The Story of AGB Star Evolution – An Intimate Connection between Theory and Observation

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Abstract

A summary is given of results of theoretical and observational studies of asymptotic giant branch (AGB) evolution. High and intermediate mass AGB model stars activate the ^{22}Ne neutron source during thermal pulses, produce s-process isotopes in a non-solar distribution, and dredge these isotopes along with fresh ^{12}C up to the surface. Observations suggest that real counterparts do not live long enough to become carbon stars, but the actual distribution of s-process isotopes is not yet known. Low mass AGB models of low metallicity activate the ^{13}C neutron source during thermal pulses, produce s-process isotopes in the solar-system distribution, and dredge freshly produced isotopes and ^{12}C to the surface when convective overshoot is assumed. Low mass AGB models of solar metallicity have not yet been persuaded to activate the ^{13}C neutron source, although they do dredge up fresh ^{12}C. Observations show that, independent of metallicity, real low mass AGB stars dredge up both carbon and s-process isotopes, the latter in the solar-system distribution.

I. *Preamble*

Over the past year, in the wake of SN 1987a's first appearance, we have been treated to a marvelous example of how theory and observation interact in astrophysics, with both theory and observation playing absolutely essential roles in guiding us to an understanding of an extraterrestial phenomenon. For the first time, we have direct evidence that stars of initial mass in the range $20 \pm 5\ M_{\odot}$ actually develop a neutron star remnant with theoretically anticipated properties, including the release of gravitational potential energy of the expected order of magnitude and the expulsion of envelope matter containing freshly produced iron-peak elements. For years, there have been conflicting theoretical (numerical, model based) inferences as to how much, if any, material from the imploding iron-nickel core of a massive star would be expelled. Now, thanks to SN 1987a, we have a quantitative understanding of how much of this core is expelled, something that really cannot be estimated unambiguously from first principles. And yet, without the prior theoretical exploration and numerical modeling, we would not have been able to interpret aspects of the observed light curve in terms of the release of nuclear energy by radioactive nickel and cobalt.

A no less important, but certainly less immediately spectacular example is our growth in understanding of asymptotic giant branch (AGB) stars. Over the past two decades, a combination of theoretical and observational discovery has given us insight into the last stages of the evolution of low and intermediate mass stars prior to their becoming white dwarfs. Both theory and observation have made essential contributions. Without observation, theory alone would have led us astray; and without a theoretical framework, the observations would be of little use in adding to our understanding.

We are now persuaded that the AGB phase is the last nuclear-burning phase which all stars of mass less than about 8 $M_{\odot}$ experience. Hydrogen and helium burn alternately in thin shells above an inert electron-degenerate carbon-oxygen (CO) core. That this phase is indeed the last burning stage for all stars of low and intermediate mass was not an initial prediction of the theory, although a few tentative theoretical speculations were advanced that this might be the case. It is really observational evidence that has taught us most convincingly that the AGB phase is terminal. For example, if all stars of initial mass in the range (1.4 - 8) $M_{\odot}$ were to remain AGB stars long enough for their CO core to grow to the Chandrasekhar mass of 1.4 $M_{\odot}$, the supernova rate in galaxies similar to our own would be over 20 times the observed rate (Iben 1981), and one could infer from this that most stars initially less massive than 8 $M_{\odot}$ must somehow lose essentially all of their hydrogen-rich envelope before their CO core grows to 1.4 $M_{\odot}$. The properties of planetary nebulae, including their occurrence frequency, offer further observational evidence that mass loss terminates the AGB phase. This same story is told even more directly and emphatically by the paucity of luminous AGB stars in the Magellanic Clouds and by the observed rates of mass loss from AGB stars in our own Galaxy.

On the other hand, theory has been able to show how AGB stars make carbon and s-process isotopes (such as radioactive ^{99}Tc) in their interiors and bring these freshly produced elements to the surface. Theory is also now beginning to converge on how mass is ejected from AGB stars. Ingredients include the formation of grains, which are pushed outward by radiation pressure to inflate the stellar envelope, and shock heating of an expanding atmosphere induced by acoustical pulsations which are driven by thermodynamic conditions below the photosphere.

In an earlier review this year (Iben 1988), I emphasized the role of observations in guiding our understanding of AGB star evolution. In this essay, I will summarize what we have learned about the activation of the neutron source in AGB stars and about the dredge up of freshly processed carbon and neutron rich isotopes to the surface, emphasizing theoretical insights.

II. *AGB Stars of Intermediate Mass*

A) *Basic Structure and Thermal Pulses*

By intermediate mass I mean stars which are sufficiently massive that they do not

