INVITED DISCOURSE B

given to participants in the General Assembly at 20^h00^m on Friday 18 August 1961 in the Auditorium of Wheeler Hall on the Berkeley Campus of the University of California by

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on

STELLAR EVOLUTION

I. RATES OF STELLAR EVOLUTION

It is perhaps one of the most important characteristics of the past decade in astronomy that the evolution of some major classes of astronomical objects has become accessible to detailed research. The theory of the evolution of individual stars has developed into a substantial body of quantitative investigations. The evolution of galaxies, particularly of our own, has clearly become a subject for serious research. Even the history of the solar system, this close-by intriguing puzzle, may soon make the transition from being a subject of speculation to being a subject of detailed study in view of the fast flow of new data obtained with new techniques, including space-craft.

In the theory of the stellar interior it has long been clear that the majority of stars, in spite of their apparent permanence, must be evolving. Simply the fact that the radiant luminosity of a star represents a persistent, enormous energy loss, makes it clear that most stars cannot remain indefinitely in their present state. Only for one type of star does this radiative loss seem to be irrelevant, namely the white dwarfs. The luminosity of the white dwarfs, we believe, is fed from the residual thermal energy still contained in the interior. However, this thermal energy in a typical white dwarf is so small compared with the gravitational energy that its eventual loss will not change the structure of the whole star to any appreciable degree. Accordingly we can consider the white dwarfs, in spite of their slowly declining brightness, essentially in a state in which they can remain indefinitely. The same does not appear to be true for any other type of stars.

In spite of the early recognition that most stars must be evolving, it was only in the last decade or two that it became possible to determine the various processes which govern the evolution of different types of stars. Three classes of such processes are now recognized: nuclear processes, thermal processes, and dynamical processes.

A star will have its slowest rate of evolution—always excluding its final white dwarf state—whenever it is in thermal and dynamical equilibrium, that is when the nuclear transmutations through their continuous alteration of the chemical composition are the only cause for any change. The rate of such a nuclear evolution is governed by the fact that a hydrogen-rich star contains approximately 10^{19} ergs/g in nuclear energy. If this energy is expended by a star of one solar mass at the rate of one solar luminosity, one finds the nuclear lifetime to be of the order of 10^{11} years.

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A faster rate of evolution is encountered in a star when it is in dynamical equilibrium but not in thermal equilibrium. The thermal rate of re-adjustment can be determined from the thermal energy content of the star, which amounts to approximately 10^{15} ergs/g for a temperature of ten million degrees. If this thermal energy—or rather the equivalent gravitational energy set free during a contraction—is expended again by a star of one solar mass at the rate of one solar luminosity, a thermal adjustment time of about 10^7 years is found.

The fastest rate of stellar evolution occurs when a star is not even in dynamical equilibrium. The characteristic time for this class of evolution can be estimated by dividing the diameter of a star by the average sound velocity within it, which for the Sun gives a time interval of a couple of hours. Clearly dynamical evolution tends to be catastrophic. We will mention later, however, cases in which the individual dynamical phenomena occur at the fast rate here indicated but for which the net changes resulting for the star as a whole accrue at a substantially slower rate.

I should like now to discuss in somewhat more detail these three classes of stellar evolution phases, in order of increasing rate—which is also in order of decreasing knowledge.

2. EVOLUTION AT NUCLEAR RATE

The most outstanding example of stellar evolution at the slow nuclear rate is the main sequence phase. This phase starts after the initial contraction of a star when the central temperature has reached a value sufficient for substantial hydrogen burning. It terminates when the hydrogen is exhausted at the star's center. For the most luminous stars, of about 100 solar masses, the main sequence phase lasts about three million years, for stars of one solar mass it will last about fifteen billion years, and for the faintest main sequence stars it may well last several trillion years. The details of the main sequence evolution phases have been computed through with fair care for a variety of stellar masses and initial compositions. I think we would feel quite content with the accuracy thus far achieved if it were not for an important application which clearly requires further main sequence evolution computations with substantially increased care and accuracy.

