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Institute for Space Studies
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THE EARLY HISTORY OF THE SUN*

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The early history of the sun is related to many aspects of astrophysics and in particular to the origin of the solar system. Ideas about its origin have been many, and these have been extensively debated for a little more than three centuries, going back to the time of Descartes. But the subject is still wrapped in mystery. The sun's role in problems of the origin of the solar system seems somewhat less complicated than those played by the planets, yet it seems safe to say that not until we understand how the sun was formed will we understand the formation of the planets.

There have been two general classes of theories concerning the origin of the solar system. One involves the theory that there was a close passage of another star near the sun during which an enormous amount of gas, from which the planets subsequently condensed, was torn from the sun. This idea, first put forward by Buffon about two centuries ago, has generally fallen into discard. Among the reasons for this is that the gas torn out of the sun would be much more likely to disperse in space than to condense and form planets, and it would contain no deuterium of the sort that we find in the heavy water mixed into the oceans. Worth noting in passing is that in this type of theory the early history of the sun would be unrelated to the formation of the planets.

In the other class the theory is that there was a condensation of interstellar gas and dust out of space, and both the sun and planets are formed from this. The conservation of angular momentum during the condensation process may be expected to flatten the condensed system into a disc with general dimensions of the order of

* The 30th annual James Arthur Lecture on the sun, delivered at the Smithsonian Institution on March 10, 1965.

those of the solar system. Some version of this general class of theory is generally believed by astrophysicists working on the problem today.

It is very instructive to look at a color photograph of a distant spiral galaxy of the general sort that is thought to resemble our own galaxy. Such a picture will show many dark absorption lanes in the general plane of the galaxy produced by dust in the space between the stars which is mixed with great quantities of interstellar gas. In addition to this dust and gas, the light coming from the central portions of the galaxy will tend to be rather yellowish or even reddish, with a large central bulge above and below the plane of the galaxy, indicative of the general class of stars that astronomers call red giants. The starlight coming from farther out in the vicinity of the gaseous galactic disc tends to be much bluer. Astronomers describe the stars producing this light as young blue giants. The red giant stars which cluster toward the center are in fact very old stars which were formed many billions of years ago. They are not much, if any, more massive than the sun. However, the young blue giants are much more massive and also enormously more luminous. They radiate energy at such a prodigious rate that they will exhaust their hydrogen nuclear fuel in periods of only a few million years. This is why we are certain that they were formed very recently in the past.

Astronomers use a variety of techniques in trying to discover how old our galaxy may be. Most of these techniques are associated with attempts to determine how long ago the oldest stars in the galaxy were formed. Such methods depend upon a variety of theoretical and empirical methods. While they cannot be trusted too closely, they indicate that the oldest stars in our galaxy seem to have been formed at least 10 billion years ago, and perhaps as much as 25 billion years ago.

The sun lies in the central plane of our galaxy, in the neighborhood of the gas and dust and newly formed blue giant stars. If we assume that the sun was formed at the same time as the remainder of the planetary system, it is then possible to determine the age of the sun by standard radioactive dating techniques. Such techniques measure the relative abundances of radioactive isotopes and their decay daughters in meteorites and in rocks derived from the mantle of the earth. The greater the amount of the radioactive daughter which has accumulated in the vicinity of its parent, the older is the age of the material. Measurements of this kind indicate that the solar system is 4.5 billion years old, thus much younger than the galaxy.

Most attempts to reconstruct the history of our galaxy tend to indicate that star formation rates were probably much higher during the early history of our galaxy than they are today. Hence it seems likely that the general physical conditions in our galaxy at the time the solar system was formed were rather similar to those we see in the galaxy today. This conclusion is very important in attempts to unravel the early history of the solar system, since it gives us a definite set of physical conditions that we can logically postulate for pre-solar-system history. Without such definite assumptions it would be difficult to know where to start.

There are regions in the interstellar gas in our own galaxy where the gas density has become quite high. We see such a region—the Orion Nebula is one—as a shining nebulosity because the gas is illuminated by nearby hot stars. It is possible to use very simple physical arguments to determine whether gas is likely to form stars in regions such as this.

Star formation will require any cloud of gas in space which is to participate to become unstable against collapse to very much higher densities. The forces which tend to bring about this collapse are gravitational in nature. The denser is the given amount of mass, the greater are the self gravitational forces on that mass. Alternatively, if we consider gas of a given density in space, then the larger the cloud containing that gas density, the greater will be the self-gravitational forces tending to pull that matter together.

There are also forces which tend to expand a cloud of gas in space. The heat energy contained by the gas which is absorbed from nearby stars is sufficient to bring about expansion. In the ultraviolet region of the spectrum which is emitted from such a star, the radiation will ionize all of the hydrogen in the vicinity of the star. (Hydrogen constitutes about three fourths of the mass of the interstellar gas.) The absorption of ultraviolet radiation will heat it to a temperature of about $10,000^{\circ}\text{K}$., and it would tend to expand very violently. However, the ultraviolet radiation beyond the ionization energy of the hydrogen is used up in this ionization after traveling some distance away from its parent star. Beyond this distance the hydrogen is not ionized, and starlight is sharply cut off at the hydrogen ionization limit. This starlight is still energetic enough to ionize certain other atoms, such as carbon, silicon, and iron, and this ionization process still imparts some heat to the gas. It is sufficient to maintain the temperature of the neutral hydrogen regions somewhere in the vicinity of 100°K .

In order to determine when star formation is likely, we must determine when the gravitational forces that tend to pull the gas together will overcome the thermal forces that tend to expand it. Most of the time the thermal forces predominate and the bulk of the interstellar gas clouds are stable against collapse. Occasionally, in a gas cloud which is dense enough or sufficiently massive, the gravitational forces predominate, and hence we expect such a cloud to collapse. However, we learn from precise physical analysis of the situation that the minimum mass of interstellar gas required to make the gravitational forces predominate is at least a few hundred times the mass of the sun, and it may be as high as 100,000 or more times. Thus the gas which starts to condense in space is much more massive than a star of the order of mass of the observed star clusters, and typical stars would have to be obtained from such a cloud after a fragmentation process.

When we look at a detailed picture of the interstellar gas clouds, we see what appear to be many fine small irregularities in them. These irregularities are likely to represent both density and velocity fluctuations in the gas. It is these irregularities which are likely to cause the gas cloud to break up into many small pieces when it collapses in space. We would identify such pieces as stars which will form and presumably become like our sun.

