Evolution of red-giant stars

Thermal instabilities in helium-burning shells are linked to the origin of certain elements heavier than iron—in one star the surface abundances of these elements increased by 25 times in the last ten years.

Allen V. Sweigart

Theorists are paying a lot of attention nowadays to the structure and evolution of highly luminous stars with low surface temperatures. These stars, referred to as "red giants" because of their color and large radii, are believed to be in an advanced phase of their evolution. Most stars pass through at least one such phase, late in their lifetimes—as will our Sun.

Why are the red-giant stars of such interest? One reason is the strong suspicion that they are the birthplaces of the so-called "s-process" elements.[1] The "s" stands for "slow": These elements, including strontium, zirconium, technetium and barium, are formed by the successive absorption of neutrons by nuclei with atomic masses close to that of iron on a time scale long compared with their beta-decay lifetimes. Observations show that some red giants possess unusual surface compositions,[2] including enhanced abundances of carbon (relative to oxygen), lithium and the s-process elements.

These composition anomalies presumably result from nucleosynthesis deep in the stellar interior.[3] Evidence that they do not merely reflect differences in a star's initial composition is provided by the remarkable behavior of the star FG Sagittae. Since 1967 the surface abundance of the s-process elements in FG Sagittae has increased to a value approximately 25 times the solar abundance, although prior to 1965 these elements were not significantly enhanced.[4] In this star we are therefore witnessing the actual mixing of s-process elements to the surface.

The discovery of radioactive technetium (which has a halflife of 2×10^5 years) in some red-giant stars also strongly indicates that s-process synthesis can occur during a star's recent evolution. Through mass loss—either by a gradual mass outflow from the surface or by a dynamical ejection of the outer layers—red-giant stars therefore can contribute to the heavy-element enrichment of the interstellar medium and in this way influence the chemical evolution of the Galaxy.

Theoretical progress during the past decade has helped to clarify our understanding of the advanced evolution of red giants and to identify possible nuclear processes by which the s-process elements are created under astrophysical conditions. This article reviews some of the characteristics of this evolutionary phase and discusses the implications of recent work for the problems of s-process synthesis and mixing between the deep interior and the surface, with particular emphasis on some of the remaining difficulties. Let us begin with a brief survey of stellar evolution.

Allen V. Sweigart is a research staff astronomer at the Yale University Observatory, New Haven, Connecticut.

How stars evolve

After its contraction from an interstellar cloud, a star begins its life as a chemically homogeneous object, its energy being derived from the fusion of hydrogen into helium. This hydrogen "burning" gradually depletes the hydrogen supply around the center of the star, so that it eventually forms an inert helium core surrounded by a hydrogen-rich envelope. All nuclear-energy generation will then shift outward to the thin shell that separates the core from the envelope.

The star reacts to this composition change by expanding its outer layers and decreasing its surface temperature. This leads it into its first red-giant phase. During this phase the hydrogen-burning shell advances outward through the mass of the star; this leads to an increased surface luminosity and to a contraction and heating of the helium core.

The first red-giant phase of a star is abruptly terminated when the temperature within its core becomes high enough to ignite helium burning (about 10^8 K) by the reactions

$$3\mathrm{He}^4 \rightarrow \mathrm{C}^{12} + \gamma$$

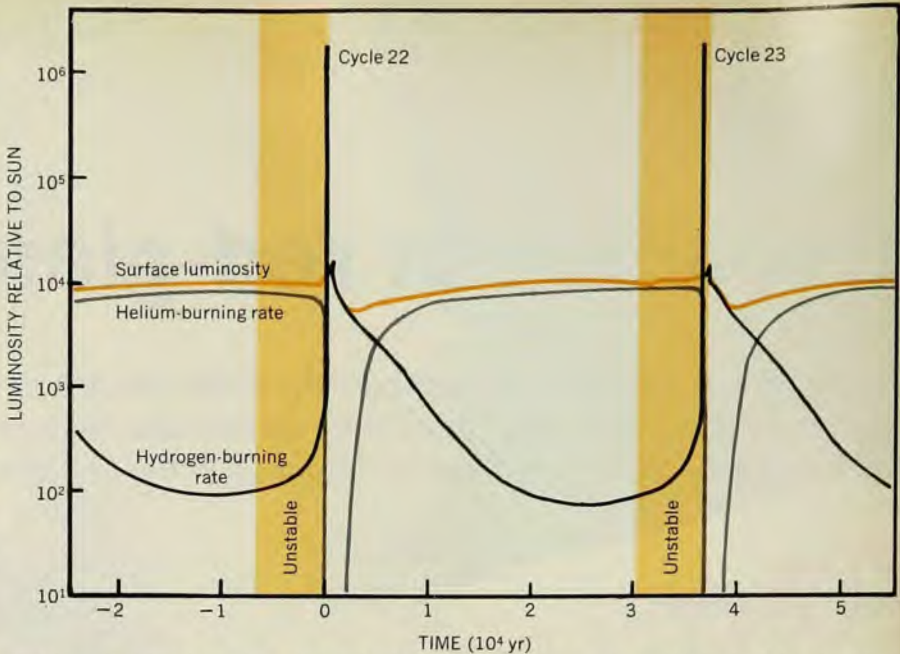
$$\mathrm{C}^{12} + \mathrm{He}^4 \rightarrow \mathrm{O}^{16} + \gamma$$

The onset of helium burning at its center fundamentally alters the structure of the star by adding a new energy source to the hydrogen-shell source already present.