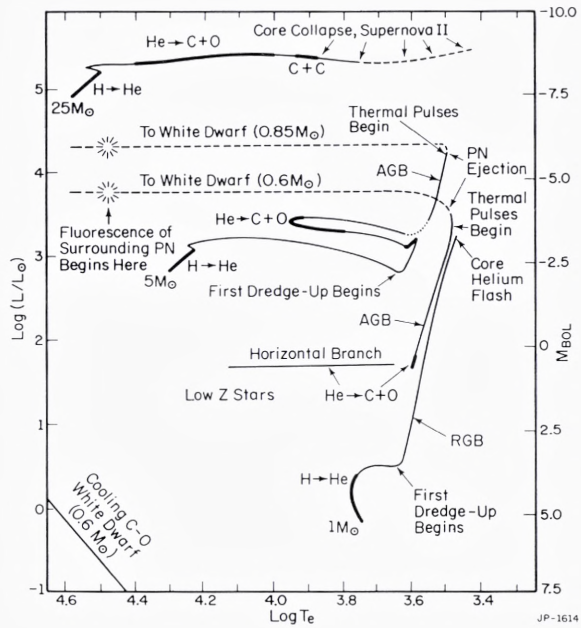

Figure 1. The evolutionary paths in the HR diagram of model stars of population I composition and of initial mass 1 $M_\odot$, 5 $M_\odot$, and 25$M_\odot$. The 25 $M_\odot$ model burns hydrogen in its core as a hot main-sequence star, helium in its core as a blue star, carbon in its core as a blue star, and experiences a core collapse and type II supernova explosion shortly after exhausting central carbon. The 5 $M_\odot$ model becomes an AGB star after exhausting helium in its core (the solid curve at the highest luminosities along the 5 $M_\odot$ evolutionary track). Observations suggest that, shortly after it enters the thermally pulsing phase, the real analogue loses most of its hydrogen-rich envelope and evolves rapidly to the blue, eventually to become a white dwarf. Along the way, it excites the nebular material about it into flourescence. A low mass star becomes a horizontal branch or red giant "clump" star while it burns helium in its core and hydrogen in a shell. After it exhausts central helium, it becomes an AGB star before losing most of its hydrogen-rich envelope and evolving into a white dwarf configuration.

form an electron-degenerate core until after they have exhausted helium at their centers, but light enough that they develop such a core before igniting carbon. In practice, this means stars with an initial main-sequence mass in the range about 2-8 $M_\odot$. Both the lower and upper limits to this mass range depend on the choice of composition, and both are highly uncertain due to the uncertainty in the treatment of convective overshoot during the main-sequence and core helium-burning phases.

After the exhaustion of central helium, helium burning takes place in a shell. The material at the helium-hydrogen interface and beyond is pushed outward to such low temperature and densities that hydrogen burning effectively ceases until the helium-burning shell almost reaches this interface. Then, hydrogen is reignited and helium burning dies down temporarily. Thereafter, hydrogen and helium burning alternate in supplying surface luminosity. When this alternation begins, the mass of the CO core is about 0.3 $M_\odot$ for stars of initial mass near the lower limit of $\sim$ 2 $M_\odot$ and increases to about 1.1 $M_\odot$ for stars of initial mass near the upper limit of $\sim$ 8 $M_\odot$. The evolutionary track of a 5 $M_\odot$ model star in the Hertzsprung-Russell diagram all the way to the beginning of the alternate-burning (or thermally pulsing) phase is shown in Figure 1.

Each time the hydrogen-burning shell has laid down a thick enough layer of helium, temperatures and densities in this layer become large enough to ignite helium

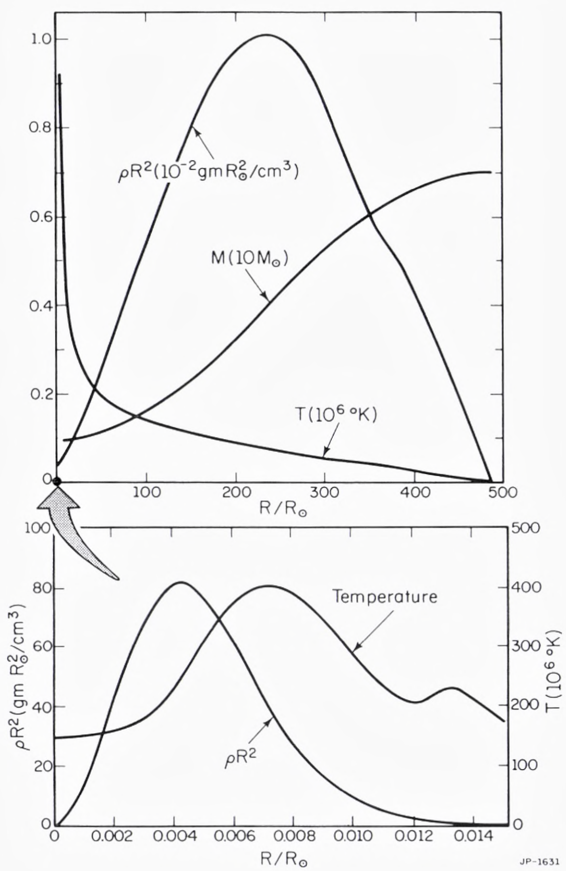

Figure 2. The density, temperature, and mass distributions within an AGB model of core mass M_{CO} $\sim$ 0.95 $M_\odot$ and total mass M_* = 7 $M_\odot$. The core characteristics are shown in the lower panel and the envelope characteristics are shown in the upper panel.

explosively. Matter at and above the helium-hydrogen interface is again pushed out to such an extent that hydrogen burning ceases. In a matter of few years to decades, depending on the mass of the CO core, the thermonuclear runaway is quenched and the star embarks on a phase of quiescent helium burning which continues until the amount of mass which has been converted into carbon and oxygen equals the amount of mass which has passed through the hydrogen-burning shell during the preceding interpulse phase. Then hydrogen burning takes over and continues until another "helium shell flash" or "thermal pulse" is excited.

The structure of a thermally pulsing AGB model of mass $M_* = 7\ M_\odot$ is illustrated in the two panels of Figure 2. At the center of the model star is a very hot white dwarf of mass $M_{co} \sim 0.95\ M_\odot$ and radius $R_{co} \sim 0.01\ R_\odot$ (lower panel). The maximum in the temperature occurs where the rate of cooling by neutrino losses is just balanced by the rate of heating due to compression. Most of the matter in the model resides in a very low density, low temperature, giant envelope (upper panel). Between the giant envelope and the central white dwarf is the "nuclear-active" region. A thermal pulse has just begun and this is reflected in the "bump" in temperature that occurs at a radius $\sim 0.013\ R_\odot$. The progress in time of this bump is illustrated in Figure 3. The outward movement and cooling of the boundary between hydrogen-rich matter and hydrogen-exhausted matter (the "XY discontinuity") is evident in this figure.