Figure 1 indicates schematically what is likely to happen to one of these fragments as it contracts. At the beginning of the sequence the fragment is shown to be nearly spherical, but it is collapsing at the center. We also suppose the fragment to be rotating to some extent. Such rotation will be a consequence of the conservation of angular momentum in the fragment from the time that it was a part of the original interstellar gas cloud, which is likely to be rotating at least as much as would be required to complete one rotation per revolution around the center of the galaxy. The interstellar gas clouds appear to be permeated by magnetic fields which connect one piece of gas to its neighbor and thus tend to make the different parts of matter move together on a large scale. If there is turbulence in the gas, this can easily increase the amount of angular momentum in any small part of the mass. The later stages of the collapse indicated schematically in figure 1 will show that as the collapse continues, the rotation will cause the fragment to become a flat disc. This is because the gas near the edge of the disc is spinning rapidly enough so that the centrifugal forces associated with the spin are sufficient to

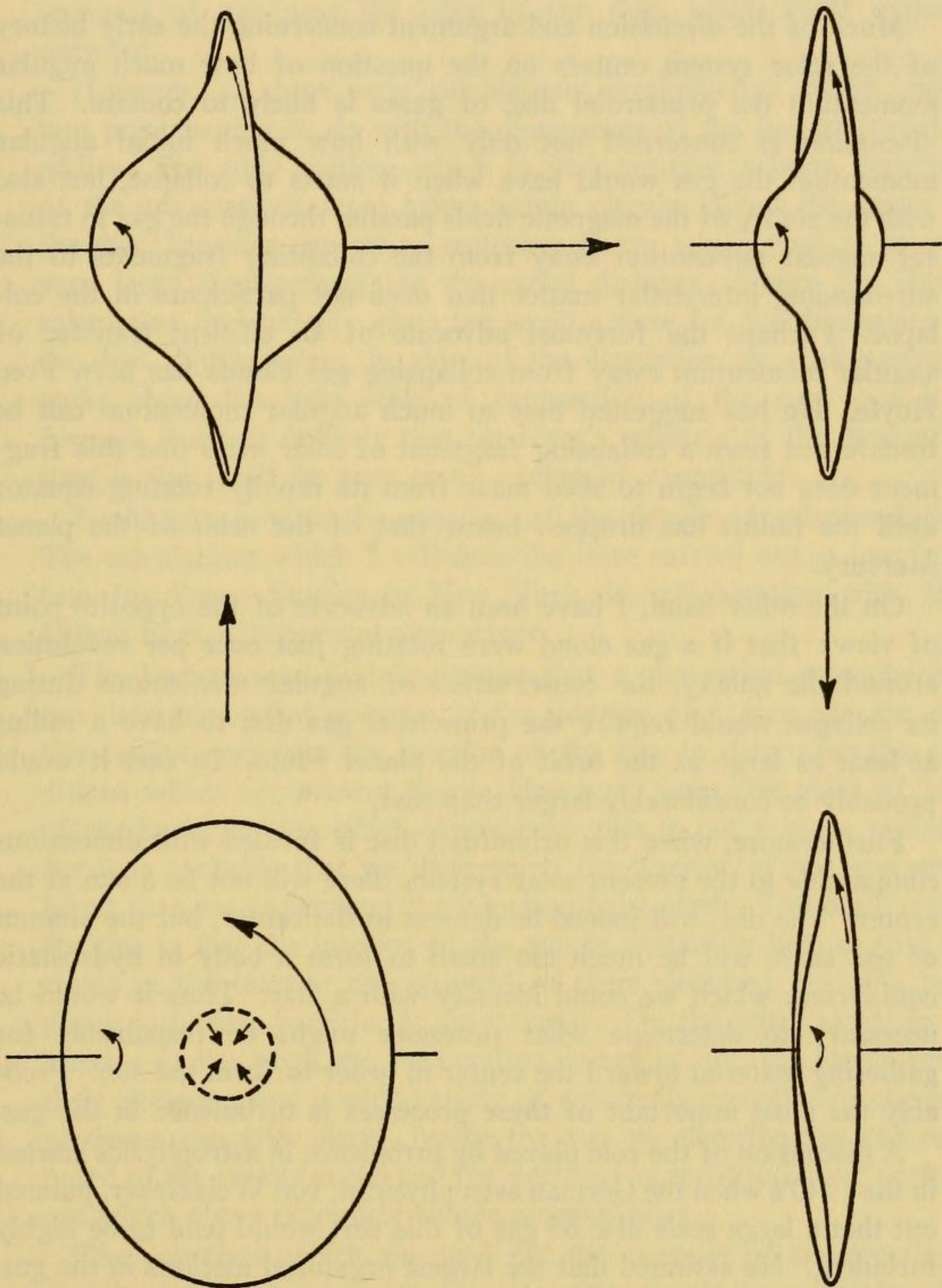


FIG. 1.—Schematic sequence of shapes as a fragment of an interstellar gas cloud collapses and flattens to a disc.

balance the gas against the gravitational forces which tend to pull it inward.

Much of the discussion and argument concerning the early history of the solar system centers on the question of how much angular momentum the primordial disc of gases is likely to contain. This discussion is concerned not only with how much initial angular momentum the gas would have when it starts to collapse, but also with the ability of the magnetic fields passing through the gas to transfer angular momentum away from the collapsing fragments to the surrounding interstellar matter that does not participate in the collapse. Perhaps the foremost advocate of an efficient transfer of angular momentum away from collapsing gas clouds has been Fred Hoyle. He has suggested that so much angular momentum can be transferred from a collapsing fragment of solar mass that this fragment does not begin to shed mass from its rapidly rotating equator until the radius has dropped below that of the orbit of the planet Mercury.

On the other hand, I have been an advocate of the opposite point of view: that if a gas cloud were rotating just once per revolution around the galaxy, the conservation of angular momentum during its collapse would require the primordial gas disc to have a radius at least as large as the orbit of the planet Pluto. In fact it would probably be considerably larger than that.

Furthermore, when this primordial disc is formed with dimensions comparable to the present solar system, there will not be a sun at the center. The disc will indeed be densest in the center, but the amount of gas there will be much too small to form a body in hydrostatic equilibrium which we could identify with a star. Thus it would be necessary to determine what processes might be responsible for gathering material toward the center in order to form the sun. Probably the most important of these processes is turbulence in the gas.