Whether or not a star remains a red giant during this central helium-burning phase depends on the stellar mass. In any case, the helium burning will convert all of the helium near the center into carbon and oxygen, forcing the star to begin helium burning in a shell just outside the helium-exhausted region. Following the transition to helium-shell burning, the star will evolve to higher luminosities and cooler surface temperatures and will thus begin its second red-giant phase.

By the time a star is in its second red-giant phase, its structure has become rather complex. There is an inert core of carbon and oxygen, surrounded by a helium-burning shell, an intershell region largely consisting of helium and, further out, a hydrogen-burning shell. The hydrogen-rich envelope outside of the hydrogen-burning shell is in a state of turbulent convection.

A few typical numbers taken from a star with a mass of $1.5\ M_\odot$ ($1\ M_\odot = 1$ solar mass $= 2 \times 10^{33}$ gm) illustrate the magnitudes of some of the quantities involved. Let M_r denote the amount of mass within a distance r from the center. At the phase of this star's evolution when M_r equalled 0.655 $M_\odot$ for r at the center of the helium-burning shell, its value was 0.669 $M_\odot$ at the hydrogen-burning shell so that the intershell region contained only a small fraction of the total mass (0.014/1.5). At that time the radii of the helium- and hydrogen-burning shells were only 1.5 and 2.6 Earth radii, respectively, while the surface radius was 48 000 Earth radii, about twice the radius of Earth's orbit around the Sun. The central density and temperature were 3×10^6 gm/cm^3 and 9×10^7 K, and consequently the electron gas was degenerate throughout most of the C–O core, although not outside of it. Essentially the structure of the star consisted of a rather dense inner region containing the two energy sources and a very extended outer envelope with a much lower density. The luminosity of the star was $10^4\ L_\odot$ ($1\ L_\odot$ = 1 solar luminosity = 4×10^{33} erg/sec) with the hydrogen-burning shell supplying *on the average* about 85 percent of the energy output and the helium-burning shell the remaining 15 percent.



Instabilities alternating with quiescent phases are here shown for the 22nd and 23rd cycles of a 1.5 $M_\odot$ star. The graphs show the time dependences of the helium-burning rate (grey line), hydrogen-burning rate (black line) and surface luminosity (colored line), all in units of the solar luminosity. The initial mass composition of the star was 68% hydrogen, 30% helium and 2% heavier elements. The time zero has been set to coincide with the 22nd helium-shell flash. The vertical colored bands indicate periods of thermal instability. Figure 1

Thermal instability

The original investigations into the second red-giant phase disclosed quite unexpectedly that the rate of helium burning, rather than varying smoothly with time, periodically undergoes fluctuations of high amplitude.[5,6] More extensive analysis demonstrated that these fluctuations were due to an inherent thermal instability of the helium-burning shell, as can be seen from the following argument:

Suppose that a positive temperature perturbation occurs within a nuclear-burning shell. Because of the strong temperature dependence of the nuclear reaction rates, the rate of energy generation ϵ within the shell will increase. Typically this increased burning rate would cause an expansion and subsequent cooling of the shell, thereby damping the temperature perturbation and insuring thermal stability. However, in some cases the star's readjustment increases the temperature, enhancing the initial temperature perturbation, and making the shell thermally unstable.

Two general conditions must be fulfilled[5] for such an instability to occur:

- The shell must be thermally thick. This means that the shell must retain some of the excess energy due to the increase in ϵ and must not permit all of it to escape.
- On the other hand, the shell must be thin enough not to disturb seriously the hydrostatic structure of the star when the shell expands.

For simplicity let us assume that the ideal gas law is the appropriate equation of state for the shell, so that its pressure is proportional to the product of its density and temperature. The expansion produced by the heating of the shell can cause a rather large drop in the density if the shell is sufficiently thin. In hydrostatic equilibrium the outward force due to the gas pressure at the shell must just balance the weight of the layers lying above it. This pressure will not be greatly changed by the expansion of a very thin shell, since the exterior layers will not be pushed outward by a significant amount; for a thick shell the weight of these layers will (by the inverse-square law) decrease considerably. If the relative decrease in the density exceeds that in the pressure, the temperature of the shell given by the ideal-gas law will rise: The result is thermal instability.

