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(With One Plate)

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(Publication 3914)

CITY OF WASHINGTON
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On several occasions one or both of us have attempted to observe the distribution of heat in the spectra of stars, with a view to the estimation of their approximate temperatures and related conditions.[1] On two other occasions Abbot and Stebbins, and Abbot and Hoover, made certain observations of the sort, but these were unfortunately vitiated by effects of stray light. In all these experiments we had the privilege of observing at the Coudé focus of the 100-inch telescope on Mount Wilson, Calif. We acknowledge with grateful thanks the encouragement and assistance given us by the staff of Mount Wilson Observatory.

On September 7, 8, and 9, 1947, we made measurements with the radiometer on eight stars. The present publication is a preliminary report, showing that the way seems open to obtain good results in this manner. We hope to amplify the results and greatly improve their accuracy in a future expedition which we propose to undertake in September 1948.

In Smithsonian Publication No. 3843 (Smithsonian Misc. Coll., vol. 104, No. 22) one of us described the apparatus proposed to be used in 1946. The expedition was delayed until 1947 because it was impossible to obtain the compound prism described in Publication 3843. A substitute for it was obtained in January 1947. Various delays in setting up the apparatus at Mount Wilson in 1947 prevented us from experimenting long enough to get maximum sensitiveness with the radiometer. Hence not more than a centimeter deflection was obtained for any of the stars observed, and consequently the minute vibrations and Brownian movements of the radiometer caused rather large percentage accidental errors in the observations, as will appear below. Nevertheless the results obtained were positive, and

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[1] Smithsonian Misc. Coll., vol. 74, No. 7, 1923; Contr. Mount Wilson Observ., No. 280, 1924; Contr. Mount Wilson Observ., No. 380, 1929.

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fairly consistent. They lead us to expect that with more time for preparation, and more numerous observations in 1948, very interesting results may be obtained.

As pictured in figure 1, Publication 3843, the proposed prism comprised a cemented combination of a 60° Jena U.V. Crown 3199 prism with an opposed Bausch & Lomb light flint L.F.3 prism of 22° refracting angle. We knew the dispersion characteristics of the Jena glass prism from our bolographic work on the solar constant, and we estimated those of the L.F.3 prism by comparison with glasses listed on page 359, Smithsonian Physical Tables, 8th revised edition. From these data the curves of figure 2, Publication 3843, were computed. It proved impossible to procure Jena 3199 glass, and the cemented combination finally prepared by Bausch & Lomb was a 60° B. & L. B.S.C.1 borosilicate crown with an opposed 23° B. & L. L.F.3 light flint prism. We were unable to determine its dispersion through the desired range at Washington before the expedition, though it was partially observed with great accuracy by Hoover and Greeley. Hence at Mount Wilson we were unable to select knowingly

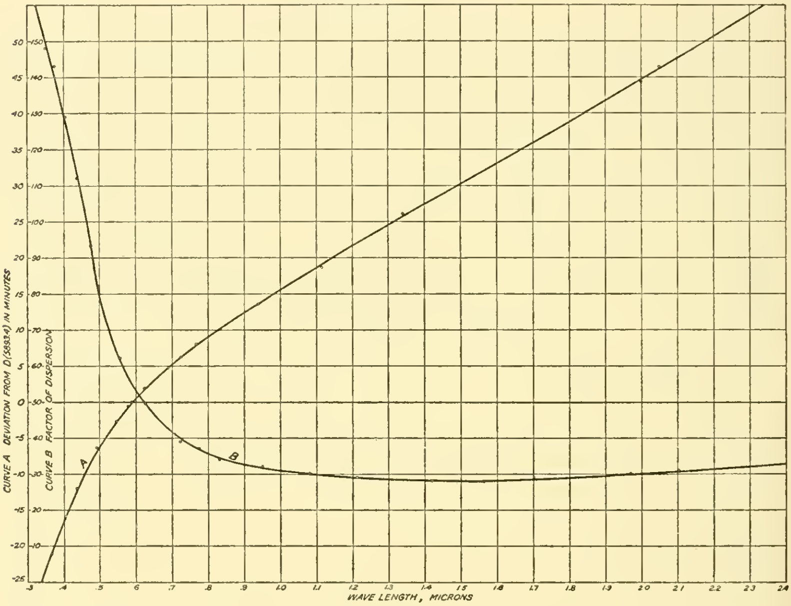

FIG. 1.—Curves of prismatic deviation, A, and wave length, and of dispersion factor, $\frac{d\theta}{d\lambda}$, B, and wave length.

the best wave lengths to observe in the stellar spectra, and we chose eight places more or less by guess. After completing our observing on September 7, 8, 9, Abbot took the prism to our station on Table Mountain, Calif., and with A. F. Moore made bolographs of the solar spectrum. From these bolographs, combined with the work of Hoover and Greeley, the curves shown here in figure 1 were computed.