A discussion of the role played by turbulence in astrophysics started in the 1940's when the German astrophysicist, von Weizsäcker, pointed out that a large scale disc of gas of this sort would tend to be highly turbulent. He assumed that the largest organized motions in the gas, the turbulent eddies, would have dimensions comparable to the distances between the planets. Basing his calculations upon von Weizsäcker's ideas, ter Haar calculated that it might take only about 1,000 years to dissipate the primordial solar nebula and form the sun. Dissipation tends to bring matter inward in the disc because turbulence tends to make the gas in the disc rotate as a rigid body. The disc can

only dissipate providing mass flows inward and angular momentum flows outward and becomes concentrated in smaller and smaller amounts of gas near the edge of the disc, which itself expands outward.

However, all these early calculations overlooked a rather important point having to do with the dimensions of the largest turbulent eddies. The eddy motion, which in part requires a large departure of the gas motions from being purely circular about the center of the disc, becomes subject to restoring forces which tend to prevent very large displacements in the radial distance. Hence ter Haar's calculation undoubtedly gives too small a time for the dissipation of the disc. Nevertheless, in view of the discussion we shall presently make about the time scale of contraction of the sun once it is formed, it seems unlikely that ter Haar's estimate of the dissipation time is too small by very many orders of magnitude.

I will turn now to the question of the details of solar evolution. The calculations which I will describe were carried out at our Institute for Space Studies in New York, in collaboration with Mrs. Dilhan Ezer, a theoretical astronomer.

The layman may find it strange that a theoretical astrophysicist can determine what goes on in the interior of a star like the sun. We cannot peer into the interior of the sun to determine the conditions which are present there. However, from the point of view of the basic physics which is involved, this is not a great problem, for it is probable that we understand the interior of the sun much better than we understand the interior of the earth. The basic reason for this is that the interior of the sun is extremely hot, so that the atoms in the interior are stripped of their electrons, and the basic physics of these particles is very simple. On the other hand, in the interior of the earth the temperature is not so hot, the atoms retain their electrons, and a wide variety of extremely complicated chemical processes can take place. Inside the sun we describe the gas composed of the atomic nuclei and the electrons as constituting a "perfect" gas which obeys extremely simple physical laws.

The equations which we need for the purpose of constructing a model of the solar interior are also very simple in principle. The equation of hydrostatic equilibrium tells us that the pressure at a given level in the solar interior must be just that amount which is necessary to hold up the layers that lie farther out. It must also be so arranged that there is a steady and continuous energy flow out of the interior of the sun. The temperature must fall off in such a

way that the energy generated in the deep interior of the sun flows to the surface in a smooth and steady fashion.

There are basically three different ways in which heat can flow in the interior of the body. These are conduction, convection, and radiation of heat. In the interior of a star like the sun conduction is not important, but both radiative and convective transfer of heat are. Ordinarily, if the temperature does not change very rapidly from one point to another, only radiative heat transfer takes place, in which heat is radiated in one place and reabsorbed in another place, with a small tendency for a net flow of radiation in the direction of decreasing temperature. However, if the temperature does vary greatly between two points, transport of heat can take place by convective transfer, in which there is a bulk motion of the gas between the two points.

What one has to do in order to construct the model of the sun is to put these various physical ideas together and to determine a solution which satisfies the basic mathematical equations. Several years ago one used to sit down at a desk calculator and grind away on its handle until, after many trial and error calculations, a satisfactory run of physical variables through different parts of the star could be found which produced a fairly satisfactory model. Now we have electronic computers to do all this drudgery, and hence we make the drudgery much greater by trying to improve the physics that is put into the problem by making it as realistic as possible.

One of the critical points in the construction of models for the early evolution of the sun is the opacity of the surface layers. The opacity is a measure of the ability of the material to absorb the radiation that is trying to stream through it. Figure 2 shows some opacities which are relevant to the problem. Each one of the lines shows the opacity for material of given density as a function of temperature. Note that the opacity tends to be very high for temperatures between 10^4 and 10^5 degrees. At lower temperatures the opacity falls off greatly.

This is the key to an argument which was given four years ago by a Japanese astronomer, C. Hayashi. He pointed out that when a star like the sun was very big just after it had formed by contraction of interstellar gases, it could not have too low a temperature on the surface. This argument can be supported by the following kind of reasoning. Suppose the surface temperature to be very low, close to 1,000 degrees. The opacity of the surface layers would then be extremely small and we would be able to see very deep into the star.

As we looked into the deeper layers, we would see material of increasingly higher temperature, and also of increasingly higher opacity. When the opacity became high enough, several thousand degrees, we would be unable to see into still deeper layers. Consequently, the