These two conditions can be satisfied only if the temperature dependence of the nuclear reaction rate is sufficiently high.[5] This is the case for helium burning, for which the energy-generation rate varies as T^{30}, but not (with a few possible exceptions) for hydrogen burning, for which $\epsilon \propto T^{16}$. Thermal instability can also occur in shells burning elements heavier than helium. Such shells are formed during the advanced evolutionary phases of massive stars, but will not be discussed here.

Whenever the helium burning reaches very high values, the region being heated and expanded will include not only the shell but also the neighboring layers. The second of the above conditions will then be violated, leading to a return of thermal stability and relaxation of the perturbed layers.

Helium burning during the second red-giant phase consequently takes place in a series of helium-shell "flashes" during which the rate of helium burning can exceed its normal quiescent value by several orders of magnitude. These flashes occur in stars covering a wide range in mass and composition, and appear to be a general characteristic of this evolutionary phase.

Because of these flashes a star will evolve through a sequence of relaxation cycles.[7] Each such cycle consists of an "active phase" during which the helium-shell flashes take place and a "quiescent phase" during which the helium burning is typically quite low. Usually the basic structure of a star does not change significantly between successive cycles. Let us begin our discussion of these results with an examination of what happens during a typical cycle.

A relaxation cycle

The 1.5 $M_\odot$ star referred to previously can again provide a convenient example for describing the characteristics of a typical relaxation cycle. Figure 1 gives the time dependence of the helium-burning rate L_{He}, the hydrogen-burning rate L_H and the surface luminosity L during two advanced cycles (the 22nd and 23rd relaxation cycles) of this star. Beginning at time $t = -0.7 \times 10^4$ yr in this figure, the helium-burning shell becomes thermally unstable and the star enters into an active phase. In response to the thermal instability the helium-burning shell flashes with L_{He} reaching a peak value of $2 \times 10^6\ L_\odot$ before the instability is relieved. There is a mild secondary maximum in L_{He} (about $10^4\ L_\odot$) at $t = 340$ yr. The main (strongest) helium-shell flash during an active phase is always the first one, but it is not unusual for there to be one or more secondary flashes which, depending on the particular star, can also be quite strong.[7] Following the secondary maximum, near $t = 0$ in figure 1, the helium burning gradually declines, marking the end of the active phase. During the subsequent quiescent phase, from about 5000 yr to 30 000 yr, the helium burning is very weak and the hydrogen burning supplies most of the surface luminosity.

The high rate of energy generation during a flash causes an outward expansion and cooling of the hydrogen-shell region, resulting in an abrupt extinction of the hydrogen burning at $t = 0$. The hydrogen burning does not recover until near the end of the active phase. Between successive active and quiescent phases the dominant energy source therefore alternates between helium and hydrogen burning. However, the variation in the surface luminosity is much smaller than the variations in L_{He} and L_H. At $t = 3 \times 10^4$ yrs, the helium-burning shell is once again thermally unstable and the sequence of events just described will be repeated for the next relaxation cycle.

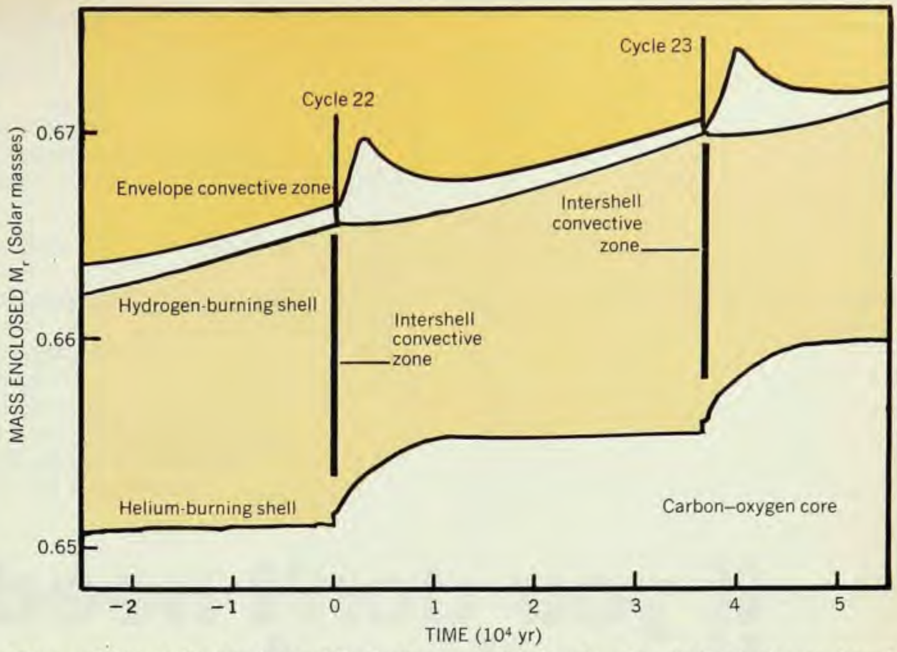
Figure 2 shows how the locations of the helium- and hydrogen-burning shells change during a relaxation cycle. The center of the helium-burning shell is defined here to be the point where the helium abundance is half of its intershell value. The hydrogen-burning shell in this star contains only $10^{-4}\ M_\odot$, which corresponds roughly to the thickness of its curve in the figure. Normally the region between the two shells is in radiative equilibrium, so that the energy in this region is transported outward entirely by the radiation field. When the helium-burning shell flashes, however, the outward energy flux becomes too great for the radiation field to carry alone. Therefore an intershell convective zone in which mass motions help carry the energy flux will develop for a brief period. The two spikes in figure 2 represent the outer edge of the intershell convective zone and thus mark the time of the main helium-shell flashes.