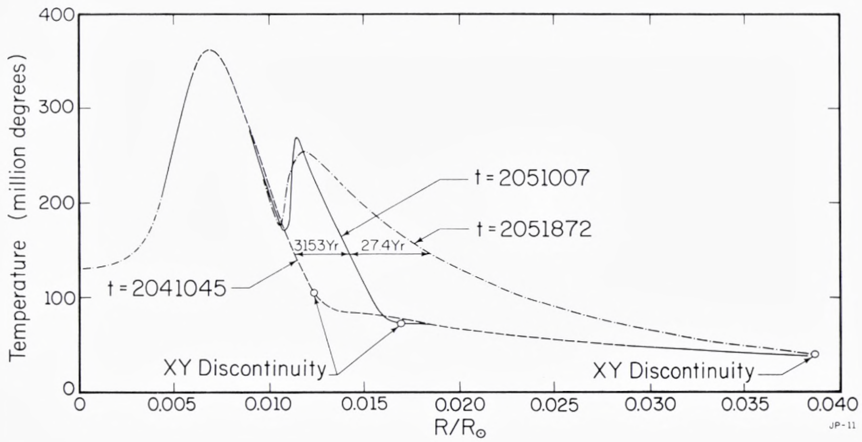

Figure 3. Temperature profiles before and during a thermal pulse in a model star of core mass $0.95\ M_\odot$ and total mass $7M_\odot$. The three times are in units of 10^{12}s.

B) *Nucleosynthesis and Dredge Up*

The dominant products of helium burning are, of course, carbon and oxygen. However, by far the most interesting aspect of nucleosynthesis during thermal pulses is the production of neutron-rich isotopes. In AGB models of large core mass (say $M_{co} \gtrsim 0.95\ M_\odot$), the major source of neutrons is the $^{22}Ne(\alpha,n)^{25}Mg$ reaction (Iben 1974a, 1976, 1977). During hydrogen burning, ^{12}C and ^{16}O are converted into ^{14}N and, during the early portion of a helium shell flash, ^{14}N is converted into ^{22}Ne within the convective shell which is formed due to the high fluxes generated by the $3\alpha \rightarrow {}^{12}C$ reactions. When the temperatures near the base of the convective shell approach and exceed 300×10^6 K, neutrons are released by the endoergic $^{22}Ne(\alpha,n)^{25}Mg$ reaction. Most of the neutrons are captured by light element filters (such as ^{22}Ne and ^{25}Mg) but enough are captured by the "seed" nucleus ^{56}Fe and by its neutron-capture progeny to build up a substantial overabundance of the so-called s-process isotopes. The basic reactions and where they occur during a thermal pulse are described in Figure 4, where the outer "speckled" region depicts the base of the convective envelope and the inner speckled region depicts the convective shell which lies between the CO core and the radiative hydrogen-rich zone.

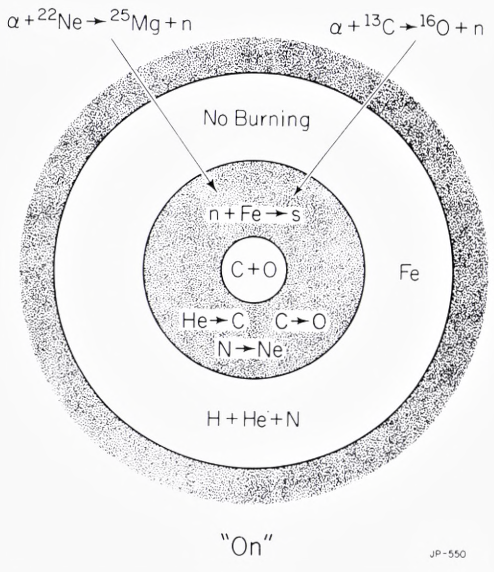

Figure 4. Nuclear burning activity and convective zones during a helium shell flash. The speckled regions are convective zones. Only the ^{22}Ne neutron source operates in intermediate mass AGB models. In low mass AGB models, the ^{13}C neutron source is active and the ^{22}Ne neutron source operates as well, but only weakly.

In general, the s-process isotopes are not made in the solar-system distribution because the neutron densities which are formed as a balance between the rate of neutron production and the rate of neutron consumption are too large by many orders of magnitude (Despain 1980, Cosner, Iben, and Truran 1980). Nevertheless, there are strong similarities between the distributions formed and the solar-system distribution. These similarities are a consequence of (a) the unique characteristic of the ^{22}Ne neutron source that the number of light element filters made during a helium shell flash is comparable with the number of neutrons released and (b) the fact that some fraction of the material that appears in the convective shell during any given flash has also appeared in an earlier flash (Iben 1975b, Truran and Iben 1977). This second feature, which is illustrated in Figure 5, leads to an exponential distribution of exposures for the matter in any given convective shell (Ulrich 1973) and it is well known that such an exponential distribution is essential for producing s-process isotopes in the solar-system distribution (Clayton et al 1961, Seeger, Fowler, and Clayton 1965).

