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FORMATION AND EVOLUTION OF THE SUN

MASTER

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I. INTRODUCTION

In these days of renewed and vigorous interest in the origin, structure, and past and future histories of the solar system, detailed knowledge of the formation and evolution of the sun has become of vital importance. For example, knowledge of the rate at which radiant energy was streaming from the solar surface, and the extent of that surface at the time of the formation of the planets is basic to any realistic theory concerning their formation. Coupled with this new and widespread interest in the time-history of the sun has been the advent of the high-speed electronic computers and the development of techniques which enable the astronomer to investigate many complicated relations which heretofore had been considered beyond reach. It is my intention to discuss briefly the present state of knowledge concerning the history of the sun, what investigations are currently going on, and to indicate some of the fields of knowledge in which uncertainties and difficulties continue to exist.

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KNOWLEDGE OF STELLAR FORMATION

A great variety of astronomical observations support the view that stars are formed from the interstellar medium. As can easily be shown, the most luminous stars are emitting radiant energy at such a rate that they cannot possibly be very old, and these stars are invariably found in intimate association with clouds of gas and dust. This is true within our own and other galaxies. In some instances the space motions of such stars can be measured and are found to be too small relative to the surrounding clouds of gas to be mere passersby. The conclusion seems to be unmistakable that these stars were born from the surrounding material.

There is a class of stars known as the T Tauri stars whose spectra and light variability suggest that they are passing through a short lived phase of their evolution, and these stars are also imbedded in clouds of interstellar gas and dust.

In a number of places in the sky, dark spheroidal globules can be seen projected against luminous clouds and the obvious interpretation is that these are protostars which will at some time in the future contract sufficiently that they will begin to glow, and thus become stars.

I hasten to point out that there have been many theoretical difficulties in providing good quantitative explanations for the above observations, but nevertheless the observations appear to give great confidence to our belief that stars are being born from the interstellar medium.

BASIC SOLAR DATA

We may well ask if the sun contains information within it which will tell us anything of its birth and its aging processes. The obvious fact about the sun, of course, is that it is shining. An inevitable result is that it must evolve, for its supply of energy can not be infinite. As this energy source must lie in the deep interior, what can we say about it?

At first glance the deep interior appears to be less accessible to scientific investigation than any region of space around us. However, if we ask the correct questions, we find that certain information about this important region of the sun is being communicated to us quite directly. First, a gravitational field is emanating from the sun and the motions of the planets and minor planets within this field allow us to determine the solar mass. Secondly, the solar radiant energy crossing a unit area of the earth's surface can be measured, and the luminosity of the sun, i.e., the rate at which energy is being emitted, is easily derived. Thirdly, the distance of the earth from the sun being known, the size of the sun can be determined quite easily. Thus we determine the three basic stellar quantities for the sun -- the mass, the luminosity, and the radius.

There are yet three additional bits of information which should be mentioned. First, through spectroscopy, something of the chemical composition of the outermost layers can be determined. This problem is fraught with difficulties but even so such derived information is very important to our understanding of what has gone on in the interior.

Secondly, some kind of lower limit can be set to the age of the sun, for certainly it cannot be younger than the earth. Furthermore the surface of the earth contains information which suggests that the luminosity of the sun has been relatively constant for very long periods of time. The third observation is so obvious that it can easily be overlooked, but it is of basic importance to the theory of stellar interiors. That is the fact that the sun is essentially spherically symmetric and in hydrostatic equilibrium -- it is neither pulsating nor blowing up, at least not on a very fast time scale.

The combination of all of the above information leads to many interesting conclusions. For example, from the known size, i.e., volume, and mass, the mean density of the sun is immediately obtained. The fact that the sun is in hydrostatic equilibrium means that the total pressure at any point must be just sufficient to support the weight of the overlying material. Making various assumptions about the density distribution, we can regulate the pressure at every point by adjusting the temperature at that point until hydrostatic equilibrium is achieved. Naturally, an arbitrarily chosen density distribution will undoubtedly result in a temperature distribution which will in no way correspond to a realistic flow of the energy such that a correct luminosity will be achieved. Obviously there needs to be a simultaneous solution for all parameters of the problem in order to match what is so "casually" observed!