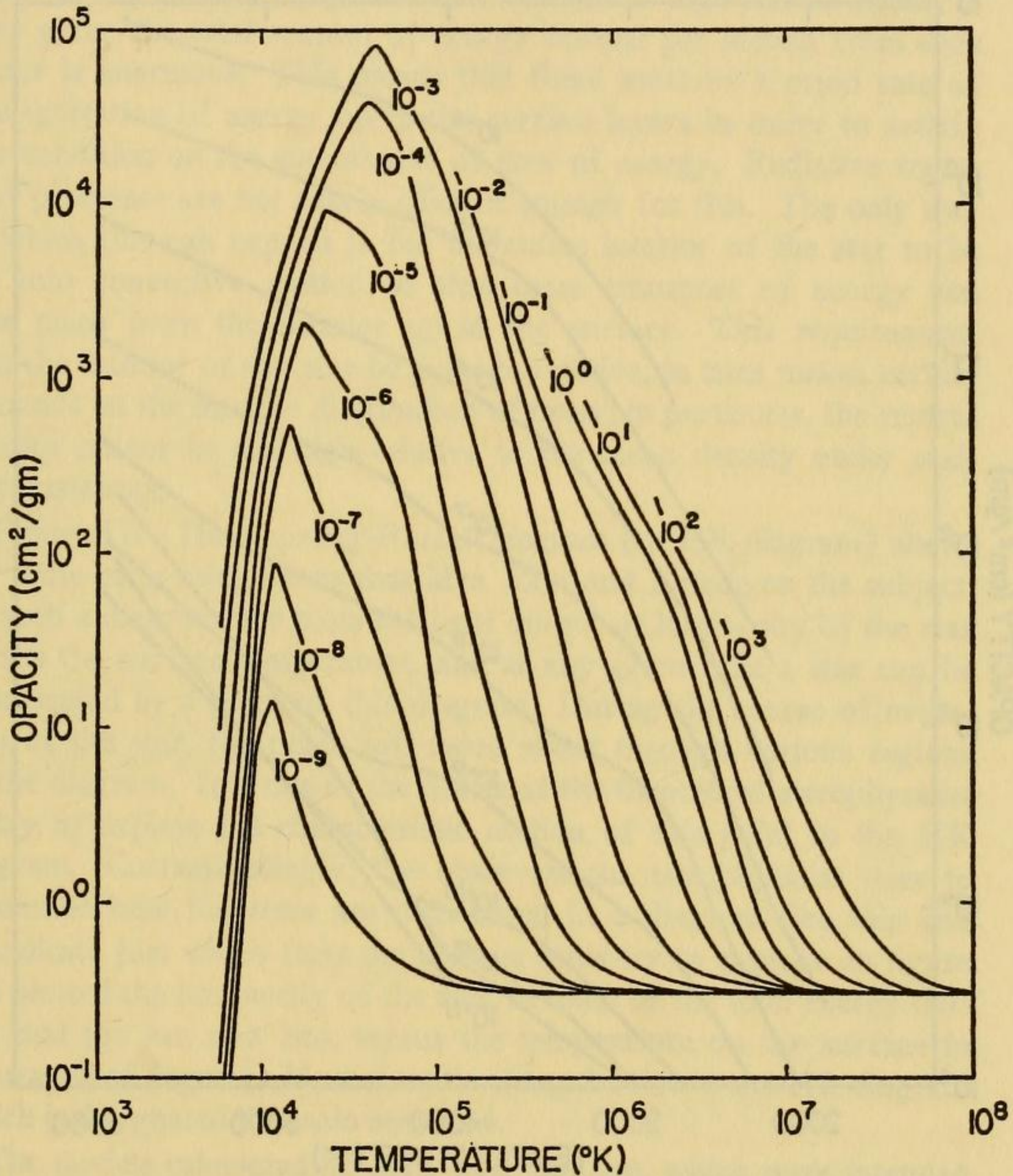


FIG. 2.—Opacity of solar material plotted as a function of temperature for lines of constant density (in gm/cm³).

layers that we would see would be those which emitted light into space. They would constitute the true photosphere of the star. The energy streaming outward from the interior would heat the outermost layers, raising their temperature and opacity, and we would then no longer be able to see so deeply into the star. This process would

continue until the temperature of several thousand degrees had worked its way up to a very shallow surface layer. This would then constitute the true photosphere of the sun. Consequently, it is not

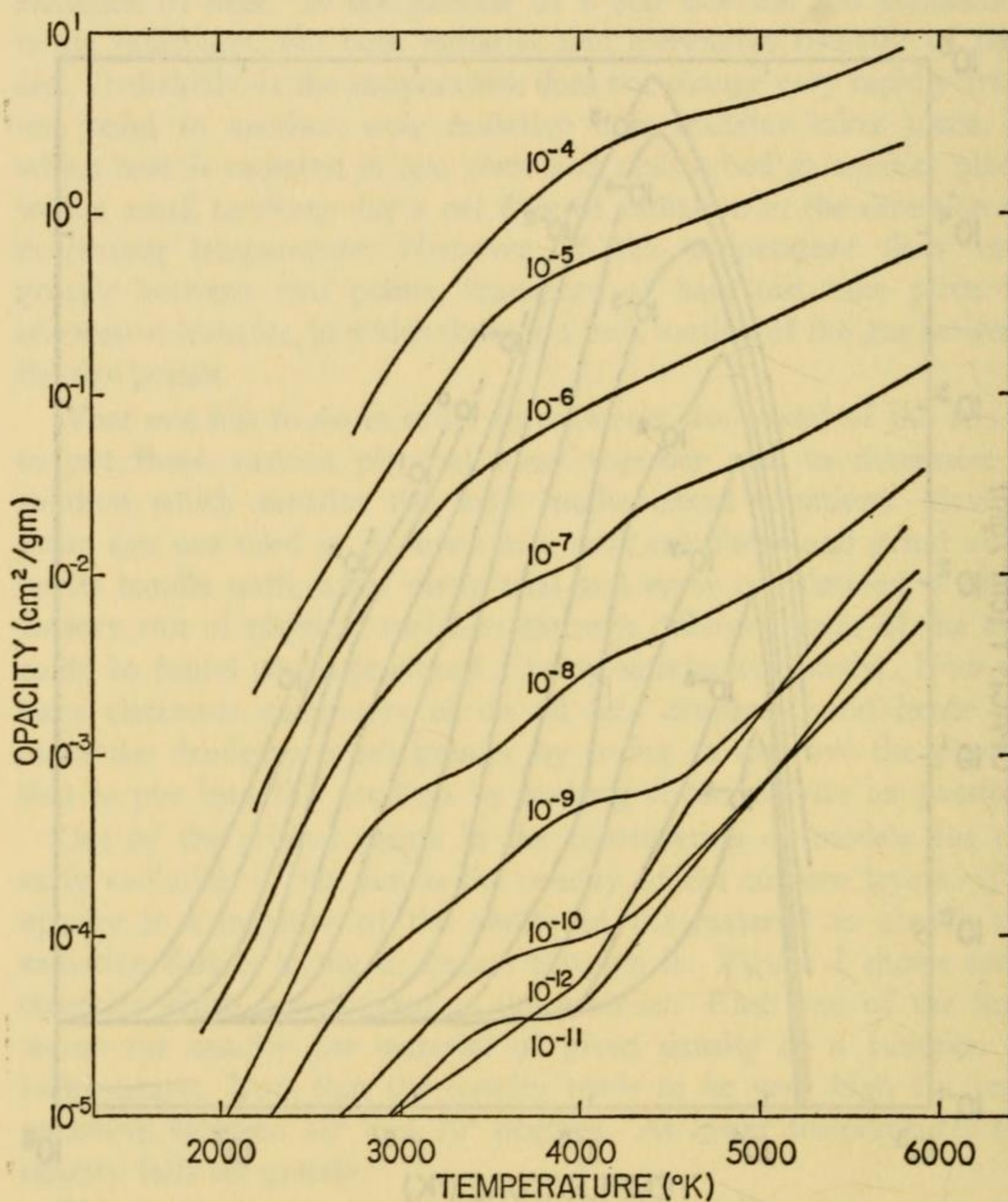


FIG. 3.—Opacity of solar material at lower temperatures, for lines of constant density (in gm/cm³).

possible to have a satisfactory model of the outer layers of the sun at too low a temperature.

Figure 3 shows the low temperature end of the opacity curve in more detail. The curves have very steep slopes in this region of a few thousand degrees. Somewhere in this region of high opacity one

would be able to find satisfactory conditions for the surface temperatures of the sun in its early stages of contraction.