This application consists of the determination of the ages of stars by comparing their observed positions in the Hertzsprung-Russell Diagram with the theoretically computed evolution curves. I should like to quote two such recent age determinations, both referring to relatively old stars. The color-magnitude diagram for the galactic cluster NGC 188, derived by Sandage, appears to agree quite well with the lower envelope of the near-by subgiants determined by O. C. Wilson and Oke. Hence, these two observational materials seem to give us two independent samples of disk population stars, which you may also consider as the oldest type of Population I stars. Sandage has recently carried out a comparison of the corresponding observed curve in the Hertzsprung-Russell Diagram with the theoretical evolution curves by Hoyle and Hazelgrove, which are at present the best evolution computations in the relevant mass and composition ranges. The result is an age for the disk population of approximately fifteen billion years. A similar comparison of the observed diagrams for globular clusters with theoretical curves, in this case, for metal-poor stars, gives an age for the extreme Population II of about twenty-five billion years. Both these numbers are preceded by a lengthy and painful history beset with errors. Clearly further investigations are needed to increase the certainty of these new determinations.

It will be clear to you that when you compare these new age determinations as they stand with the best present value of the Hubble constant for the expansion of the universe (about thirteen billion years) they present a fascinating cosmological problem. The age determination for the globular clusters would have to be reduced by about a factor three if it were to be fitted to the simplest classical solutions of general relativity for an expanding universe with zero cosmological constant. It is hard for me to believe that our present age determinations could still be that wrong. Nevertheless, we have to remind ourselves that on the basis of the same world model we are trying here to follow the evolution of stars over time intervals quite comparable with the total age of the universe. Can we be quite sure that over such time intervals our present physical laws can be extrapolated safely? What if Dirac should be right and the gravitational constant measured in atomic units should decrease with time? All the theoretical evolution computations would have to be repeated, and it is easy to see that substantially reduced stellar ages might result.

Enough of unsafe flights of the imagination. Let us turn to another example of evolution phases proceeding on the nuclear rate. A number of authors have recently studied in detail stellar models with two energy sources, helium burning in the core and hydrogen burning in the shell. It seems highly likely that during the latter part of their lives, heavier stars will pass through phases represented by such models. These new investigations all seem to show the following striking feature. The numerical results for the double source models appear to be enormously more sensitive to the numerical values employed, such as for the stellar mass, initial composition, and nuclear cross-sections, than are those for the main sequence models. This may well have as a consequence that different stars will follow very different routes in their advanced evolution phases. Accordingly, it will be much harder to predict accurately the advanced evolution phases for any given star, than it was for the earlier main sequence phases. This disadvantage may well be compensated by the likely corollary that a careful comparison of observed and theoretical stars in advanced evolution phases will teach us much more about the goings-on within individual stars than we could learn from the study of main sequence stars.

3. EVOLUTION AT THERMAL RATE

If we now turn to the next faster class of evolution phases, those in which thermal and gravitational energies play a determining role, we should obviously start with the pre-main sequence contraction. During this phase the star changes from a globule of interstellar matter to a star on the initial main sequence. During this contraction gravitational energy is set free. One half of it goes into heating the interior, the other half supplies the luminosity of the star. Model sequences covering this phase have been computed for a variety of stellar masses, and the corresponding theoretical evolution curves in the Hertzsprung-Russell Diagram have been derived. It was exciting, indeed, when Walker was able to extend the photometric observations in young clusters to fainter magnitudes, and discovered that these clusters did, in fact, contain faint stars to the right of the main sequence, as had been expected from the theory of stars still in the pre-main sequence contraction.

This discovery however, was fast followed by the realization that the observed contracting stars were not lying on the narrow, nearly horizontal line in the Hertzsprung-Russell Diagram, as predicted by theory, but rather scattered over a large area stretching from the predicted line downwards, with some extreme stars lying more than three magnitudes below the expected location. Not only do the extremely young clusters with ages of a few million years show this disturbing phenomenon, but more recently H. L. Johnson and others have shown that the same phenomenon appears to exist in the Pleiades with an age of about a hundred million years. It seems to me that these new observations force us to search for a major modification in our present theory of the pre-main sequence contraction.