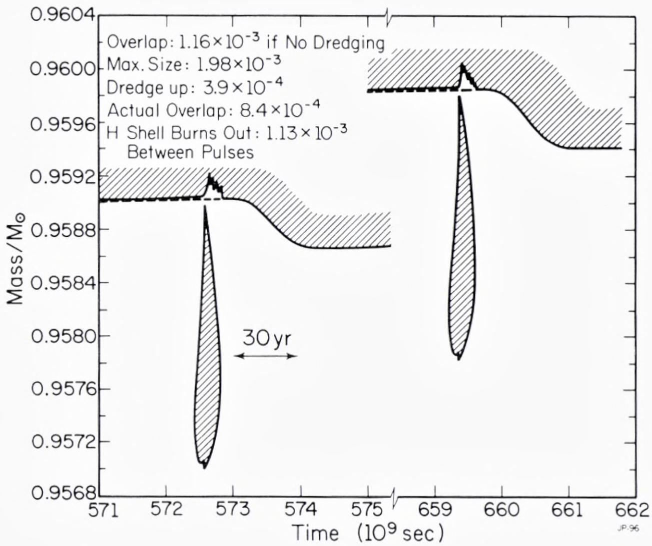

Figure 5. Convective zones (hatched regions) as a function of time in a model of core mass $M_{CO} = 0.95\ M_{\odot}$, total mass $M_* = M_{\odot}$. Both the properties of overlap (some of the matter appearing in a convective shell during a given pulse has also appeared in the convective shell formed during the previous pulse) and of dredge up (following a pulse, the base of the convective envelope extends into the region containing freshly made ^{12}C and s-process isotopes and these nuclei are carried to the surface by convection) are evident.

Figure 5 also demonstrates the property of "dredge up" (Iben 1975a, 1976) which occurs in intermediate mass AGB models after the helium shell flash subsides. The base of the convective envelope moves inward (in mass) and into the outer portions of the region once occupied by the convective shell during the height of a flash. Fresh ^{12}C and s-process isotopes are then dredged to the surface.

Enough studies have now been conducted of the nucleosynthesis expected in the environment provided by intermediate mass AGB stars which activate the ^{22}Ne neutron source that it appears to be inescapable that such stars are not responsible for the production of the bulk of the s-process isotopes in the solar-system (e.g., Mathews and Ward 1985, Howard et al 1986, Malaney and Boothroyd 1987, Busso et al 1988). From this one might infer that: (a) real intermediate mass stars do not reach the thermally pulsing phase; (b) such stars do reach this phase but do not dredge up to their surfaces material which has been processed through convective shells powered by helium burning during a thermal pulse; or (c) such stars reach the thermally pulsing AGB phase, dredge up material "nuclearly" processed in convective shells, but do not live long enough as thermally pulsing AGB stars to contribute substantially to the galactic abundances of neutron-rich isotopes.

The model studies indicate that option (b) is not likely. That is, if the CO core mass is large enough to permit activation of the ^{22}Ne neutron source, then dredge up of processed material will occur in a natural fashion, without the necessity of invoking

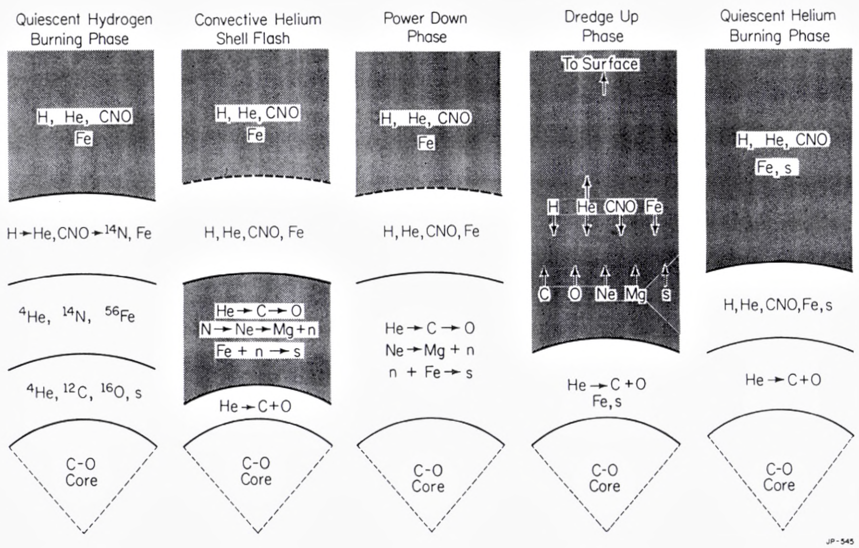

Figure 6. Schematic showing convective zones and nucleosynthesis activity during five stages of a thermal pulse cycle. Zone sizes are not to scale.

a physical process (such as overshoot) for which there exists as yet no easily quantifiable theory. As discussed in the next subsection, observations rule out option (a) and support at least the first portion of option (c).

The nucleosynthesis activity and the convective mixing activity which take place over a complete thermal pulse-interpulse cycle of an intermediate-mass AGB model with a large CO core is summarized in Figure 6.

C) *Lessons from the Observations*

In the preamble it is noted that, if all intermediate mass stars were to evolve along the AGB until the mass of their CO core reached the Chandrasekhar limit, the supernova rate in a galaxy such as ours would far exceed the observed rate. The logical inference is that real AGB analogues must lose most of their hydrogen-rich envelopes before this occurs and the existence and properties of planetary nebulae and of their central stars provides some direct confirmation of this inference. The kinematical and mass loss characteristics of OH/IR sources suggest that these sources are the consequence of mass loss from an underlying AGB star and are in fact in the process of becoming planetary nebulae (de Jong 1983, Habing 1986, Kwok 1987).

Limits on how long a real AGB star of large core mass can spend in the thermally pulsing phase is provided by observations of bright stars in the Magellanic clouds, coupled with theoretical estimates of how long an AGB star must spend in the AGB phase to (a) achieve carbon star characteristics and (b) contribute significantly to the galactic nucleosynthesis of neutron-rich isotopes.