During the quiescent phases the location in mass of the helium-burning shell remains almost fixed. There is a considerable overlap of the material in the intershell region between cycles.

Although the cycle characteristics in figures 1 and 2 remain qualitatively correct for other stars, they can differ substantially in their actual numerical values. These characteristics depend primarily on the mass M_c within the carbon–oxygen core, with the total mass and composition of a star being usually of secondary importance. For example, there is an approximate relation between M_c and L given by the equation[8]

$$L/L_\odot = 59\,250(M_c/M_\odot - 0.522)$$

This relation shows the sensitive core-mass dependence of the surface luminosity. The cycle length τ has been found to be a strongly decreasing function of M_c.[9] Typical values for τ range from about 10^6 yr at $M_c = 0.39\ M_\odot$ to 2500 yr at $M_c = 0.95\ M_\odot$.[10] The core mass at the time of the first helium-shell flash increases with the total mass M, being[7,11] about 0.4–0.5 $M_\odot$ when M is one solar mass or less and[10] 0.95 $M_\odot$ at $M = 7\ M_\odot$. The amount of mass between the two shells becomes less for larger values of M_c. During the initial relaxation cycles this intershell mass is[7] generally just under 0.1 $M_\odot$ for M less than or equal to one solar mass, while[10] at $M = 7\ M_\odot$ it is only 0.002 $M_\odot$.



Time variation of the locations of the hydrogen- and helium-burning shells, the inner edge of the envelope convective zone and the outer edge of the intershell convective zone (when it is present) for the star and time period of figure 1. The positions are given in terms of the mass M_r enclosed by a sphere of radius r about the center of the star. Figure 2

The active phase

Whether s-process synthesis and extensive internal mixing can result from a helium-shell flash depends on the star's behavior during an active phase. Figure 3 illustrates how L_{He}, L_H and L vary during an active phase of the 1.5 $M_\odot$ star. There is a brief period of thermal instability between 54 and 106 years, which helps drive L_{He} down to lower values after the main flash. At the peak of the main flash, most of the energy from the helium burning goes into heating and expanding the helium-burning shell and the intershell region without increasing substantially the outward energy flux at the hydrogen-burning shell.

The abrupt termination of hydrogen burning at $t = 0$ produces a decrease in the surface luminosity for t between 7 and 65 years. During this interval the envelope contracts as the star tries to maintain its surface luminosity by the release of gravitational potential energy. Eventually at $t = 65$ yr the energy from the helium burning reverses this contraction and causes a rather rapid rise in the surface luminosity. It is near the subsequent maximum in L that the envelope convective zone reaches its deepest inward penetration in mass. In effect the envelope acts as an energy reservoir upon which the star can draw to minimize changes in its luminosity.

The locations of the two shell sources and the various convective edges during the 23rd active phase of the 1.5 $M_\odot$ star are given in figure 4. The intershell convective zone appears just above the helium-burning shell shortly before the flash peak and grows in extent until it reaches from the center of the helium-burning shell outward to just inside the inner edge of the hydrogen-burning shell. Later, as L_{He} drops off, the intershell convection recedes and finally disappears.

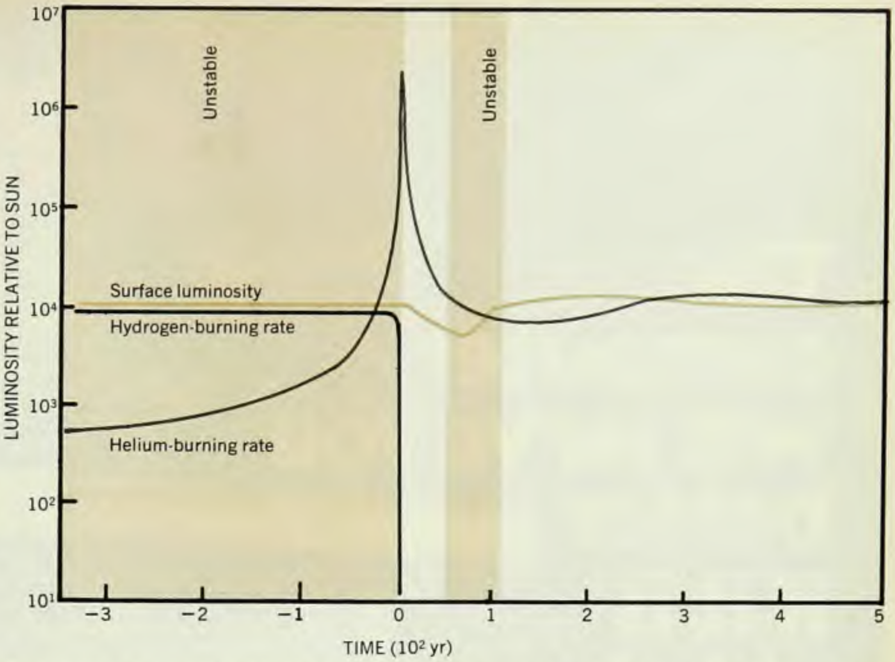
The existence of intershell convection strongly modifies the composition distribution in this region of the star.[7] The convective motions will carry carbon outward from the helium-burning shell. A discontinuity in the carbon abundance will therefore be created at the outer edge of the intershell convec-