Spitzer has made a plausible suggestion for this modification, namely to drop the earlier assumption that the mass of a star remains substantially constant during the contraction phase. If we follow this suggestion and assume that in the last portion of the contraction the star usually either splits or ejects a large fraction of its mass (which incidently is also suggested by the spectroscopic appearance of the T Tauri stars) we can easily explain the observed appearance of very faint stars in the clusters in question, stars so faint that they never could have reached their present observed position in the Hertzsprung-Russell Diagram in the alloted time, if they had had their present low mass and low luminosity throughout the preceding contraction. An alternative explanation of the unexpected appearance of very faint stars in young clusters has recently been suggested by Hayashi. He has pointed out the possibility that very deep convective envelopes may occur during the contraction phases. Such envelopes could produce very high luminosities and hence much faster evolution rates than had been expected for the stars in question. Clearly, the final answer for this puzzle is still in the future.

Recently we have become acquainted with another type of evolution phase in which the thermal energy plays a governing role. This is the helium flash in Population II giants, which Mestel predicted several years ago, and which we have computed through in some detail during the past year in Princeton. May I use this point to emphasize that by far most of the research which I am reporting on in this discourse has not been carried out by us in Princeton but by other astronomers in many different places, and that you would be making a big mistake if you assumed that just because I am reporting this work, I were the author of more than just a small fraction of it. Back to the helium flash. When the degenerate helium core of a Population II red giant gets heated by compression to a temperature of about eighty million degrees, helium burning starts. The energy liberated by the helium burning raises the temperature of the core, which in turn increases the rate of the helium burning. Thus, a thermal runaway occurs. The runaway proceeds so fast that very little of the energy set free can penetrate through the relatively opaque outer layers of the star.

This new situation differs significantly from the evolution phases discussed earlier, if you look at it from the point of view of the energy conservation law. In the main sequence phases the energy lost by the radiative flow is balanced by the nuclear energy generation. In the pre-main sequence contraction the energy lost by the radiative flow is balanced by the gravitational energy set free by the contraction. In the helium flash, however, the loss by the radiative flow is negligible, and the energy liberated by the helium burning goes directly into the non-nuclear internal energy of the star.

The thermal runaway comes to a halt when the temperature reaches about 300 million degrees (and the rate of nuclear energy production corresponds to the luminosity of a whole galaxy). At this point the center of the core becomes non-degenerate, and subsequent energy production by the helium burning leads to an expansion of the core with its automatic cooling and the corresponding calming down of the helium burning. The main net effect of the helium flash thus is the raising of the degenerate core out of its deep gravitational potential well and its transformation into a normal non-degenerate convective core. If this is all, we might well in future skip the laborious computations of the helium flash and jump directly from the state in which the helium flash starts to a state immediately after its end, presumably represented by a model with helium burning in a non-degenerate core and hydrogen burning in a shell. However, another more profound consequence of the helium flash is possible. During the declining portion of the flash a steadily growing convective core developes. Our computations are at present not advanced enough to be sure, but they suggest that this core might well reach the hydrogen-rich outer portion of the star or even contact the deep convective envelope that is characteristic of these giants. If the latter should happen, the star would get convectively mixed from center to surface, would start a new evolution phase, homogeneous in composition though rich in helium, which would place it on the left-hand end of the well-known horizontal branch, and would proceed evolving along that branch toward the right.