However, Hayashi's contribution to this problem went far beyond the observation that the surface temperature of a giant star must be high. If the surface temperature of the star is high and its radius is very great, the total amount of energy emitted per second from such a star is enormous. This means that there must be a rapid rate of transportation of energy up to the surface layers in order to satisfy our condition on the smoothness of flow of energy. Radiative transport processes are not nearly efficient enough for this. The only way in which this can happen is for the entire interior of the star to be set into convective motion so that mass transport of energy can take place from the interior up to the surface. This requirement, that the interior of the star be fully convective, in turn makes certain demands on the interior distribution of mass; in particular, the central density cannot be too high relative to the mean density under such circumstances.

Figure 4 is a Hertzsprung-Russell diagram (or HR diagram) showing some early calculations that Mrs. Ezer and I made on the subject. In such a diagram one plots the light output or luminosity of the star versus the surface temperature, and at any given time a star can be represented by a point on this diagram. During the course of evolution of the star, the point will move about through various regions of the diagram. It is one of the duties of the theoretical astrophysicist to try to explain the characteristic motion of this point in the HR diagram. Correspondingly, the observational astrophysicist tries to determine how the stars are distributed in a diagram like this and to indicate just which facts the theorist must try to explain. In figure 4 is plotted the luminosity of the sun, in units of the total energy output that the sun now has, versus the temperature on the surface in thousands of degrees. Most stars lie along the line in the HR diagram which is designated the main sequence.

The models calculated by Mrs. Ezer and me, which were intended to represent an evolutionary sequence on the HR diagram, were computed according to a very simple assumption. The energy sources were taken to be not nuclear but gravitational in origin. As the matter in a star shrinks in its own gravitational field, it releases gravitational potential energy in the interior. This leads to the heating of the interior layers of the star. Now there is a fundamental theorem, called the virial theorem, which tells us that, under normal circumstances, half the energy that is released by gravitational con-

traction is stored in the interior and increases the temperature as the shrinking takes place. The other half is radiated away from the surface of the star. However, in order for this other half to be

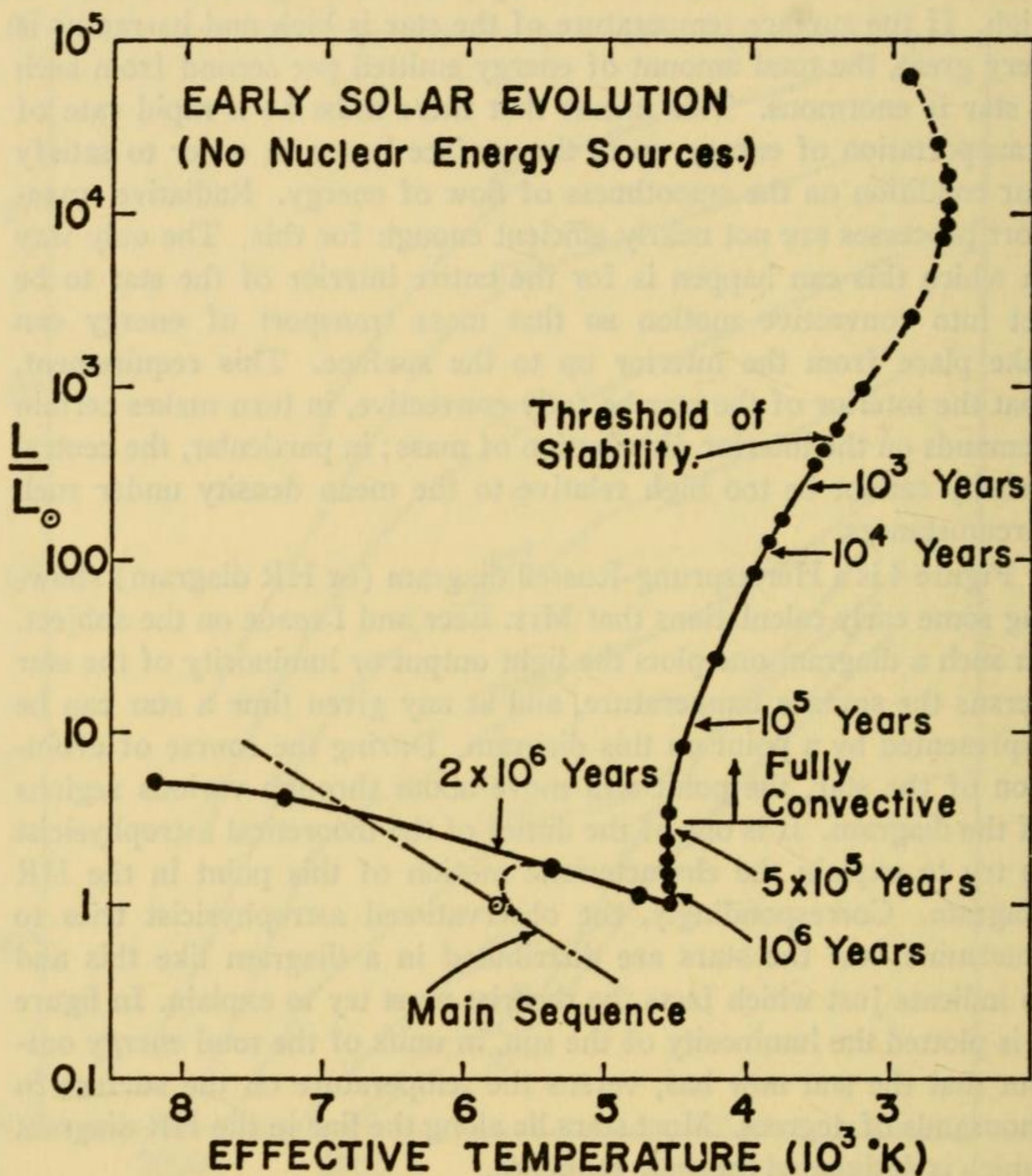


FIG. 4.—Hertzsprung-Russell diagram for the early evolution of the sun. Points show discrete models calculated with the assumption of homologous contraction. Indicated times are ages commencing from the threshold of stability.

radiated away, it has to be transported to the surface. Hence the rate of shrinkage of the star will be just that rate at which half of the gravitational potential energy that the star releases upon contraction can be transported to the surface and there radiated away. We assumed, in making these models, that the relative density distribu-

tion in the interior of the sun would not be changed during the contraction, or, technically, that the sun was contracting homologously. This was obviously not an exceptionally good assumption, since the various models along our track had somewhat different density distributions in the interior; nevertheless, it sufficed to indicate the general way in which the evolution would go.

