reveals an effect of this kind. Among the clusters listed in table 1, those possessing later spectral types (say, F 7 to G 2) have a mean distance of 11 kpc from the nucleus, while those possessing earlier types (say, A 5 to F 6) have a mean distance of 21 kpc from the nucleus. Again, the effect would be more distinct if clusters in the 10° to 20° zone were added to the sample.

If the centroid of the system of globular clusters in our galaxy is assumed to coincide with the galactic nucleus, one can check the zero point of the cluster-type variables against the present estimate of the sun's distance from the nucleus (about 8 kpc). The variable-rich clusters seem to be quite well centered on the nucleus if the conventional value of $M=0$ is adopted for the variables, but the variable-poor clusters appear to prefer a slightly brighter value, perhaps half a magnitude. While scarcely more than qualitative due to the smallness of the sample, this result is nicely consistent with figure 1.

There are several observable globular clusters inhabiting the immediate vicinity of the galactic nucleus. One or two of these may be transients just passing through, but others are suspected of being permanent residents and of being quite peculiar. It would be especially interesting to see how they fit into the over-all type-distribution picture described above.

The individual space motions of globular clusters in the galaxy are unknown because they are too distant to have reliable proper motions. Nevertheless, some general conclusions can be drawn from their radial velocities, which range from −360 km/sec to +290 km/sec. As already remarked, the globular clusters probably do not share to any large degree in the general rotation of the galaxy. The present evidence suggests that the rotational velocity of the cluster system is less than a third of the rotational velocity of the disk. It may be difficult to pin this figure down more closely due to the limited number of clusters and to their large individual motions. Relative to the clusters, the sun's orbital velocity is about 200 km/sec in roughly the same direction derived from differential rotation. The cluster system shows no indication of a general contraction or expansion.

Efforts have been made to determine whether globular clusters favor orbits of high ellipticity passing through the galactic nucleus or whether they travel in approximately circular orbits at constant radii from the nucleus. Although arguments have been advanced for both models, the present radial velocity data do not make a clear case for either. Probably the truth is somewhere in between, and perhaps the situation is further complicated by the form of the potential function of the galaxy. In any case, the time required for a cluster to make one loop or one oscillation is of the same general order as the period of galactic rotation; hence, each cluster has passed through the galactic plane quite a few times since its birth.

The spatial distribution of the stars in a globular cluster has been the subject of several observational and theoretical studies. Observationally, the data consist of star counts or surface brightness measures as a function of radius from the cluster center. To a first approximation, these quantities vary as $(\text{constant}+r^2)^{-2}$, and the corresponding integrated luminosity rapidly approaches a well-defined asymptotic limit for large r. This two-dimensional profile is very different from that of an elliptical galaxy, whose integrated luminosity continues to increase as $\log(\text{constant}+r)$ and which shows no tendency for a limit except that imposed by the domain of its neighbors.

Since the profile of a globular cluster is a manifestation of internal dynamic conditions, it is related to the numbers of stars having various masses, to their mass-luminosity ratios, and to the manner in which energy is partitioned. We know that nearly all of the light of a globular cluster comes from stars above its main sequence and that their masses should all be of the same order because they all evolved from the same region of the main sequence; thus a single mass-luminosity ratio applies fairly well to the surface-brightness profile. This has been checked by noting that the difference in integrated color between inner and outer regions of a cluster is generally small and that the radial spread of the red-giant population does not differ significantly from the spread of the subgiants and the blue stars. However, since the exchange of energy in the central region of a cluster is believed to be sufficient for equipartition, one should expect the profile for the main-sequence membership to be broader than the profile for the brighter stars, and there is observational evidence in support of this. Differing amounts of internal energy per unit mass from cluster to cluster probably account for their differing degrees of over-all compactness.