That thermally pulsing AGB stars of large core mass exist and that the theoretical predictions of dredge up and neutron-capture nucleosynthesis are basically correct is (in my mind) demonstrated unequivocally by the long period variables in the Magellanic Clouds. The strengths of ZrO lines in the LPV's with bolometric magnitudes brighter than M_{bol} = - 6 mag (corresponding to CO core masses larger than $\sim$ 0.85 $M_\odot$) imply overabundances of Zirconium (an s-process element) and therefore suggest both the present activity of a neutron source and the reality of dredge up (Wood, Bessel, and Fox 1983). The paucity of bright LPV's ($\sim$ 100-300) relative to the number of Cepheids ($\sim$ 2000-4000), which are presumably the core helium-burning progenitors of LPV's, suggests that the lifetime in the thermally pulsing AGB phase is of the order of 10 % of the Cepheid lifetime. This latter lifetime is estimated in a semi-empirical fashion to be of the order of 10^6 yr (Becker, Iben, and Tuggle 1977). Since the CO core mass of an AGB model grows by $\sim$ 0.1 $M_\odot$ per 10^6 yr and the mean brightness of the model increases by $\sim$ 1 mag in this time, the inference is that shortly after a real star of intermediate mass reaches the thermally pulsing AGB phase with a CO core mass $\gtrsim$ 0.85 $M_\odot$ it "evaporates". That is, it loses its hydrogen-rich envelope in 10^5 yr or less after having increased its initial CO core mass by only a few percent, but not before having produced and dredged to the surface the results of some fresh neutron-capture nucleosynthesis.

The inferred short lifetime of thermally pulsing AGB stars of large core mass explains why there are essentially no carbon stars brighter than $M_{bol} \sim -6$ mag – it requires $\sim 10^6$ yr for C-star characteristics to be achieved (Iben and Truran 1978, Renzini and Voli 1981, Iben and Renzini 1983) – and reconciles (a) the fact that model AGB stars of large core mass produce s-process isotopes in an apparently non-solar-system distribution with (b) the fact that, in real objects, s-process isotopes tend to be in approximately the solar-system distribution. Iben and Truran (1978) show that, if AGB stars of large core mass were to live long enough to increase their initial core mass by $\sim 0.1\ M_\odot$, they should be able to account for ~ 2 times the estimated galactic abundance of s-process isotopes. Observation and theory suggest that AGB stars evaporate before having increased their core mass by over ~ 0.01-$0.02\ M_\odot$ and, thus, all is well: the stars which activate the ^{22}Ne source contribute 10-20 % at most to the galactic nucleosynthesis of s-process isotopes.

What is urgently required is that high dispersion spectroscopy and s-process isotope abundance analysis be undertaken for the LPV's in the Magellanic Clouds to see whether or not the abundance distributions are consistent with the ^{22}Ne neutron source, which nuclear reaction data and stellar model theory together suggest is operating in these stars.

III. *AGB Stars of Low Mass*

A) *Development of a Common CO Core and Thermal Pulse Characteristics*

By definition, a star of low mass is one which develops an electron-degenerate helium core after exhausting central hydrogen. As such a star evolves upward along the giant branch (see Figure 1), its helium core grows until its mass reaches ~ 0.45-$0.5\ M_\odot$, at which point helium is ignited. After a series of shell flashes (e.g., Mengel and Sweigart 1981), the degeneracy of the core is lifted and the star continues to burn helium in the core, but now quiescently, and to burn hydrogen in a shell. If it is of population I composition, a star spends this phase confined to a small "clump" region along the giant branch in the H-R diagram; if it is of population II composition, it resides on the "horizontal branch" (see Figure 1). The clump or horizontal branch phase lasts for approximately 10^8 yr. During this time, the hydrogen-burning shell processes approximately $0.05\ M_\odot$ of matter, so that the mass of the hydrogen-exhausted core of a low mass star becomes ~ 0.5-$0.55\ M_\odot$, nearly independent of the total mass of the star.

After exhausting central helium, a low mass star evolves over a period of $\sim 10^7$ yr along the "early" asymptotic giant branch, processing helium into carbon and into oxygen in a shell above a growing electron-degenerate CO core. Hydrogen does not burn. When the CO core mass reaches $\sim$ 0.5 $M_\odot$, hydrogen-burning is reactivated and the star enters the thermally pulsing AGB phase.

The properties of the thermal pulse cycle of a low core mass AGB star are in most respects qualitatively the same as those of a high core mass AGB star. That is, there is the same long period of quiescent hydrogen burning interrupted periodically by a helium-burning thermonuclear runaway which relaxes into a quiescent helium-hurning phase lasting about 10 percent of the duration of the quiescent hydrogen-burning phase. The duration of each phase, however, is much longer for stars of small core mass than for those with large core mass. The time between thermal pulses varies inversely as the tenth power of the core mass, being about 2000 yr when M_{CO} $\sim$ 0.95 $M_\odot$ and about 200,000 yr when M_{CO} $\sim$ 0.6 $M_\odot$. The light curve of a low mass model is shown in Figure 7.

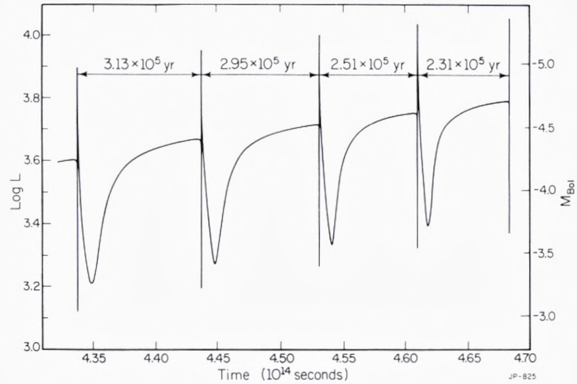

Figure 7. The light curve of an AGB model of low metallicity (Z = 0.001), low mass ($M_* = 0.7\ M_\odot$), and small core mass (M_{CO} $\sim$ 0.57 - 0.61 $M_\odot$).