Perhaps the most striking conclusion concerns the energy, for the average rate of energy release is about 2 ergs per gram per second, and apparently there have been no marked changes in this rate for four or five billion years.

The proposed sources for this energy have been varied. Perhaps the oldest suggested source is that of combustion. But proportioning the mass in the most ideal way into carbon and oxygen, the maximum age of the sun would only be about three thousand years. Clearly, another source must be sought. It has been suggested that solar material might be supplemented by an infall of meteoric material, but the density of the material in the vicinity of the sun is quite insufficient to be held responsible for any significant contribution to the solar energy.

A little more than a century ago H. von Helmholtz proposed that gravitational contraction was the source of energy for the sun and stars. The gravitational energy stored in the sun is approximately equal to 5×10^{15} ergs/gram and if contraction were responsible for the luminosity of the sun, the solar diameter would be decreasing at about the rate of 40 meters/year, or about 4 kilometers in a century -- a rate which is not observable. (Good angular diameter measurements of the sun can be obtained only for about the last two centuries.) However, the length of time for the solar material to contract from an infinitely large size to its present dimension would be only a few tens of millions of years. This is also an interval of time which is much too short.

Finally, increased knowledge of the atom has led to the relation between mass and energy, $E = mc^2$, or approximately 9×10^{20} ergs/gram. This is a source so plentiful that in four billion years and at the present luminosity, the sun would have decreased in mass only about 0.02 per cent. It is clear that the sun is feeding upon its mass and at the present rate of consumption, apparently has a long life ahead.

II. BASIC DIFFERENTIAL EQUATIONS OF STELLAR STRUCTURE

From the above information, and with the assumption of spherical symmetry, the following differential equations can be derived.

$$1. \quad \frac{dP(r)}{dr} = -G \frac{M(r) \rho(r)}{r^2} \quad \text{Equation of Hydrostatic Equilibrium}$$

$$2. \quad \frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \quad \text{Continuity Equation Conservation of Mass}$$

$$3. \quad \frac{dL(r)}{dr} = 4\pi r^2 \rho(r) \epsilon \quad \text{Luminosity Equation}$$

$$4. \quad \text{a. } \frac{dT}{dr} = -\frac{3}{4ac} \frac{K \rho(r)}{r^3(r)} \frac{L(r)}{4\pi r^2} \quad \text{Radiation} \quad \text{Energy Transport Equations}$$

$$\text{b. } \frac{dT}{dr} = \frac{\Gamma-1}{\Gamma} \frac{T}{P} \frac{dP}{dr} \quad \text{Conduction}$$

5. a. $P = \frac{k}{\mu H} \rho(r) T(r) + \frac{a}{3} T^4$

Equation of State

b. $P_{\text{electron}} = \text{Const} \left(\frac{\rho}{\mu} \right)^{5/3 \text{ or } 4/3}$

The definitions of the variables in the above equations are:

r	radial coordinate	P	total pressure
G	gravitational constant	ρ	density
M(r)	mass interior to a sphere of radius r	L(r)	energy crossing the surface of radius r
e	energy generated gram ⁻¹ second ⁻¹	T	temperature
a	radiative constant	c	velocity of light
K	Rosseland mean opacity	μ	mean molecular weight
k	Boltzmann's constant	μ'	average mass/electron
Γ	adiabatic exponent	H	mass of unit atomic weight

Three quantities, μ , the mean molecular weight, K, the Rosseland mean opacity and e, the energy generated per gram per second, have been introduced in the above equations. Each of these is a function of the chemical composition, the density and the temperature, and all are presumed to be known. The calculations of the latter two quantities, while quite feasible with electronic computers, are enormously complicated and require elaborate machine codes and experimental results. However, assuming them to be known, the object is to determine the temperature, pressure, density, mass interior and the energy crossing the sphere at every point

r within the star. Since there are, in effect, five equations in five unknowns, a model for the sun or a star is obtainable.