The combination prism actually prepared is not as uniform in its dispersion as that which we hoped to obtain, whose characteristics are shown in Publication 3843, figure 2. The actual prism has a range of $\frac{d\theta}{d\lambda}$ of fivefold in dispersion between wave lengths 3300 and 22,000 A. Still it is more than twice as uniform in dispersion as a simple 60° Jena Crown glass prism, such as we use for solar-constant work, and it is almost completely uniform in dispersion between the wave lengths of the D sodium lines and 22,000 A.

Not knowing the dispersion of the prism before the observing of September 7, 8, 9, we chose places which afterward were found to have the following wave lengths:

TABLE 1.—*Places observed in stellar spectra*

Prismatic deviation from the D lines..........	−13′.5	−10′.8	−8′.4	−5′.4	−1′.8	+1′.8	+7′.1	+9′.5
Wave lengths, microns..	0.423	0.448	0.471	0.505	0.559	0.622	0.750	0.817
Exposure range, microns	0.0140	0.0154	0.0172	0.0206	0.0248	0.0324	0.0416	0.0444

The radiometer vanes, as stated in Publication 3843, were each 0.20 millimeter high and 0.44 millimeter wide. The spectrum, as it fell upon them, extended vertically, and was intercepted by the dimension 0.20 millimeter. With the spectroscope as about to be described, this corresponded to an exposure of 2′.07 in the spectrum, and the exposures range in wave length as given in line 3, table 1 above. Thus within the wave-length interval observed in 1947 the range of dispersion was about threefold.

With a prism of such small total dispersion it was important to avoid stray light scattered from one region of spectrum to another. This we accomplished by greatly lengthening the travel of the beam after its dispersion by the prism, before focusing it by the image-forming lens. The graph, figure 2, shows the optical path schematically. It will be perceived that the range of spectrum which could fall within the radiometer is limited by the angle subtended by the lens *h* at a distance of 61 feet from the prism. This angle is 12′. At

0.423μ this corresponds to 0.08μ and at 0.813μ it corresponds to 0.25μ. However, the ends of these spectrum intervals were much weakened by obstructions within the radiometer itself. So the spectrum that could be seen in the eyepiece of the radiometer appeared only about three times as high as the radiometer vanes. The other parts of the spectrum, which might have scattered extraneous light onto the radiometer, were lost in part by overrunning the mirror *f*, and those remaining were lost in large part by overrunning the mirror *g* and lens *h*. Such fragments of these extraneous spectral rays as fell on the mirror *f* and the mirror *g* were scattered over the surface of these mirrors at such angles that they must have been almost entirely lost from the observed wave-length intervals falling on the radiometer vanes. In place of a slit at the Coudé focus we used a round aperture 1.5 millimeters in diameter, so as to avoid mainly variable losses of light with changes of atmospheric "seeing."