A more important difference is the fact that the dredge up of freshly produced carbon does not occur in an unforced way. It is necessary to assume that some form of convective overshoot at the base of the convective envelope occurs. In the work of Iben and Renzini (1982a,b), for example, dredge up is achieved by forcibly mixing material into regions which are, initially, formally stable against convection and which lie successively further below the formal base of the convective envelope. If the matter in the freshly mixed-in region becomes formally unstable against convection, this procedure is continued until, on tentatively adding one final zone to the fully mixed region, it transpires that the matter in this zone is still formally stable against convection. Thus, a self consistent inward motion (in mass) of the base of the convective envelope is achieved. Hollowell (1988) adopts a diffusive mixing algorithm with various choices for the mean distance which a convective element can overshoot the formal base of the convective envelope. Wood and Zarro (1981) and Boothroyd and Sackmann (1988a,b) show that by increasing sufficiently the mixing length to scale height ratio in a mixing length treatment of convection, dredge up can also be achieved, given large enough envelope mass.

Another very important difference between AGB models of small and large core mass is that, in models of small core mass, the ^{22}Ne neutron source is only mildly activated, with at most only about 1 % of the neon which enters the convective shell during a pulse reacting with α particles (Becker 1981, Iben 1982, Hollowell 1988). Since, as argued in section II, s-process isotopes are produced in a non-solar distribution when ^{22}Ne is the dominant source of neutrons, this weakness may be a virtue. On the other hand, the activation of the ^{13}C neutron source has been demonstrated to occur only in low core mass models of low metallicity (Iben and Renzini 1982a,b, Iben 1983, Hollowell 1988, Hollowell and Iben 1988, 1989); as a word of caution, it must be mentioned that other independent investigations (Lattanzio 1986, 1987, 1988, Boothroyd and Sackmann 1988a,b) have not succeeded in confirming this.

B) *Carbon Recombination and Semiconvection*

Sackmann (1980) pointed out that, following the disappearance of the convective shell in a low mass model, the carbon-rich matter which was once at the outer edge of the convective shell at its maximum extent is propelled outward to such low temperatures and densities that the contribution of carbon to the opacity may become significant and play an important role in the dredge up process. An explicit suggestion as to how this might come about and as to how it might also lead to the activation of the ^{13}C source was made by Iben (1982). The essential features of this suggestion are illustrated in Figure 8. The occurrence of convective motions and mixing is denoted by shading. The idea was that, after the disappearance of the main convective shell (the snail-like shapes in Figure 8) and upon cooling of matter at the edge of the carbon-rich zone left behind by the primary convective shell, the opacity of the carbon-rich material would lead to a secondary phase of convective shell mixing. Overshoot at the edge of this secondary zone would carry fresh carbon outward, causing an increase in opacity, thereby forcing the outer edge of the convective zone to move into a region which earlier contained only hydrogen and helium.

Once the secondary convective shell vanished, the base of the fully convective envelope would extend inward, dredging up the fresh products of helium burning and neutron-capture nucleosynthesis contained in the region once occupied by the secondary convective shell, even though the base of the convective envelope did not, as extant models suggested, extend as far inward as the point defined by the outermost extent of the primary convective shell.

The ^{13}C source would be activated in the following way. In the lower portion of the region once within the secondary convective shell (the portion not affected by dredge

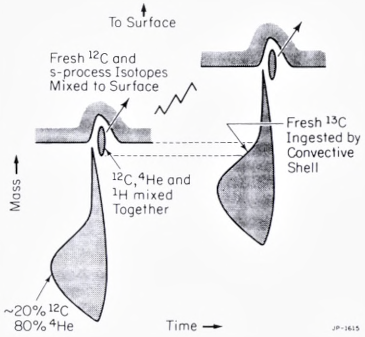

Figure 8. Schematic showing how convective zones might behave in an AGB star of small core mass. The primary convective shell (lowermost of the three shaded zones) and the base of the convective envelope (lower boundary of the uppermost convective zone) are consequences of model evolution when the opacity due to partially recombined carbon is neglected. The small, intermediate convective zone is a fabrication, based on the hope that recombination opacity may force the development of a fully convective zone which brings fresh ^{12}C and ^{1}H together at comparable number abundances.

up) both ^{12}C and ^{1}H are to be found. When this region heats up sufficiently, ^{12}C is converted into ^{13}C following a proton capture and a β decay. If the initial number abundances of ^{1}H and ^{12}C in the region are comparable, then most of the freshly formed ^{13}C is not destroyed by further proton capture. When the next thermal pulse occurs, the ^{13}C is ingested by the growing primary convective shell; it will be convected to the base of the convective shell where temperatures become large enough ($\geqslant 150 \times 10^6$K) to activate the $^{13}C(\alpha,n)^{16}O$ reaction.

This hypothetical scenario is close to, but not quite like what actually happens in current model calculations. Instead of being fully convective, the secondary mixing zone is actually semi-convective (Iben and Renzini 1982a,b, Hollowell 1988, Hollowell and Iben 1988, 1989). The reason for this is that, in the region where carbon is partially recombined with electrons, the opacity is nearly proportional to the carbon abundance. Small, shifting convective regions appear near the outer edge of the zone formerly contained in the primary convective shell and convective overshoot carries some carbon outward into a region containing hydrogen, raising the opacity there. The opacity in the region from which this carbon comes is reduced, thus lowering the degree of instability against convection. Ultimately, the abundance of ^{12}C throughout a large region readjusts in such a way that the radiative gradient equals the adiabatic gradient. This is just the classical requirement for semiconvection.