The boundary equations for these equations are as follows:

At $r = R$ = the radius of the sun, the pressure, the density and the temperature are presumably known. At $r = 0$, the mass interior, $M(r)$ and the net flow of energy across that sphere, $L(r)$, must equal zero. These conditions are two too many, and some freedom of choice in their use is possible. In practice, the two are used as a check upon the calculations. In general, the history of the entire problem has been the changing application of these boundary conditions.

To obtain a model of the sun, or any star, one needs the mass, luminosity, radius, and the chemical composition. In general these are a function of time, hence a model of the sun represents the sun for only one moment in time. However, since the temperature, density and chemical composition are finally known for every point within the model, the rates of conversion of mass to energy are known for every point, and therefore the rate of change of the chemical composition is also known. Such a change will alter the molecular weight, the opacity and the energy generation and these will in turn alter the structure of the model. Thus, having a model for one moment in time, the model for a subsequent time is determined.

The calculation of a model on a desk calculator is an exceedingly laborious and time-consuming effort. The wide-spread use of electronic

computers has made possible the calculation of such a model in a few seconds and a number of different techniques have been developed. Because of the great interest in the sun, models for stars of one solar mass have received a great deal of attention.

III. EVOLUTIONARY SEQUENCES FOR MODELS OF ONE SOLAR MASS EARLIER RESULTS

The first detailed calculations of a sequence of models which represented the contraction phase of the sun were made by Henyey, Le Levier, and Levee*. Somewhat later, using a different computational technique, Brownlee and Cox[†] calculated evolutionary sequences using improved opacities and considering the role of an outer convection zone and all sources of nuclear energy generation. Among the latter, the possible role played by deuterium was investigated. The results are shown in the theoretical Hertzsprung-Russell diagram in Figure 1.

From the initial model for these tracks, when the radius was approximately thirty times that of the present sun, the contraction was traced until the transmutation of hydrogen into helium in the center of the model yielded enough energy to cause the rapid contraction to cease. At the outset, about 97 percent of the gravitational energy was still present. Thus calculations ranged over a time during which almost all

* Henyey, L. G., Le Levier, R., and Levee, R. D. 1955, Pub. Astronom. Soc. Pacific, 67, 154.

[†] Brownlee, R. R. and Cox, A.N., 1961, Sky and Telescope, 22, 252.

Fig. 1. The Theoretical Hertzsprung - Russell Diagram

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of the potential energy was converted into internal energy and radiated energy. When no deuterium was present, this period of time was greater than 100 million years. When deuterium was added in an amount equal to that found in the earth and in meteorites, about 2 hundredths of a percent by mass, there was a significant pause in the contraction at the moment the central temperature and density were sufficient for the proton-deuteron reaction to occur. This caused a total increase in the contraction time of a factor of about two. An additional calculation was made on the assumption that the deuterium was constantly mixed throughout the model, and again the contraction time was increased.

Figure 2 shows plotted the radius of the model vs time. The moment the deuterium began to burn is quite apparent, as well as the moment in which the resulting energy release stopped supporting the outermost layers.

Figure 3 shows plotted the Energy Balance as a function of time.

Figure 4, in addition to showing the radius vs time plot and the change of the potential and internal energies with time, shows the temperature changes vs times as well. Of particular interest in this figure is the abrupt halt in the increase of the temperature in the center indicated as some one. A short time later the temperature changes fall to zero throughout the model, and this is said to be the time of the primordial solar model or the initial sun.

Fig. 2. Model Radius vs Time

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Fig. 3.

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After the model has reached the main sequence of stars its path in the Bolometric Magnitude-Log Effective Temperature diagram is drastically altered. Changes in structure still occur, but on a much longer time scale. As the hydrogen in the central regions is converted to helium, the mean molecular weight increases, the central regions collapse slightly, the opacity decreases, and the density and temperature are increased. The energy production is thus enhanced and the luminosity of the model rises. The outer regions actually expand during this phase, so that the radius and luminosity of the model slowly increase. (The decrease in mass during this phase is essentially negligible.) After some period of time the model should pass through or near the position of the present sun, depending upon its resemblance to the sun.