tive zone. For the 1.5 $M_\odot$ star the intershell carbon abundance after 23 cycles was 30 percent by mass. However, only a small amount of oxygen is deposited into the intershell region, since little oxygen is produced by the reaction

$$C^{12}(\alpha, \gamma)O^{16}$$

under conditions of high helium abundance.[3]

The drop in the hydrogen-burning rate at $t = 0$ causes the inner edge of the convective envelope to retreat outward initially, for t between 3 and 48 years. Later, when the surface luminosity increases, the envelope convection moves inward, with its deepest penetration occurring at $t = 211$ yr. The maximum extent of the intershell convection and the deepest penetration of the envelope convection do not happen simultaneously—in fact, the convective envelope starts to recede as the intershell convection approaches close to the hydrogen-burning shell.



An expanded view of the active phase of the 23rd cycle of the star described in figure 1. The zero of the time scale is here reset to the peak of the main helium-shell flash (3.67×10^4 yr in figure 1). When the hydrogen burning stops, the envelope contracts. Figure 3

S-process synthesis and mixing

Two crucial questions can now be asked concerning the possibility of s-process synthesis and mixing during a helium-shell flash:

▸ Does the intershell convective zone at its maximum extent penetrate outward into the hydrogen-burning shell? If such penetration takes place, protons from the hydrogen-burning shell will be mixed into the intershell region. There they will react with the abundant carbon-12 nuclei to form (mainly) carbon 13 by the reactions

$$\begin{aligned} C^{12} + p &\rightarrow N^{13} + \gamma \\ N^{13} &\rightarrow C^{13} + \beta^+ + \nu \end{aligned} \qquad (1)$$

provided the number of protons is small compared with the number of C^{12} nuclei.[12] The C^{13} thus produced will be carried inward by convection until it is destroyed by the reaction $C^{13}(\alpha, n)O^{16}$ at the higher temperatures that prevail near the helium-burning shell. The net result therefore is the liberation of one neutron for each proton that is mixed into the intershell region. The s-process elements can then be built up by the successive absorption of these neutrons on the iron-peak nuclei.[12,13] If such mixing occurs for one flash, it will probably occur for a few subsequent flashes, since the structure of a star changes only slightly from one cycle to the next.

▸ Does the envelope convection at its deepest penetration reach through the hydrogen-burning shell and into the intershell region? Such a deep penetration would transport helium and carbon, as well as any s-process elements previously formed, outward to the surface.

Tentative answers to these questions can be obtained from recent calculations of stellar models. In the description of these calculations, it is most convenient to consider stars in different mass ranges separately. Let us discuss first the case of the higher mass stars, for which the theoretical results are particularly encouraging.

Extensive calculations have demonstrated that the intershell convective zone does not reach into the hydrogen-burning shell during the first ten relaxation cycles of a 7 $M_\odot$ star.[10] However, the absence of any proton mixing does not preclude s-process synthesis in this case for the following reason:

In this 7 $M_\odot$ star, hydrogen burning proceeds *via* the so-called "carbon–nitrogen–oxygen bi-cycle," a set of nuclear reactions in which C, N and O act as catalysts for the fusion of hydrogen into helium. The CNO bi-cycle will transform most of the CNO elements into nitrogen 14, which is then deposited into the intershell region by the outward advance of the hydrogen-burning shell. During the flashes, the N^{14} in the intershell region is converted into neon 22 by two successive alpha-capture reactions. It seems quite plausible that the additional reaction

$$Ne^{22}(\alpha, n)Mg^{25}$$

can proceed at a significant rate during later cycles when the maximum flash temperatures are higher. This reaction would then yield the necessary neutrons for s-process synthesis. By the tenth cycle of this 7 $M_\odot$ star, the envelope convection reached into the region that had been previously part of the intershell convective zone. Unfortunately this mechanism for s-process synthesis and mixing probably does not operate in stars of much lower mass for two reasons: A deep penetration of the envelope convection is less likely, and the high temperatures needed for the reaction $Ne^{22}(\alpha, n)Mg^{25}$ would probably not occur.