The origin of globular clusters is still shrouded in mystery. It seems fairly evident that most of them in our own galaxy were formed during an early epoch in its evolution. We do not know, however, whether they condensed out of interstellar material originally in the domain they now inhabit or whether they were created in denser central regions and ejected due to the high turbulent energy which may have existed at that time. M 87, which is a very massive elliptical in the Virgo cluster of galaxies, provides a possible clue to this question. It has two unusual features: there are an astonishing number of globular clusters associated with it, and there is a peculiar blue jet streaming from its nucleus with several pronounced globules along it. Is it possible that M 87, because of its unusual mass and energy, has a slow rate of dynamic development and is still in the stage of making globular clusters? Perhaps the range of integrated color indices of the M 87 clusters will help to decide whether any of them can be young, but the problem is observationally difficult. It is also of interest to note that the radial distribution of the globular clusters in M 87 is approximately the same as the distribution of the nonclustered population (judged from the surface brightness profile). Since the relaxation time of a galaxy is theoretically long compared with the average age of these clusters, this result implies that the conditions of formation have been such as to produce similar distributions since the beginning.

In closing, we should not neglect to consider the value of globular clusters as tools in other astronomical problems. Their usefulness in surveying the structure of our own galaxy is already evident from earlier remarks, but their importance in extragalactic studies also deserves comment. Globular clusters belonging to other galaxies are convenient distance indicators. Their luminosities can be used for intercomparing the distances of galaxies as far as the Virgo cluster of galaxies, which serves as a cosmic yardstick for everything beyond. A recent estimate based on the globular clusters associated with M 87 places the Virgo cluster of galaxies at 10 megaparsecs. If new results for more distant clusters of galaxies are adjusted to this scale value, one obtains a Hubble constant of 150 km/sec per megaparsec, whose inverse is 6.5 billion years. Much more work is needed on this problem, not only in connection with the photometry of globular clusters in remote galaxies but also in connection with establishing a better luminosity function by which the clusters belonging to different galaxies can be compared. We must also worry about whether the luminosity function for clusters is necessarily the same in all kinds of galaxies.

A fair amount of observational work has been done on the globular clusters in the Andromeda galaxy (M 31). In some respects they provide a better sample than those in our own galaxy for investigating colors, luminosities, compactnesses, motions, and distribution. The brightest are around 15th apparent magnitude, which corresponds to $M \sim -9$. They are close enough that we can even compare their profiles with those of clusters in our own galaxy to obtain an obscuration-free check on the distance of M 31.

The present paper outlines some of the problems in a very broad field. So many different workers have had a part in building our present state of knowledge that it would have been foolish to attempt the incorporation of anything approaching a complete system of bibliographical references into the present text. An excellent 80-page bibliography, by Helen B. Sawyer, already exists (Publ. D. Dunlap Obs., vol. 1, p. 383, 1947), but anyone actually planning to work in the field will also want to become acquainted with at least part of the work done since that date. Recent publications and current programs include work by the following: Arp, Artiukhina, Baade, Baum, W. Becker, Belserene, Bernstein, Cuffey, Deutsch, Eggen, Fatchikhin, Florya, Gaposchkin, Gascoigne, Greenbaum, Greenstein, Hoag, von Hoerner, Huang, Idlis, Irwin, H. L. Johnson, Kholopov, I. King, Kron, Kukarkin, Lohmann, Mayall, Melbourn, Minin, Morgan, Münch, Oort, Oosterhoff, Osterbrock, Parenago, Reddish, Roberts, Roman, Rosino, Sandage, Savedoff, Sawyer-Hogg, Schürer, Schwarzschild, Shapley, Stebbins, Swope, Tayler, Walker, Wahlquist, Wallerstein, Whitford, Wilkins, O. C. Wilson, van Woerden, and others. Some of these activities are summarized and referenced in the 1948, 1952, and 1955 reports of Commission 37 of the International Astronomical Union (see Trans. Int. Astron. Union, vols. 7–9).

Stellar Structure and Evolution

By M. Schwarzschild[1]

The theory of the internal constitution of the stars entered a basically new phase in 1938 with the discovery of the particular nuclear processes that provide the main energy sources for the stars, and, soon thereafter, with the fairly accurate determination of the reaction rates of these processes.