One can obtain a formal sequence of models along the line indicated in this diagram. However, all those models lying above the point indicated as the threshold of stability cannot exist in nature. At the beginning of the indicated sequence the sun would have a radius of about 1,000 times its present radius and would be much larger than the solar system. At the threshold of stability, which occurs at about 60 times the present radius of the sun, the released gravitational potential energy due to the contraction up to that point is just sufficient to supply the internal thermal energy of the model, plus the energy needed to dissociate hydrogen molecules, and ionize the hydrogen and helium in the interior to the extent called for by the model. In the models corresponding to a larger radius than the threshold of stability, the released gravitational potential energy is not sufficient to supply these energy demands. Hence the threshold of stability denotes the maximum radius the sun could ever have on purely energetic grounds. Any larger object would be dynamically unstable and collapse immediately. Beyond the threshold of stability the sun supports itself in hydrostatic equilibrium and slowly shrinks as it gets rid of its gravitational potential energy of contraction.

The initial shrinkage beyond the threshold of stability is very rapid. The track denoting solar evolution falls almost vertically in the HR diagram. This means that the surface temperature is remaining nearly constant while the radius rapidly shrinks. When the sun becomes small enough, in the vicinity of twice its present radius, the center of the sun ceases to be completely convective. The region of convection after that gradually recedes from the center toward the surface, and in the central region of the sun energy transport becomes primarily by radiative transfer.

When the central half of the mass of the sun becomes radiative, the track representing the evolution of the sun in the HR diagram ceases to fall rapidly; it turns around and starts increasing toward the upper left. This occurs because the bulk of the energy deposition by gravitational contraction now takes place in the inner layers of the sun where energy transport is by radiation. Under these circumstances

it becomes the opacity of the deep interior rather than the opacity of the surface that principally governs the luminosity of the sun.

As the sun continues to contract, it becomes rather easy for the energy to flow out to the surface from the interior radiative portion, and hence the luminosity can now start gradually to increase. Since the radius is continuing to decrease, the surface temperature now increases at a regular rate, and the track of the sun lies toward the upper left.

At the time we made these calculations we were principally interested in testing Hayashi's ideas on the high luminosity and completely convective nature of the contracting sun. Consequently, we did not make allowance for thermonuclear reactions to produce energy in the interior of the sun as it contracted. However, we put in a dashed line in figure 4 to indicate the probable track the sun would follow when thermonuclear reactions became important. Because of their high temperature sensitivity, thermonuclear reactions generate energy much closer to the center of the sun than corresponds to the energy deposition by gravitational contraction. As a result there is a greater amount of mass for the energy to flow through before it reaches the surface, and the increased opacity thus cuts down the luminosity of the sun somewhat.

After this preliminary look at the situation we tried to carry out these calculations a little more seriously, paying more attention to the details of all the physical conditions that would be involved in the interior.

Whereas we used traditional methods of computation in constructing the models shown in figure 4, in which one integrates the differential equations of the structure both inward from the surface and outward from the center to a fitting point, to obtain the models shown in figure 5 we used a much more modern method of computation developed by Henyey for use with computers. We calculated two evolutionary tracks which corresponded to two different assumptions about the efficiency of the energy transport by turbulent convection inside the sun.

Consider what is involved in turbulent convection of gases. Imagine a blob of gas at some point in the interior of the sun. Let us raise this blob of gas slightly, not letting radiation flow across its surface, but keeping it in pressure equilibrium with its surroundings. At the higher level there will be a smaller pressure, so the blob of gas will be cooled by its expansion. The subsequent motion of the blob depends entirely on whether its temperature in its displaced position is higher

or lower than the temperature of the surrounding medium. If the temperature is higher, the blob of gas will be less dense than its surroundings, and buoyancy forces will come into operation, causing