Another mechanism, applicable to somewhat less massive stars, is the model for plume mixing.[14] The plume model essentially describes the hydrodynamic events that might follow from a contact between the intershell convective zone and the hydrogen-burning shell. The occurrence of such contact—and hence proton mixing—represents a basic assumption in this model. Detailed flash calculations have shown that the intershell convective zone consistently comes close to, but does not touch, the hydrogen-burning shell for stars with masses appropriate for plume mixing. Nevertheless such contact cannot be ruled out in view of the uncertainties and simplifications in the calculations (such as the assumption of spherical symmetry and the neglect of rotation and magnetic fields[15]). Consequently we should look briefly at some of the main features of the plume model.

Any protons mixed inward will be consumed by reactions 1. Provided the temperature at the mixing interface is high enough, these reactions will take place primarily in the outermost part of the intershell convective zone, where the reaction rates will be enhanced by the relatively large carbon abundance. Some of the carbon 13 thus formed will be carried inward, producing neutrons and s-process elements in the manner

EMR's Optical Data Digitizer provides direct computer input from a visual source.

Until quite recently, visual data had to be manually or mechanically pre-processed before the computer could synthesize it into meaningful information. The new EMR Optical Data Digitizer has made this off-line pre-processing a thing of the past. With the O.D.D., the compter perceives visual data on-line as it controls dwell and scan—looking out for itself!

By eliminating the pre-processing operation and by permitting the selection of pertinent input, the O.D.D. expands the service capability of the computer into visual applications such as:

- Inspection/quality control
- Film reading and image analysis
- Medical instrumentation
- Astronomy
- Dimensional Analysis

The Optical Data Digitizer creates the binary equivalent of a two-dimensional optical image and thus prepares it for immediate input for the computer. Having complete control over the O.D.D. scan along the X,Y coordinates enables the computer to select the size of each scanning step, choose the direction of the scan, determine the dwell time per element, all with random access capabilities. The computer, based on predetermined instructions, can then perform computations and initiate procedures in accordance with the kind of data it receives.

For technical specifications on the EMR Optical Data Digitizer, fill out the coupon and mail to:

EMR
Schlumberger

EMR PHOTOELECTRIC

Box 44, Princeton, New Jersey 08540
Telex 84-3459 • Telephone 609•799-1000

SALES OFFICES

Eastern
Box 44
Princeton, New Jersey 08540 609·799-1000

Western
4676 Admiralty Way
Marina del Rey, California 90291 213•822-1441

International
EMR PHOTOELECTRIC
1 Rue Nieuport
78140 Velizy Villacoublay, FRANCE 946-96-50

EMR Photoelectric
Box 44
Princeton, New Jersey 08540

☐ Send technical specifications.
☐ Have sales representative call.