It had long been known that a star of given mass and chemical composition has a unique equilibrium structure. But it was not possible actually to determine this unique structure as long as one of the fundamental relations, that for the rate of energy production by nuclear processes, was unknown. Now that the necessary nuclear data are available we can not only determine the internal structure of a star in its initial state when it just starts burning its hydrogen fuel, but we can also follow, step by step, in a quantitative non-speculative manner, the evolutionary changes caused by the nuclear transmutations.

Many possibilities are now within our grasp: to interpret the Hertzsprung-Russell diagram in terms of stellar evolution, to determine the ages of star clusters and even of individual stars, to sort out the oldest stars and by analyzing them to gain insight into the composition of our galaxy at its earliest phases, and to obtain clues to the origin of the elements by a comparative analysis of the oldest and the youngest stars.

Only the very first steps have as yet been taken in this large field of new and fundamental problems. The future speed and success of the developments will depend not only on the number of specialists working in the subject and on their ingenuity but also, much more than in earlier decades, on the advances in neighboring scientific and technical areas. Clearly, more highly accurate determinations of reaction rates for a larger variety of nuclear processes will be needed from nuclear physics. Similarly, for many star clusters color-magnitude diagrams of high precision at faint magnitudes are needed from observational astronomy. In both these fields, which are fundamental to the theory of stellar evolution, progress has been very rapid and encouraging in recent years. There are, however, three other neighboring fields which should be actively cultivated if the investigation of stellar evolution in its broadest sense is to progress.

Computing facilities are our first concern. The basic problem of stellar structure and evolution can be formulated mathematically in terms of a fourth-order boundary-value problem, whose solution depends on the stellar mass and chemical composition and varies with time. To find the solution, numerical methods have to be employed. Much useful preliminary computation can be done with desk machines. The numerical work needed, however, to obtain a sufficient range of solutions with satisfactory detail and accuracy is so extensive that it cannot be tackled effectively with desk calculating machines; large electronic machines are needed. At a small number of institutes such large machines have generously been made available for pure astronomical research. Astrophysical research absolutely requires the help of large electronic computers if it is to grow from its present promising beginning to the maturity the problems demand.

The second area we need to develop is photometric spectroscopy with high dispersion to determine the chemical composition of many sample stars. This observational work, which is basic to many branches of astrophysics but which is very tedious and time consuming with traditional techniques, has progressed very slowly in recent years despite its importance. These investigations may expand as soon as it becomes practicable to use electronic image

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tubes for this purpose. The advent of this new instrumentation, however, will have its full revolutionizing effect only if at the same time a larger number of technicians becomes available to build and maintain the new instruments and to reduce the data.

The third field is that of the turbulent phenomena in stellar atmospheres. Recent investigations have shown that these phenomena are of interest not only for the theory of stellar atmospheres but also play a decisive role in determinations of the stellar radius for many types of stars; hence they are essential for the complete theory of stellar structure. Laboratory experiments and theoretical investigations in hydrodynamics have resulted in great progress, during the last decade, in our understanding of turbulence. However, in this difficult subject extrapolation from the laboratory to the stars will always involve some risk; therefore, direct observations of turbulence in stellar atmospheres would be highly valuable. This is, in principle, possible for the photosphere of the sun. In practice, however, it is extremely difficult because of interference from the disturbances of the earth's atmosphere. In consequence, very little progress has been made in this field during the past 50 years. Now, however, observations from high-altitude vehicles appear to open up new possibilities; if they can be realized, the final major difficulty in the theory of the stellar interior may be resolved.

At present, no serious block seems probable in the necessary development of any of these fields. Thus, research in the theory of stellar structure and evolution presents many unsolved, but solvable, basic problems and may result in a great advance in answering objectively certain cosmological questions. The rate of successful progress in this field will depend essentially on the ingenuity and the number of workers who apply themselves to it.

Radio Sources

By John D. Kraus[1]

Perhaps you have seen a distant landscape compared in two photographs, one taken in ordinary light and the other in infrared. In the ordinary photograph the distant objects are largely hidden by haze, but in the infrared picture the distant hills and valleys stand out clearly. Infrared rays are longer than light rays and more easily penetrate the haze. Radio waves are millions of times longer than light and have an even greater power of penetration than infrared. Because of this fact, radio—applied to astronomy—cuts through the cosmic haze caused by the clouds of gas and dust in interstellar space and presents a view of vast regions that will always remain hidden to ordinary telescopes. Radio has, in effect, opened a new window on the universe.