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An indirect argument may be added in favor of complete mixing at the end of the helium flash. A few years ago Zhevakin and, more recently, Cox and Kippenhahn and Baker have shown that stellar pulsations may be caused by an indirect effect of the second ionization of helium for stars which are rich in helium in their envelopes. As you know, the horizontal branch of the globular clusters contains the RR Lyrae variables. The pulsations of these variables can now be explained if we accept the possibility that convective mixing at the end of the helium flash has brought out into the envelope a part of the helium produced in the core during the preceding evolution phases. If this mixing does not occur, the pulsations of the RR Lyrae variables remain a mystery since the low helium content usually assumed for the initial composition of Population II stars, would hardly suffice to make the helium ionization mechanism effective. Right at this time, I think I am ready to bet that stellar evolution along the horizontal branch proceeds from the left to the right. But you might be wise to suspect that my main motivation is still the fact that almost everybody else seems to bet on the opposite direction.

Whatever resolution there may be to this particular question, we may well expect that short thermal evolution phases scattered between longer nuclear phases during the later portions of a star's life may profoundly affect its evolution and may lead to big differences in the advanced evolution phases caused by rather minor initial differences.

4. DYNAMICAL EVOLUTION PHASES

I know of only one phenomenon which we can be reasonably sure presents a stellar evolution phase proceeding on the fast dynamical rate. This is the super-nova explosion. Clearly the initial phase of this phenomenon proceeds ferociously fast and, equally important, the super-nova explosion causes a profound evolutionary change in the star; a single super-nova explosion suffices, we think, to put the star into a state radically different from its preceding condition. Several proposals have already been made as to the basic cause of the super-nova phenomenon. But perhaps the time is not yet ripe to select the correct one with definiteness, and as far as I know nobody has yet attempted to follow the dynamical evolution of this explosion in any detail.

Another good example of a dynamical stellar process is the outburst of an ordinary nova. Here again such an outburst clearly proceeds at a rapid dynamical rate. In contrast to a super-nova, however, a single nova outburst does not appear to amount to a major evolutionary step; the star several years after an outburst probably differs rather little from its state before the outburst. There exist indications, however, that a single star will undergo many nova outbursts distributed more-or-less regularly over a very long time interval and that the accumulated effects of these outbursts may amount to a substantial evolutionary change. Thus the nova phenomenon may represent the prototype of an evolution phase in which dynamical processes persistently occur within the star, with each individual such process occurring on a fast rate but with the overall resulting evolutionary changes accruing much more slowly.

The third item on my list of dynamics in the stellar interior is pulsations. Radial pulsations are by far the best understood dynamical process occurring in stars. Not only did Eddington already derive their main characteristics, but recently their basic driving mechanism seems to have been found, at least for the classical Cepheids and the short-period variables, as I have mentioned earlier. That much the more disappointing it is that these pulsations, as far as we can discern at present, do not seem to have any evolutionary consequences. They appear to be much like the measles; almost everybody has them at an appropriate time of his development, but in his subsequent life it is of little consequence whether he had them or not. On the other hand, stellar pulsations are certainly a powerful research tool. For example, the period-density relation provides us with an independent check on our models for the relevant evolution states, and more complicated arguments such as we have just applied to the horizontal branch of the globular clusters can give us valuable hints as to the preceding evolution phases.

Fourth and last on the list of dynamical phenomena are those processes which lead to strong mass ejection from a star. We have already discussed one evolution phase in which such a process may be active, the pre-main sequence contraction. That strong mass ejection may play a decisive role in this early phase was realized only very recently. To the best of my knowledge no detailed dynamical analysis has yet been attempted for this phase.