Name ______ Title ______

Affiliation ______

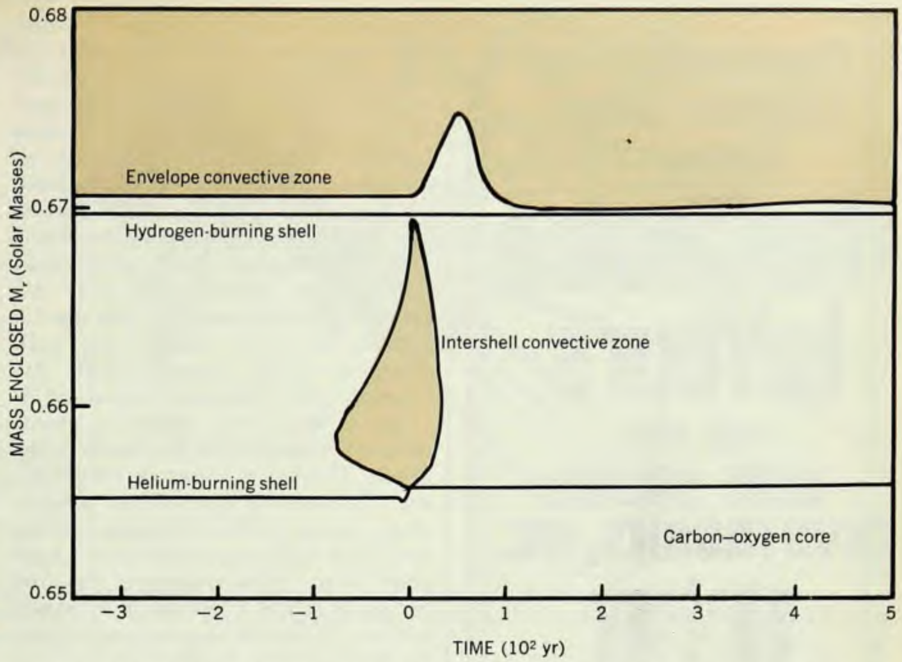
Address ______

City ______ State ______ Zip ______

Circle No. 42 on Reader Service Card

18272

described above. The heating caused by the proton burning will create a buoyant force on mass elements just inside the mixing interface. As the proton mixing continues and these mass elements grow in size, they become increasingly able to retain more of the energy from the proton burning. Eventually the buoyancy becomes so great that bubbles of matter will rise upward through the hydrogen-burning shell in the form of plumes, thereby bringing carbon and s-process elements into the envelope. Additional protons will be captured by the plumes through the process of entrainment. In effect the plumes represent a form of convection which is driven by an internal energy source (the proton reactions with C^{12}) rather than by a steep temperature gradient, as is normally the case. A high temperature is required at the mixing interface for the proton-burning reactions to drive the plumes and this restricts plume mixing to stars of mass greater than about two solar masses.[14]. The problem of finding a mixing mechanism therefore still remains for stars of lower mass.



Movement of the shells and convective zones (colored) of the active phase of the same star as in the previous figures, on the time scale of figure 3. The intershell convective zone appears just before the flash peak and grows almost to the hydrogen-burning shell. Figure 4

Difficulties for low-mass stars

A number of theoretical difficulties have been encountered in attempting to explain s-process synthesis and mixing in stars with masses of about one solar mass or less—despite observational evidence indicating that some low-mass stars do in fact produce s-process elements.[2,16]

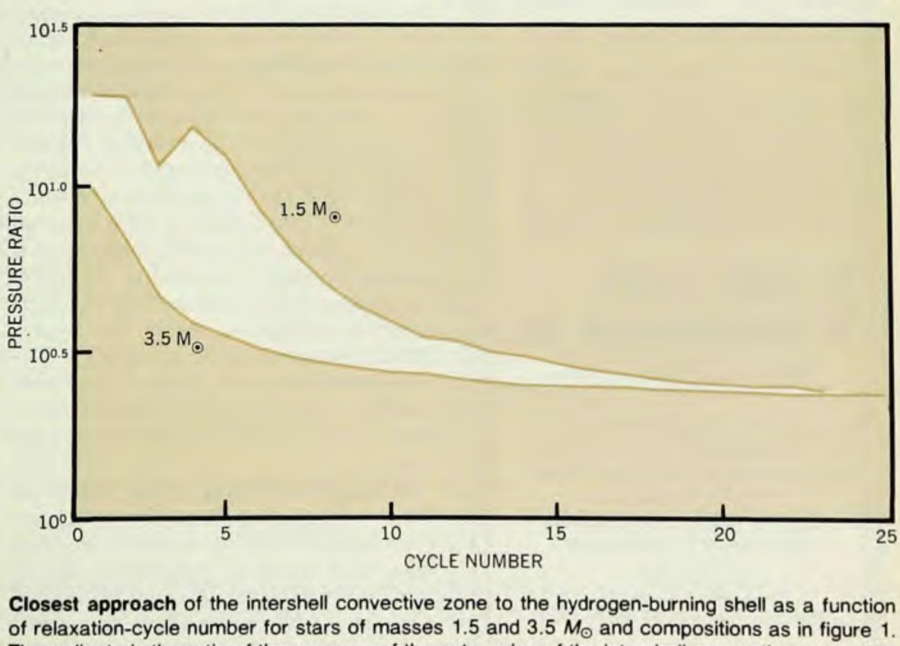
One mechanism proposed for the low-mass stars involves the following scenario.[9] Suppose that the intershell convective zone penetrates deeply into the hydrogen-burning shell during a helium-shell flash. The protons mixed inward will react with C^{12} nuclei to create a new energy source within the intershell zone. Some of this energy might possibly go into increasing the outward energy flux near the hydrogen-burning shell. This could cause an outward extension of the intershell convective zone by enhancing the degree of convective instability. In fact, one could imagine an unstable situation in which any extension of the intershell convective zone would bring in enough protons to release the additional energy needed to drive the convection outward even further. Such a convective runaway could conceivably lead to a merging of the intershell convective zone with the envelope convective zone and thus to a complete mixing of the layers above the helium-burning shell. Both carbon and the s-process elements would then be transported up to the surface. This sequence of events, although plausible at first glance, has unfortunately not been substantiated by detailed flash calculations.

The scenario of the last paragraph rests on the two assumptions that

- a helium-shell flash can induce appreciable proton mixing and
- the energy released by the proton burning can force a significant extension of the intershell convective zone.

The response of the intershell region to proton mixing has not been adequately investigated so far, but preliminary results indicate that substantial proton mixing might cause it to split into two separate convective regions.[17] The outer of these two regions might perhaps extend further into the hydrogen-burning shell. For small amounts of proton mixing, however, the energy from the proton burning will be almost entirely absorbed by the expansion of the intershell region and hence will not extend the convection.[17] A convective runaway would only be possible, if it occurs at all, after a flash has initiated major proton mixing.