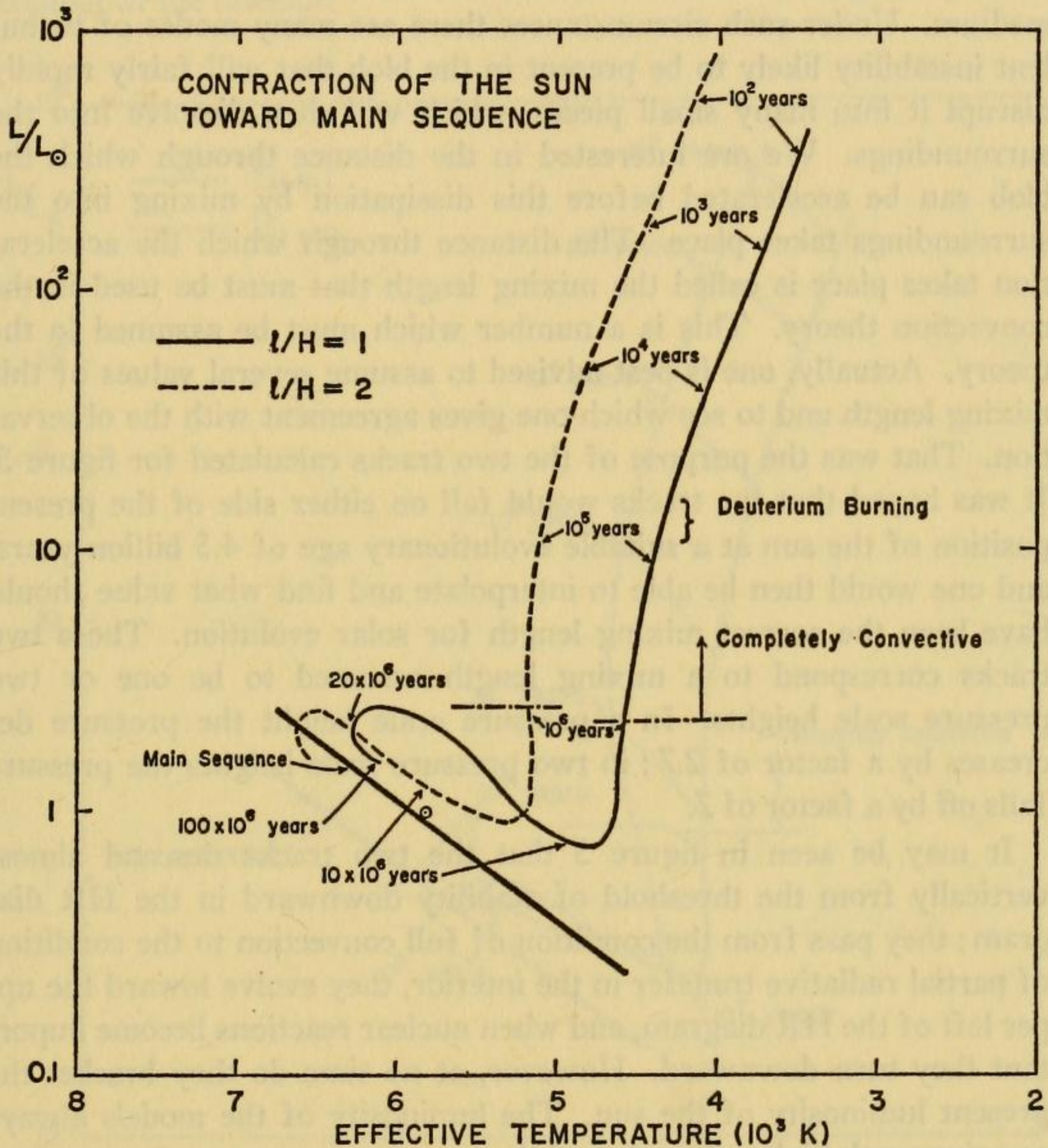


FIG. 5.—Hertzsprung-Russell diagram for the early evolution of the sun, with the evolutionary model sequences calculated by the Henyey method. The two evolutionary sequences correspond to two values of the ratio of turbulent mixing length to pressure scale height, l/h . The composition contains about one-third helium by mass.

it to be thrust upward. This is the condition in which convective energy transport takes place and turbulent mixing of the gases occurs. If the temperature of a blob is cooler than its surroundings, negative buoyancy forces will come into effect and the blob will be thrust back toward its starting position. Under such conditions the medium is

stable against convection and the only energy transport which is possible is radiative transfer.

The most efficient transport takes place for the largest blob that we can imagine to be formed and to rise through the interior of medium. Under such circumstances there are many modes of turbulent instability likely to be present in the blob that will fairly rapidly disrupt it into many small pieces, which will then dissolve into the surroundings. We are interested in the distance through which the blob can be accelerated before this dissipation by mixing into the surroundings takes place. The distance through which the acceleration takes place is called the mixing length that must be used in the convection theory. This is a number which must be assumed in the theory. Actually, one is best advised to assume several values of this mixing length and to see which one gives agreement with the observation. That was the purpose of the two tracks calculated for figure 5. It was hoped that the tracks would fall on either side of the present position of the sun at a suitable evolutionary age of 4.5 billion years, and one would then be able to interpolate and find what value should have been the correct mixing length for solar evolution. These two tracks correspond to a mixing length assumed to be one or two pressure scale heights. In a pressure scale height the pressure decreases by a factor of 2.7; in two pressure scale heights the pressure falls off by a factor of 7.

It may be seen in figure 5 that the two tracks descend almost vertically from the threshold of stability downward in the HR diagram; they pass from the condition of full convection to the condition of partial radiative transfer in the interior, they evolve toward the upper left of the HR diagram, and when nuclear reactions become important they turn downward. However, at no time do they bracket the present luminosity of the sun. The luminosity of the models always remains much higher than that of the sun.

Under such circumstances we must conclude that the opacity in the interior of these models of the sun is too small. This suggests, in turn, that we were using the wrong composition for the solar interior. The composition chosen for the models in figure 5 consisted of the relative abundances of the elements as deduced from solar spectroscopic analyses, plus chemical analyses of meteorites, plus spectroscopic analyses of certain other stars, particularly for the helium-to-hydrogen ratio. The helium assumed for the models was about one-third of the mass of the sun, corresponding to the amounts analyzed to be present in massive O and B stars recently formed in

space. It is evident from figure 5 that improved fits to the solar luminosity would be obtained if the opacity in the interior could be increased, which, in turn, would correspond to raising the hydrogen content of the interior.