The time-dependent behavior of convection in the semiconvective zone of a model of low core mass, low mass, and low metallicity is shown in Figure 9 (Hollowell 1988, Hollowell and Iben 1988, 1989). Analytic approximations to Cox-Kidman (1986) opacities are used and overshoot has not been explicitly taken into account.

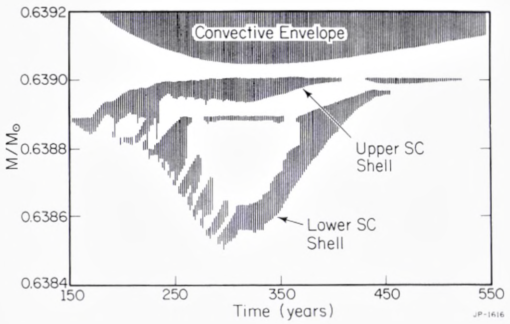

Figure 9. Structure of semiconvective (SC) regions in a model AGB star of low metallicity when the opacity due to partially recombined carbon is included. Hydrogen is carried downward by the lower of two main branches and carbon is carried outward by the upper branch. Dredge up does not occur in this instance, as overshoot has not been assumed.

The vertical bars depict the extent of convection in selected models. Once fresh carbon is mixed with some hydrogen, the progress of convective flow proceeds in two directions. An upper "semiconvective shell" carries carbon further outwards into hydrogen-rich material and a lower semiconvective shell carries hydrogen deeper into carbon-rich regions. The total mass of hydrogen mixed in with fresh carbon is of the order of 10^{-6} $M_\odot$.

Long after the semiconvective episode is completed and toward the end of the ensuing quiescent helium-burning phase, the matter once within the semiconvective zone is heated to the extent that protons react with ^{12}C. Within the inner portion of this zone, the final product is mostly ^{13}C (at a total mass of $\sim 5 \times 10^{-6}$ $M_\odot$). In the outer portion of the zone, the final product is mostly ^{14}N. Thus a thin layer of matter containing ^{13}C is topped by another thin layer containing ^{14}N.

When the next thermal pulse occurs the two layers lie approximately half-way between the base of the primary convective zone which is formed and the location of the hydrogen-helium discontinuity. As the primary convective shell grows, its outer edge encounters the ^{13}C containing layers and, over the ensuing $\sim$ 10 yrs, ^{13}C flows into the convective shell.

C) *Nucleosynthesis of Neutron-Rich Isotopes*

When the ^{13}C is ingested by the primary convective shell, it participates in the convective flows which carry matter back and forth within the shell at the rate of one transit per $\sim 3\times 10^4$ s. The lifetime of ^{13}C against α capture with neutron release varies from ~ 100 yr at the top of the shell, where the temperature is ~ 10^8K, to ~ 10 days at the base of the shell, where the temperature is ~ 1.5 × 10^8K. Hence, ^{13}C burns effectively only near the base of the shell and each ^{13}C nucleus which is introduced experiences roughly 30 transits of the convective shell before capturing an α particle and releasing a neutron near the base. It requires approximately $\tau_{in} \sim 10$ years for the ^{13}C-rich layer to be ingested by the outwardly growing convective shell, so that the effective rate at which neutrons are released is governed, not by the rate at which ^{13}C transits within the shell nor by the rate at which ^{13}C burns at the base of the shell, but by the rate at which ^{13}C is engulfed by the shell (Iben 1983, Hollowell 1988, Hollowell and Iben 1988, 1989).

The neutron density which results at the base of the shell where neutron-capture nucleosynthesis occurs is particularly interesting. In the model constructed by Hollowell (1988), the total mass of ^{13}C ingested by the convective shell is $M_{13} \sim 5 \times 10^{-6}$ $M_\odot$. One may assume, in first approximation that neutrons are released in a "burning" zone of mass M_{burn} near the base of the convective shell and that the rate at which neutrons are released in this zone is

$$\dot{N}_n^+ = (M_{13}/13M_H) \frac{1}{\tau_{in}} M_{burn} / M_{CS}, \tag{1}$$

where $M_H \simeq$ mass of a neutron and M_{CS} ($\sim$ 0.01 $M_\odot$) is the mass of the convective shell during the ingestion phase.

The rate of neutron captures in the burning zone is

$$\dot{N}_n^- = n_n \sum_i n_i < \sigma_i \, v_i > (M_{burn}/ \varrho), \tag{2}$$

where n_n = neutron number density (cm^{-3}), ϱ = density (gm cm^{-3}), n_i = number density of the i^{th} neutron absorber, σ_i = neutron capture cross section of the absorber, v_i = relative velocity of neutron and absorber, and brackets denote an average over a Maxwell-Boltzmann distribution.

Equating expressions (1) and (2), one has

$$\frac{M_{13}}{M_{CS}} \frac{1}{\tau_{in}} = n_n \sum_i < \sigma_i v_i > X_i \; (13/A_i), \tag{3}$$

where X_i is the abundance by mass of the ith absorber and A_i is its atomic mass (in units of M_H). From Hollowell (1988) and Hollowell and Iben (1988, 1989), one has that

$$\sum_i < \sigma_i v_i > X_i \; (13/A_i) \sim 4 \times 10^{-19} \; Z \; cm^3, \tag{4}$$

where Z is the abundance by mass of elements heavier than helium and it has been assumed that these elements are in the solar-system distribution. This assumption is a dangerous one to make since both ^{22}Ne and ^{12}C are present at abundances far in excess of solar (relative to each other).