All of the above mentioned calculations were made with an assumed chemical composition of 74.4 percent by weight of hydrogen, 23.6 percent by weight of helium and 2 percent by weight of the heavier elements. It was found that the model took entirely too much time to reach the luminosity and radius of the present sun--a period of about 11 billion years. An altered chemical composition was suggested, since a decrease in the initial abundance of hydrogen and a corresponding increase in the abundance of helium would serve to shorten the time between the initial and present solar conditions.

RECENT RESULTS

In the earliest stellar models, the simplest possible surface boundary conditions were used, i.e., that the pressure, temperature and density all vanished at the surface. While these conditions were quite adequate for making preliminary and general calculations of stellar interiors, experience has shown a need for greatly refined boundary conditions. In fact, it is now clear that nothing short of a well determined model stellar atmosphere will suffice to establish a proper surface boundary condition. This is proving to be especially true for the study of contracting solar models.

Hayashi* was the first to point out that the calculations described above for the earliest phases of the contraction would have resulted in an entirely different history had the convection in the outermost layers been handled correctly. His prediction was the result of his study of the importance of convection in the outer envelopes of the late-type giant stars. In the models just described the boundary condition used was derived from atmospheric models by Swihart and Fischel† and with an assumption of constant gamma between the point of the onset of convection and the outermost mass point of the interior. The assumed value of gamma was apparently too large and the envelope structure and

* Hayashi, G., 1961, Pub. Astron. Soc. Japan 13, 450

† Swihart, T. L., and Fischel, D., 1961, Ap.J. Suppl. 5, 291

the depth of the convection region are very sensitive to the value of γ used. The correct boundary condition should consider the variable γ and the convective efficiency, as Hayashi has done. The result is a lower temperature for the outermost mass point of the interior, a corresponding change in structure, and a much deeper convective region.

Recent results verifying Hayashi's prediction have been reported by Ezer and Cameron*, and Weymann and Moore.† Ezer and Cameron calculated twenty-seven models by a technique which did not yield a strict evolutionary sequence but which served to delineate such a sequence. They found that for all models above 2.5 solar radii, the convection was complete all the way to the center. The efficiency in carrying energy by convection is so much greater than that by radiation flow that the luminosities of the models are very high when compared with the previously reported results. Further, since the energy is emitted at such a great rate, the collapse of the model is greatly hastened and the corresponding conversion of gravitational energy is greatly accelerated. The final result is a greatly shortened calculated time for the model to reach the initial main sequence of stars, i.e., its primordial state.

* Ezer, D., and Cameron, A.G.W., 1962, The Early Evolution of the Sun, preprint

† Weymann, R., and Moore, E., 1962, The Abundance of Lithium and the Structure of Gravitationally Contracting Stars of One Solar Mass, Preprint

Recent work at Los Alamos is in qualitative agreement with that of Hayashi and Ezer and Cameron. Since the techniques used and the various assumptions necessary to the determination of boundary conditions, the convective energy flow and the chemical composition are similar but not necessarily the same, exact agreement is certainly not to be expected.

The chemical composition for the results described below was 59.6 percent by weight hydrogen, 30.4 percent by weight helium, and 2.0 percent by weight heavier elements.

The opacities for this composition as calculated by Stewart and Cox at Los Alamos are shown in Figures 5 and 6. The code which is used to calculate these opacities considers bound-bound, bound-free, and free-free absorption, electron scattering and negative ion absorption. For the data shown, the range in temperature is from 4.343×10^{-4} kilovolts (5040°K) to 10 kilovolts ($1.1603 \times 10^8^\circ\text{K}$). The range in density is from 10^{-14} gm/cm³ to 10^3 gm/cm³.

The equation of state data used have also been computed by Stewart and Cox for the identical ranges of temperature and density.

Some of the results of the most recent calculations are shown in the figures which follow.

In Figure 7 the luminosity as a function of radius is shown for a particular model with $R/R_0 = 24.2$. As the boundary conditions being used are considered preliminary, the actual value of the luminosity is to be given little weight. Note that each particular region of the model is contributing some of its gravitational energy to the luminosity.