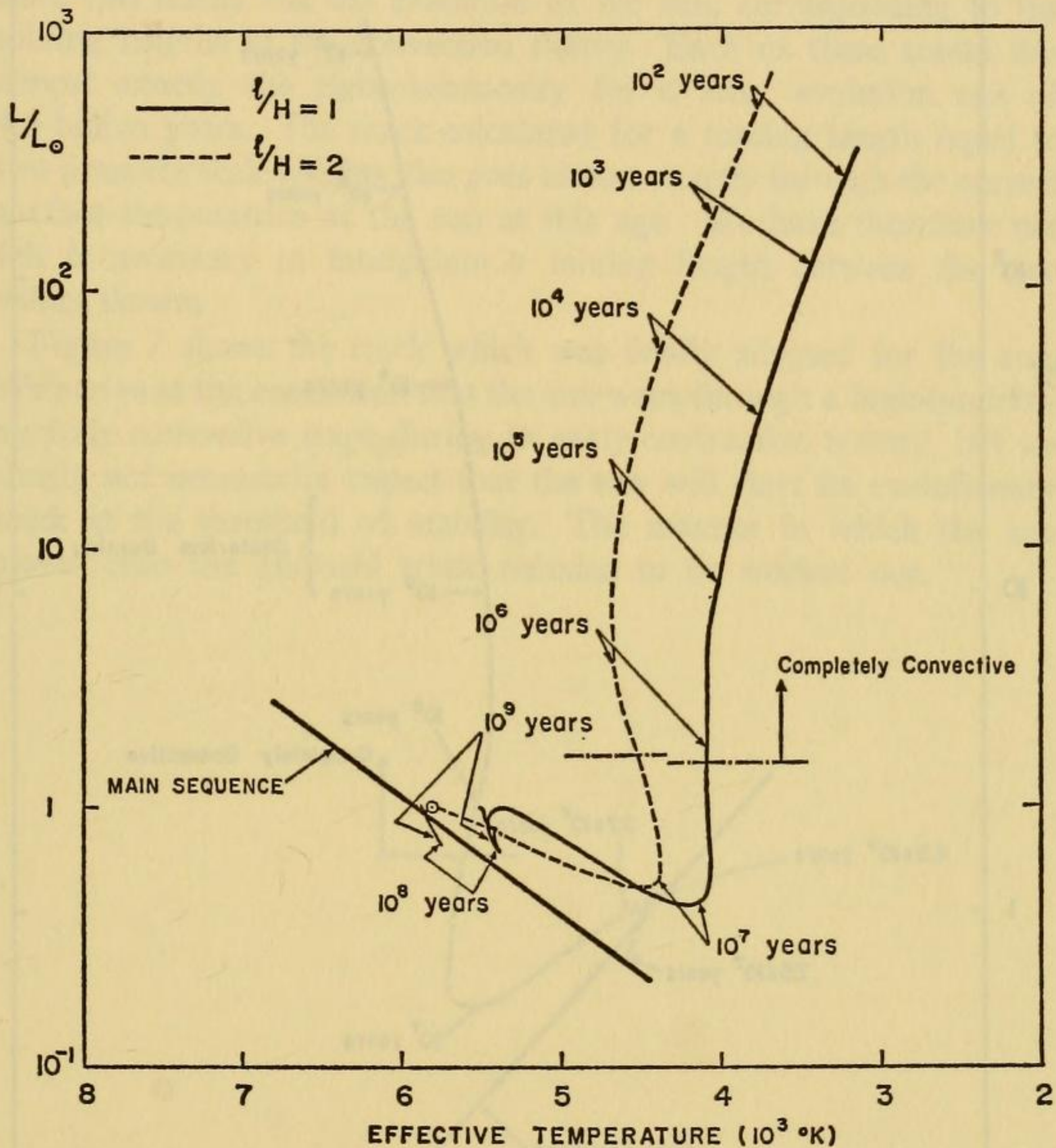


FIG. 6.—Hertzsprung-Russell diagram for the early evolution of the sun. This is similar to figure 5, but the helium content has been reduced to 24 percent by mass.

Just at this time our attention was brought to an indirect way of determining what the probable helium content of the sun is. A rocket flight flown by a group of experimenters at the Goddard Space Flight Center had measured the relative abundances of heavy ions in the solar cosmic rays. These established the relative abundances of helium and oxygen nuclei in the solar cosmic rays. When the solar composi-

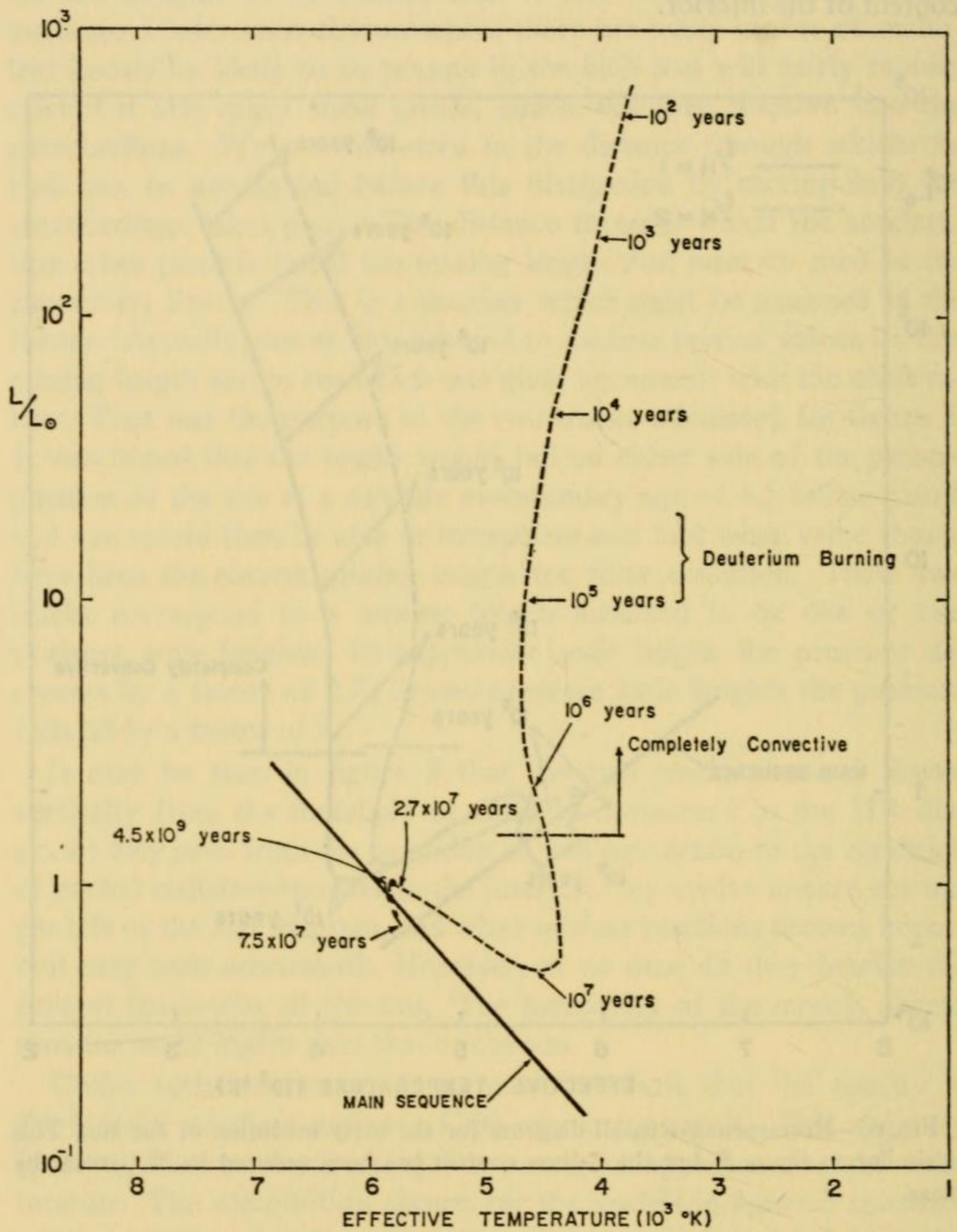


FIG. 7.—The adopted Hertzsprung-Russell diagram for the early evolution of the sun.

tion of helium is recomputed on this basis, the helium comes out at 24 percent of the mass. Consequently the calculations shown in figure 5 were repeated with the new composition for the solar interior deduced from solar cosmic rays.

The results of this recomputation are shown in figure 6. Again we have two tracks for the evolution of the sun, corresponding to the mixing lengths in the convection theory. Each of these tracks has almost exactly the right luminosity for a solar evolution age of 4.5 billion years. The track calculated for a mixing length equal to two pressure scale heights also goes almost exactly through the correct surface temperature of the sun at this age. We have therefore not felt it necessary to interpolate a mixing length between the two values shown.

Figure 7 shows the track which was finally adopted for the sun. We arrive at the conclusion that the sun went through a high-luminosity fully convective stage during its early contraction history, but we should not necessarily expect that the sun will start its evolutionary track at the threshold of stability. The manner in which the sun moves onto the Hayashi track remains to be worked out.