The basic question therefore is whether proton mixing actually results from a helium-shell flash. With one exception no flash calculations have shown any significant proton mixing even though a rather wide variety of stars has been studied. The only ex-



Closest approach of the intershell convective zone to the hydrogen-burning shell as a function of relaxation-cycle number for stars of masses 1.5 and 3.5 $M_\odot$ and compositions as in figure 1. The ordinate is the ratio of the pressure of the outer edge of the intershell convective zone at its peak extent to that at the inner edge of the hydrogen-burning shell. Figure 5 ception was found in the case of a one-solar-mass star.[7] In all other cases the intershell convective zone consistently missed reaching into the hydrogen-burning shell by a small but definite amount. Even for the 1 $M_\odot$ star, the intershell convection never reached outward beyond the inner tail of the hydrogen-burning shell so that the amount of proton mixing was always quite small. Furthermore, during the more advanced relaxation cycles of this star the amount of proton mixing per cycle dropped greatly even though the strength of the flashes had increased.[18]

The difficulty with producing proton mixing is illustrated more clearly in figure 5. This figure shows that the intershell convective zone comes progressively closer to the hydrogen-burning shell with each successive cycle. After about ten cycles, however, the two curves in figure 5 decline more slowly and may in fact be approaching a limiting value of 0.4. Similar behavior has been found for other stars. These results indicate that proton mixing is unlikely to occur during cycles beyond the 25th.

There remains the possibility that the mass motions within the intershell convective zone might overshoot the formal edge of this zone. Such convective overshooting would, however, have to overcome a number of obstacles. The region just outside the intershell convective zone is in general quite stable against convection. Furthermore, the discontinuity in the carbon abundance at the edge of the intershell convective zone will produce a density discontinuity (for pressure balance) with the heavier material on the inside. This likewise will hinder any overshooting. The convective overshooting would also have to be quite efficient, because the phase of maximum intershell convection lasts only a short time.

The remaining possibility for extensive mixing depends on a penetration of the envelope convective zone into the intershell region. The envelope convective zone is generally found to move inward during the phase of rising surface luminosity that follows a flash (see figure 4). In low-mass stars, however, this inward advance is stopped at the top of the hydrogen-burning shell by the large pressure difference across the hydrogen-burning shell at this phase.[17] The envelope convective zone is therefore unlikely to mix material from the intershell region to the surface in low-mass stars.

From these results we may conclude for low-mass stars that the hydrogen-burning shell acts like a barrier blocking both an outward penetration by the intershell convective zone and an inward penetration by the envelope convective zone. The question of how s-process synthesis and mixing can occur during the advanced evolution of low-mass stars remains an outstanding problem.

An active area

We have seen that a key reason for the current interest in the advanced evolution of red-giant stars has been the discovery of thermal instability of the helium-burning shell, the phenomenon that causes the helium-shell flashes. These flashes appear to be closely linked with the origin of the s-process elements observed in the Galaxy. The descriptions developed to explain s-process synthesis are most successful for stars of higher mass; for the low-mass stars the question of how s-process synthesis can occur remains unresolved. It is the existence of such questions, however, that makes the subject of red-giant evolution an active area of research.

* * *

This article is adapted from review presented at the March 1975 meeting of the American Astronomical Society in Bloomington, Indiana, as part of a special session on "Evolution of Giants and Supergiants." Support of grant GP 32485 from the National Science Foundation is gratefully acknowledged.

References

1. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).
2. G. Wallerstein, Ann. Rev. Astron. and Astrophys. **11**, 115 (1973).
3. J. W. Truran, in *Proceedings of the Conference on Red Giant Stars* (H. R. Johnson, J. P. Mutschlecner, B. F. Peery, eds.), Bloomington, Indiana, page 394 (1973).
4. G. E. Langer, R. P. Kraft, K. S. Anderson, Astrophys. J. **189**, 509 (1974).
5. M. Schwarzschild, R. Härm, Astrophys. J. **142**, 855 (1965).
6. A. Weigert, Z. Astrophys. **64**, 395 (1966).
7. M. Schwarzschild, R. Härm, Astrophys. J. **150**, 961 (1967).
8. B. Paczyński, Acta Astron. **21**, 417 (1971).
9. I.-J. Sackmann, K. H. Despain, Astrophys. J. **189**, 523 (1974).
10. I. Iben Jr, Astrophys. J. **196**, 525 (1975).
11. R. A. Gingold, Astrophys. J. **193**, 177 (1974).
12. R. H. Sanders, Astrophys. J. **150**, 971 (1967).
13. A. G. W. Cameron, W. A. Fowler, Astrophys. J. **164**, 111 (1971).
14. J. M. Scalo, R. K. Ulrich, Astrophys. J. **183**, 151 (1973).
15. E. H. Levy, W. K. Rose, Astrophys. J. **193**, 419 (1974).
16. O. J. Eggen, Astrophys. J. **177**, 489 (1972).
17. A. V. Sweigart, Astrophys. J. **189**, 289 (1974).
18. A. V. Sweigart, Astrophys. J. **168**, 79 (1971).