Fig. 5. Opacity vs Temperature for Specified Densities

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Fig. 6. Opacity vs Temperature for Specified Densities.
Density Curves are Labeled as in Figure 5.

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Fig. 7. The Luminosity (in units of 10^{24} ergs/sec) vs Fractional Radius for a Model with a Radius Equal to 24.2 Times the Present Solar Radius

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Figure 8 shows the pressure profile for the same model. The pressure is in units of 10^{16} ergs/cm³.

Figures 9 and 10 show the temperature (in kilovolts) and the log of the density vs radius, respectively. These two figures are to be compared with figures 11 and 12 which show plotted the same quantities, but for a model of radius $R/R_0 = 1.29$. The great increase in temperature and density throughout the star during the course of the contraction can easily be noted.

Figures 13 and 14 show similar results derived from the earlier work done at Los Alamos. When these are compared with the four preceding figures, the different temperature and density distributions are quite striking. The difference is simply that in the initial solar model, the convection region does not extend throughout the star but is rather confined to an outer region and a small central core. The model which is convective throughout shows quite flat profiles.

It is of interest to see how the actual temperature gradient differs from the adiabatic gradient of the model with $R/R_0 = 24.2$. This can be seen in Figure 15, where the excess of the temperature gradient over the adiabatic is plotted versus the radius. As the successive models approach the radius of the present sun, this difference becomes less and less. Eventually the opacity in the central regions becomes sufficiently low that the convection ceases. In the outer regions the temperature gradient becomes that of the adiabat.

Fig. 8. Log Pressure vs Fractional Radius for Model R = 24.2 ©

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Fig. 9. - Temperature vs Fractional Radius for Model R = 24.2 $^{\circ}\text{C}$

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Fig. 10. Log Density vs Fractional Radius for Model R = 24.2 $\odot$

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Fig. 11. Temperature vs Fractional Radius for Model R = 1.29

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Fig. 12. Log Density vs Fractional Radius for Model R = 1.29 $\odot$

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Fig. 13. Temperature vs Radius for a Model of the Initial Sun

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Fig. 14. Log Density vs Radius for a Model of the Initial Sun

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Fig. 15. The Excess of the Temperature Gradient over the Adiabatic Gradient vs Fractional Radius for Model R = 24.2 $\odot$

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THE SOLAR FUTURE

Finally, a few comments should be made about the future history of the sun. From work done by many workers in the past and from calculations currently being made at the University of California by Menyey, at the California Institute of Technology by R. L. Sears, at Princeton by Schwarzschild, at the NASA Institute for Space Studies by Ezer and Cameron, at the Los Alamos Scientific Laboratory, and a number of other places, it is clear that the amount of information regarding the total life history in the sun has just begun to accumulate. Even so we can state with some certainty what the "immediate" future of the sun will be.

By comparing the "age" of the model when it most closely represents the sun with the age of the sun as derived by other methods, it is possible to select a chemical composition which will give the "correct" age. This composition, depending on the opacities one uses, etc., appears to be about 63 to 65 percent by weight of hydrogen, 2 to 3 percent by weight of the heavier elements, the remainder being helium. Thus an additional "observed" fact is used to determine an additional model parameter.

Currently, the best models seem to suggest that in the central regions of the present sun about one half of the original hydrogen has been converted to helium. This process will continue until all of hydrogen is burned, at which time the central regions begin to contract somewhat more rapidly. The outer regions gradually accelerate in their expansion and finally--current models suggest after about six or seven

1
billion more years--the sun will turn away from the main sequence rather abruptly and become a giant star.

The central temperatures and densities will have become sufficiently high that the helium will itself begin to be transmuted into carbon. There will follow a colorful period of the sun, as a giant star, making many elements within it. Unfortunately, for the present the theoretical understanding of this epoch, and those to follow, however exciting, is rather imperfectly held. The anticipated increases of our knowledge in the near future promise to make the field of stellar models a very profitable one.