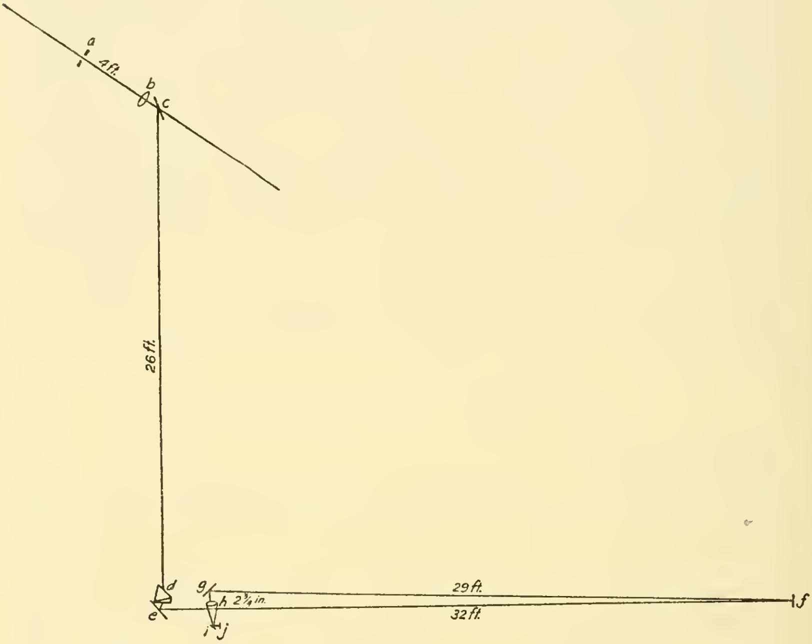

FIG. 2.—Diagram of the optical path. The star beam focused on the slit at *a* is made parallel by the quartz lens *b*. Thence it is reflected by the mirror *c* through the prism *d* onto the mirror *e*, thence to the mirrors *f* and *g* and through the quartz lens *h* to the mirror *i* which reflects it to focus on the radiometer vane at *j*.

The radiometer itself has been sufficiently described in Publication 3808. Abbot constructed a brass gadget with which he was able to dismount the radiometer suspension and pack it into a little wooden box without any chance of breaking the invisibly fine quartz fiber, or the delicate suspension. In this box he carried it in his suitcase to Mount Wilson, and within a half hour after arrival at the observing room hung it, entirely unharmed, within the radiometer case, previously leveled. Two powerful magnets reduced the time of single swing in air at radiometer pressure (about 0.2 mm. Hg.) from about 2 minutes when free, to about 10 seconds under magnetic control. With two other magnets coarse and fine adjustments in azimuth could be made, so that the spot of light for reading purposes could be brought readily to any part of the reading scale at 5 meters distance. The light spot was furnished by one short length of the filament of a 200-watt Mazda lamp, situated about 2.5 meters above the radiometer. Two pinhole diaphragms 2 meters apart limited the beam to about 6 millimeters diameter where it fell upon the quartz plate through which it entered the radiometer. The spot was further largely shorn away there by other obstructions. Still it is feared that too much light entered the radiometer in this beam. Variations of voltage of the lamp may have produced radiometrically minute vibrations of the suspension. The ordinary range of these vibrations on the scale at 5 meters was less than 1 millimeter, and sometimes hardly observable at all, yet it is hoped to reduce this range in future experiments.

The positions of the light spot on the scale, as the spectrum was swung from one vane to the other of the radiometer by pulling a cord, were read on the special device described and shown in figure 4 of Mount Wilson Observatory Contribution No. 380, of 1929. The places of the light spot were observed on a divided circle of 100 divisions, one complete revolution of which corresponded to a movement by a screw of $\frac{1}{8}$ inch, approximately 3 mm. So the positions were recorded to 0.03 millimeter. Maximum deflections in the spectra of stars ranged from about 100 to about 300 divisions. It was found in reducing the observations that the average individual deviation from the mean in a set of readings was 42 divisions. Generally four swings from one vane to the other were made at each wave length. Hence the average deviation of the mean of such a set of readings would be of $\frac{42}{2}=21$ divisions. This is from 20 down to 7 percent of the deflection at maximum in the spectra of the stars observed.

This percentage accidental error is obviously far too great to give satisfactory spectral energy curves. In future work we hope to reduce it: 1, by increasing the radiometer effect by substituting hydrogen for air, and adjusting the hydrogen pressure for largest deflection at a time of single swing of 12 seconds; 2, by excluding much more of the light from the reading-beam lamp; 3, by having means to set the focus of the image-forming lens from a distance, without approaching personally near the radiometer (we found indications of a slight temperature effect from this cause in 1947). We intend also to choose other wave lengths, so as to cover the spectrum of blue and white stars in the ultraviolet, and of yellow and red stars in the infrared; 4, by taking twice as many readings at each wave length; 5, by observing the same star on several more nights.

We now give as a sample the readings on the star Arcturus at wave length 4710 A. The numbers express the positions on the scale in whole turns and fractions thereof, and the differences caused by shifting the spectrum from one vane of the radiometer to the other.