The present situation is quite different in another phase with substantial mass ejection, that of the red giants. During the past several years a variety of investigations, among them a stimulating spectroscopic analysis by A. Deutsch, have provided more and more indications that mass ejection occurs at an impressive rate in the red giant phase. A number of theoreticians have started to investigate the possible causes of this ejection, and the following picture, though still beset with theoretical difficulties and apparent discrepancies with observational data, has tentatively emerged. The red giants possess deep convective envelopes in which the turbulent velocities in the photosphere are frequently only just sub-sonic. Such strong turbulence will act as an effective source of mechanical waves—be they hydrodynamic or hydromagnetic—of which a good portion may travel upwards and thus provide the energy source for a chromosphere and corona. For the case of the Sun, detailed investigations suggest that such progressive waves are really the cause of the corona. For the red giants much more massive chromospheres and coronas might be expected. Matter will evaporate from a hot corona, and this evaporation may take the form of a steady outward flow of matter in the upper corona and beyond. For the case of the Sun, the existence of such a 'wind' seems fairly safely established. But, the solar wind is so unsubstantial that it will surely not amount to any noticeable mass loss for the Sun during its main sequence lifetime. On the other hand, for the red giants it now seems entirely plausible that their winds are sufficiently strong to reduce their masses by an appreciable factor before the red giant phase is over.

Altogether it would rather seem that for the evolution of the majority of the stars the important dynamical processes are not the cataclismic ones, but rather the weak but persistent ones, and only for a small fraction of all stars does the cataclysmic super-nova phenomenon appear to represent a decisive finale.

5. PROBLEMS AHEAD

I would like to conclude my discussion by pointing out three problem areas which follow closely from the evolutionary processes we have discussed, which I think may be ripe at this time for a detailed attack, and which, I feel, could greatly further our understanding of cosmology as far as this can be furthered through the theory of stellar evolution. I want to imply by no means that these three areas are the only ones worthwhile at present to be worked on in the theory of the stellar interior. For example, the initial formation of stars, the origin of the heavy elements, and the interaction of the evolutions of the components in binary systems are obviously equally exciting problems. The three areas which I would like to mention are simply those that seem to me to cover the most important unsolved facets of the evolution of the majority of individual stars.

The first of these three items is a new attack on the main sequence phases of stars around one solar mass, with the aim of reaching an accuracy substantially higher than it was possible to reach up to now. Only by such an undertaking, I think, can we hope to overcome the present tantalizing situation in which our stellar age determinations based on the main sequence theory have an uncertainty just sufficient to spoil any decisive conclusions in making comparisons with the Hubble constant. Such a new investigation would have to take into account in much more detail than has been done thus far the outer convection zone of the stars in question. Parallel to such theoretical work there will be needed a corresponding push in the accuracy of the color-magnitude diagrams of old clusters. Only when the theoretical and the observed curves in the Hertzsprung-Russell diagram agree in form much more closely than they do now can we accept the resulting stellar ages with confidence.

While the first problem area was related to evolution on the slow nuclear rate, my second area involves the faster thermal phases which appear to be scattered throughout the advanced stages of stellar evolution. For all of us working in this area, I think it is by now abundantly obvious that we will need substantially improved mathematical methods to cover these phases effectively and securely. It is true that we seem to be able to muddle through these phases with a patchwork of methods and with the help of very large electronic computers. The efficiency of the present methods, however, is so low as to be seriously discouraging. New thoughts in this area appear to be developing at several places, including right here at Berkeley, and optimism in this direction might well turn out to be justified.

My third and last area belongs to the field of dynamical evolution phenomena and covers the processes causing mass ejection from red giants. Exciting first steps have been made in this field. However, we clearly do not have a quantitative theory now which permits us to compute the actual rate of mass ejection from stars. Only when such a theory is developed will we be able to follow a star through its later evolution phases and identify these phases with observed types of stars down to the white dwarfs.

Altogether it seems to me in the whole field of stellar evolution there is only one major mistake we can make at this time, and that is to assume that just because exciting progress has been made in this field in the last decade we now have solved the main problems. I do suspect that we now truly understand the main physical processes relevant for the main sequence, but the same can hardly be said for any other phase of a star's life. And surely we must admit that the main sequence, though well populated, is rather a pedestrian section of the whole of the Hertzsprung-Russell diagram. Indeed, I would think that it must be to you, Professor Hertzsprung, cause of appreciable puzzlement to have watched throughout your life a stream of eager theoreticians working hard on these problems and succeeding to understand even by now only the most obvious feature in the diagram which you plotted for the first time more than fifty years ago.