Equating expressions (3) and (4), one obtains

$$n_n \sim 4.2 \times 10^6 \ cm^{-3} \ /Z, \tag{5}$$

which, for the $Z = 10^{-3}$ model constructed by Hollowell gives $n_n \sim 4.2 \times 10^9 \ cm^{-3}$, a value too large by perhaps one order of magnitude or so to give a solar system distribution of s-process isotopes.

The situation is improved if one takes into account that both ^{12}C (Gallino et al 1988) and ^{22}Ne (Hollowell and Iben 1988, 1989) are overabundant in the convective shell relative to solar, since both are products of α burning. As a next approximation, one may write

$$\begin{aligned} \Sigma < \sigma_i v_i > X_i \ (13/A_i) \sim & [4 \times 10^{-19} Z \\ & + 0.2 \times 7.1 \times 10^{-20} \ X_{22} \\ & + (0.003 - 0.2) \times 1.3 \times 10^{-19} \ X_{12}] \ cm^3 \ s^{-1}, \end{aligned} \tag{4'}$$

where the cross section for neutron capture on ^{22}Ne at $T = 150 \times 10^6$ K is assumed to be ~ 0.2 mb and that of ^{12}C is assumed to be between 0.003 mb (Fowler 1967) and 0.2 mb (Bao and Käppeler 1987). The abundance by mass of ^{12}C is typically 0.2 and that of ^{22}Ne is ~ (0.5-1.5)Z (Hollowell and Iben 1988, 1989). Hence,

$$\Sigma \ (\sigma_i v_i \ X_i \ 13/A_i) \sim [5.4 \times 10^{-19} Z + 2.6 \times 10^{-20} (0.003\text{-}0.2)] cm^3 \ s^{-1} \tag{4''}$$

and, in the $Z = 0.001$ model, $n_n \sim 2.7 \times 10^9 \ cm^{-3}$ if $\sigma_{12} \sim 0.003$ mb and $n_n \sim 2.9 \times 10^8 \ cm^{-3}$, if $\sigma_{12} \sim 0.2$ mb.

The situation is improved further by taking into account the fact that neutron capture on ^{12}C produces ^{13}C which can then, on α capture, recycle neutrons (Gallino et al. 1988). The effect is to spread the neutron-capture episode over a longer time, thereby reducing the average neutron density. The final improvement comes when it is recognized that the final s-process distribution "freezes out" at a neutron density considerably less than the average one (Cosner, Iben, and Truran 1980). Gallino et al. (1980) show that freezeout occurs at $n_n \sim 2 \times 10^8 \ cm^{-3}$, almost precisely the density required for producing the solar-system distribution! Not only that, but the abundance distributions currently being found at the surfaces of carbon stars in our own galaxy (and these must be the product of thermal pulse evolution) are showing that real AGB stars are producing s-process isotopes in nearly the solar-system distribution (Lambert 1988). The only untidy note in this otherwise beautifully developing scenario is that it has not thus far been demonstrated that models of population I composition can activate the ^{13}C neutron source, although dredge up does occur (Iben 1983).

Observations and analysis of peculiar red giants in the Galactic disk (e.g., Scalo and Miller 1979, Lambert 1988, and Jura 1988) show that population I AGB stars of small initial mass ($\sim$ 1.5 $M_\odot$) and small core mass certainly activate the ^{13}C neutron source and dredge up freshly processed material. It is obvious that those of us in the theoretical modeling business have not yet completed our task.

IV. *Epilogue*

The tantalizing promise of ultimate concordance between theory and observation occasions me to close with a personal observation.

Over 20 years ago I gave a lecture at a Stonybrook conference organized by H. Y. Chiu. Bengt Strömgren was in the audience. In my lecture I very proudly demonstrated how a very simple back-of-the-envelope calculation using basic physics provided as good an estimate of the central temperature of the Sun as that provided by the most sophisticated stellar model calculation with the most sophisticated input physics. After the lecture, Bengt came up to me and said: "you were very lucky."

Some fourteen years ago I found by accident that intermediate-mass AGB model stars activate the ^{22}Ne neutron source and dredge up freshly made s-process isotopes and freshly made carbon to their surfaces. In response to a referee's comment about my first cursory speculations concerning the production of s-process isotopes, I spent several months becoming acquainted with the nuclear astrophysics lore in this field and wrote a companion paper extolling the virtues of the ^{22}Ne source. In subsequent papers with Jim Truran and Ken Cosner, and in countless reviews I continued to extol the virtues of this source, absolutely convinced that intermediate-mass AGB stars produce s-process isotopes in the solar-system distribution and not fully appreciative of the knowledgeable nucleosynthesists' arguments that the neutron densities during the neutron-capture episode are too large.

Over the next ten years, the observations of Magellanic Cloud AGB stars showed that intermediate-mass AGB stars do not live long enough in the thermally pulsing phase to be major contributors to the galactic nucleosynthesis of s-process isotopes, and theoretical nucleosynthesis studies showed this to be just as well, as otherwise a major discrepancy between theory and observation would have persisted (see, e.g., Iben 1988 for a summary). Had Bengt Strömgren spoken to me after I had given a talk describing the debacle of a lovely, but oversimplified theory, he might have said: "you were very unlucky."

On this occasion, I am reluctant to claim that I know where and how solar-system s-process isotopes are made, even in stars of low metallicity. Past experience cautions that, once again, those of us in the model making business may have been (temporarily) very lucky.

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