TABLE 2.—*Sample readings at wave length 4710 A. on Arcturus*

Time	Right vane	Left vane	Deflection	Deviation from mean
$7^h\ 17^m\ 15^s$	41.78	41.07	0.71	11
45				
7 18 30	41.90	41.53	0.37	23
19 00				
7 19 30	41.97	41.78	0.19	41
20 15				
7 20 45	43.29	42.17	1.12	52
21 30				
		Mean........	0.60	0.32

Such mean observations were first multiplied by correcting factors for prismatic dispersion, so as to reduce them to a uniform scale of wave lengths. It was then needful to correct the results for atmospheric transmission, to reduce them to outside the atmosphere. For this purpose all the solar-constant observations of the month of September made at Mount Wilson in the years 1915, 1916, 1917 were considered. From Annals, Astrophysical Observatory, volume 4, table 37, the mean values of atmospheric transmission for September in these three years were computed as follows:

TABLE 3.—*Mean atmospheric transmission*

Wave length	0.35	.40	.45	.50	.60	.70	.80	1.00	1.20	1.60
Transmission	.587	.718	.797	.847	.890	.935	.956	.970	.975	.980

These values were plotted, and values were interpolated at the wave lengths observed in the stellar spectra. Air masses were computed corresponding to the median time of observation of each wave length for each star. From these data factors were computed to reduce all the mean deflections to what they would have been if observed outside the atmosphere.

One other correction was desired to allow for the effect of the imperfect reflection of the numerous mirrors in the optical train. We had intended to determine this by observing the solar spectrum with the identical apparatus, and comparing with the known energy spectrum of the sun. But we were unsuccessful in this experiment on the one afternoon when we could try it. Hence as a substitute we estimated the transmission of the optical train as follows. In a future expedition we intend to observe the solar spectrum very carefully.

Including the telescope and spectroscope there were eight aluminized mirrors in the train. We shall neglect selective absorption and reflection in the two fused-quartz lenses and the prism, thinking that the selective differences, while doubtless not negligible, would be small in these parts within the wave-length range 4230 to 8170 A. All the mirrors were recently aluminized and may be assumed to have the following reflection characteristics:

TABLE 4.—*Factors for optical train*

Wave length	.423	.448	.471	.505	.559	.622	.750	.817
Reflection %	94	94	94	94	93	93	92	92
Eighth power of %....	.61	.61	.61	.61	.56	.56	.51	.51

Owing to the large percentage accidental error of the observations, and our expectation of publishing greatly improved results next year, we do not give here the results for individual stars. We divide the eight stars in groups with regard to spectral class. Moreover, in taking mean values within the groups, we reduce the stars to about equal levels of brightness, by considering their respective magnitudes. Applying these several reductions we arrive at table 5.

TABLE 5.—*Average energy distribution for spectral types, as of outside the atmosphere*

	Energy values for given groups of stars and spectra			
Wave length	Rigel B_8 Sirius A Vega A	Altair A_5 Fomelhaut A_3	Capella G	Arcturus K Aldebaran K_5
.423	336	105	3	99
.448	162	266	35	127
.471	179	72	82	123
.505	69	105	103	159
.559	20	115	73	138
.622	41	82	73	67
.750	...	...	92	49
.817	...	...	86	57

FIG. 3.—Mean curves of prismatic energy and wave length for groups of stars of various spectral classes.

These values are shown graphically in figure 3. That they do not fall in smooth reasonable curves of energy distribution is of course apparent, but is easily understood by recalling that the average deviations of mean values range from 20 down to 7 percent of the maximum ordinates for the individual stars.

Nevertheless the curves show a progressive displacement of the maxima toward the red for advancing spectral types. Moreover the maximum for Capella, probably occurring at a little shorter wave length than 0.505 micron, is close to that of the sun at 0.476, both stars being of spectral type G. As stated above, we regard these tentative results as offering much promise for the proposed expedition of 1948, and still more if it should later be possible to use the 200-inch reflector on Mount Palomar.

General View of the Radiometer Set-up within the Constant-temperature Room of the 100-inch Telescope

At *a* the brilliant Mazda lamp, with tube ending at *b* with pinhole diaphragms at either end of the tube. At *c* a mirror to reflect spectra directly downward through the quartz lens at *d* into the radiometer case at *e*. Opposite *f* are mirrors to reflect the reading beam 5 meters to the scale and reading device *h*. At *g* is the micrometer to set and read spectrum positions. Opposite to *i* is the cord for moving the spectra from one radiometer vane to the other.