It was about 1873 that Maxwell postulated the possibility of radio waves. About 15 years later Hertz produced them and demonstrated their transmission over a distance of a few feet. In 1901 Marconi received radio signals across the Atlantic and an era of worldwide radio communication was begun. Thirty years later Jansky detected radio waves from the center of our galaxy and initiated a new method for exploring the cosmic universe. It was 60 years from Maxwell to Jansky, from a man's idea to its cosmic application. And today, some 20 years after Jansky's discovery, this application of radio to astronomy is rapidly developing into a new science called radio astronomy.

Radio observations of outer space are made with an antenna and a radio receiver. The antenna gathers and focuses the radio waves as does the lens of an optical telescope, while the receiver detects and records the signal much as does the photographic plate of an optical telescope. By analogy, the antenna and receiver may be called a radio telescope.

As observed with a radio telescope, the sky looks strangely different. None of the familiar stars of the night sky are observable, but in their places are many radio sources forming totally unfamiliar constellations. Some of these sources can be identified with supernova remnants and other gaseous nebulosities and with extragalactic nebulae. There are a couple dozen sources thus identified, at least tentatively, but there are hundreds more not identified with any optical object and the bulk of them may never be. It is as though radio and optical telescopes "see" two different universes with only an occasional object observable by both. And those objects that can be detected by both appear to be of different sizes and shapes in the two telescopes. For example, the sun has a visual diameter of about one-half degree, but at certain radio wavelengths the diameter measures several degrees because the radio waves originate in the upper regions of the corona or solar atmosphere.

If our eyes were sensitive to radio waves instead of to light, the winter sky would appear somewhat as suggested in figure 1. The contours are lines of equal surface brightness showing the radio background. The background is a maximum along a ridge close to the plane of our galaxy or Milky Way system. On this background are dots and circles that show the position of some of the strongest or brightest radio sources. Their brightness is indicated by a radio magnitude scale analogous to the visual magnitude scale. Some of the sources are of an extended type with diameters of more than 1°. These are shown by the open circles. Others are more localized or pointlike, and these are indicated by the solid dots. A few sources have been identified with optical objects and

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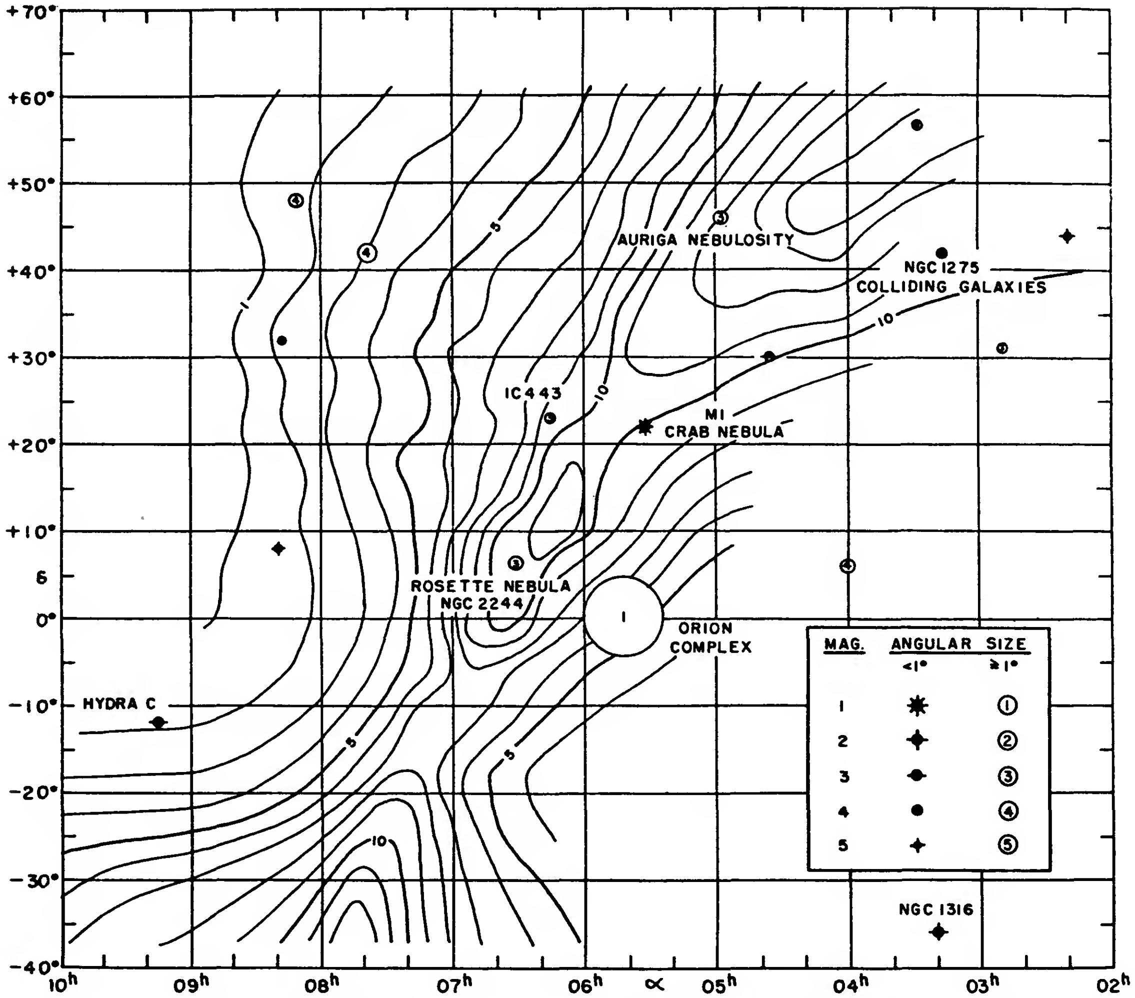

FIGURE 1.—Map of the radio sky at a wavelength of 124 cm made with the radio telescope at Ohio State University (Ko and Kraus, 1955).

for these the optical designation is given. Note for example the Crab Nebula (M 1), which is a supernova remnant, or the gaseous nebulae designated IC 443 and NGC 2244. However, many of the sources on the map have not been identified with an optically observable object and this is true for most radio sources, particularly the weaker ones not shown on the map.

The identification of radio sources with optical objects is a challenging problem that requires close cooperation between radio and optical astronomers. Accurate radio position and size determinations are vital in this work. One of the outstanding achievements of radio astronomy was the identification of the second brightest radio source (other than the sun) with a faint pair of colliding galaxies at a distance of some 200 million light-years. Teamwork by radio astronomers at Cambridge, England, and Sydney, Australia, and optical astronomers at Mount Palomar was required for several years before the identification was made (Baade and Minkowski, 1954). If this object were at 10 times the distance it would still be a readily observable radio source but would then be at or beyond the range of the largest optical telescope. It is this fact which suggests that radio telescopes may open to exploration vast regions of space that lie beyond the range of any optical instruments.

The known radio sources are now numbered in the hundreds, with lists published by Ryle, Mills, Bolton, Brown, Haddock, and Ohio State University. However, those that are reliably established are much less numerous and those identified with optical objects are only a dozen or two (Pawsey, 1955).

The work of radio exploration has barely begun and great discoveries lie ahead as larger radio telescopes are built and more radio sources are found. Many of these sources may emit too little light for optical detection or may be hidden by clouds of cosmic dust, while many others may be at distances beyond the range of any optical telescope. Studies of these sources, individually and collectively, are bound to supplement and alter our purely optical picture of the universe in a most significant way. From Maxwell to Hertz, to Marconi, to Jansky, to the outermost reaches of our universe are big steps, but they do not end there and new advances are being made daily. Perhaps you may become the radio astronomer who will make the next big step.

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