THE CHEMICAL COMPOSITION OF ASYMPTOTIC GIANT BRANCH STARS - THE s-PROCESS

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ABSTRACT. This review discusses the chemical composition of AGB stars in the light of predictions for intermediate-mass (3-8 $M_\odot$, $^{22}Ne(\alpha,n)$ = the neutron source) and low-mass (< 3 $M_\odot$, $^{13}C(\alpha,n)$ = the neutron source) stars. LM-AGB models can be constructed with envelopes having a composition quite similar to that of solar system material, the SiC grains recently discovered in meteorites, and real AGB stars in the sequence of spectral types M → S → C. Stellar counterparts of the IM-AGB models have yet to be discovered.

1. Introduction

Merrill's discovery (1952) of technetium in the spectra of S stars must rank high in the annals of nucleosynthesis. The presence of this unstable element demonstrated beyond a shadow of a doubt that the stars that we now call asymptotic giant branch (AGB) stars must be synthesizing Tc and other elements. Some of these other elements contribute to those molecules whose bands have long been noted as greatly strengthened relative to their intensities in the spectra of M stars of similar temperature: *e.g.*, Y, Zr, and La. Quite elementary principles suggest that synthesis occurs by successive captures of neutrons such that the heavy elements are synthesized from the abundant Fe-peak nuclei present when the star was formed. A more thorough scrutiny of the relevant nuclear physics and of the elements which are enriched in the S stars suggests that the synthesis occurs at a low neutron density such that the first unstable neutron-rich isotope of any element, in general, decays rather than capturing yet another neutron. This form of synthesis by neutron captures we now refer to as "the s-process" following the pioneering paper on nucleosynthesis by Burbidge, Burbidge, Fowler, and Hoyle (1957).

In this review, I intend to show how investigations of the chemical compositions of AGB stars may be used to constrain theoretical models of these stars and the s-process that operates in their He-burning shells. No-one can read the preceding reviews on the models for AGB stars and fail to appreciate the need for observational guidance and constraints! Although I shall restrict discussion to the composition of AGB stars, I should be remiss if I did not point out that valuable clues to the internal structure and nucleosynthesis of AGB stars may also be provided by examining descendants of AGB stars: the post-AGB stars, the proto-planetary nebulae, planetary nebulae and their central stars. To this list of descendants, we should add the Barium stars (and *their* relatives) because they are binary stars in which mass was transferred from an AGB star, now present as a white dwarf, to a companion, most probably a main sequence star, now seen as the Barium star. Since the Barium main sequence, subgiant and giant stars are generally warmer than the AGB s-process enriched stars, their spectra are less cluttered with molecular bands and, hence, more amenable to quantitative abundance analyses.

Considerable information on the s-process has been garnered by detailed analysis of the 'cosmic' abundances of heavy elements as provided by accurate analysis of the carbonaceous chondrites. I shall refer to the 'classical' analyses of the cosmic abundances and briefly remark on an exciting recent discovery - the isolation and analysis of interstellar grains of silicon carbide

G. Michaud and A. Tutukov (eds.), Evolution of Stars: The Photospheric Abundance Connection, 299–316.

within meteorites. Such grains have survived intact the long journey from their formation in the wind off cool carbon stars to their end in a laboratory here on earth.

2. AGB Stars and the s-Process

Often, striking observational advances in astrophysics are made at a time when theoretical work on the same topic is stagnant or dormant - and *vice-versa*, of course. Merrill's discovery of Tc was far in advance of theoretical ideas on the internal structure of S stars. Slowly, we came to realize that such luminous cool stars consist of a degenerate C-O core, a thin He-shell, and a large H-rich convective envelope. A key theoretical advance was made by Schwarzschild and Härm (1967) who showed that AGB stars must experience He-shell flashes (thermal pulses). A second seminal theoretical work is the series of papers by Iben (1975) in which he showed that intermediate mass (IM) AGB stars run the s-process with the neutron source $^{22}Ne(\alpha,n)^{25}Mg$ in the intermittently active He shell and that the products dredged subsequently up into the deep convective envelope have the cosmic/solar-system distribution of s-process abundances. A key aspect of the ^{22}Ne source is that the ^{22}Ne supply and, hence, the maximum number of neutrons released is set by the IM-AGB's initial composition: C, N, O are converted to ^{14}N by the CNO cycles and prior to He-burning ^{14}N is burnt via ^{18}O to ^{22}Ne. Later it was shown that IM-AGB stars could return sufficient mass to the interstellar medium to control the galactic abundance of s-process nuclides (Truran and Iben 1977; Iben and Truran 1978).

Recently, the identification of IM-AGB stars as the principal donor of s-process elements has come under fire. In their paper "Are s-elements really produced during thermal pulses in intermediate-mass stars?", Busso *et al.* (1988) conclude that "the role once attributed to IMSs is probably played by different astrophysical sources." Before I sketch the arguments behind this conclusion, I must stress that current models of IM-AGB stars predict that products of the s-process driven by the $^{22}Ne(\alpha,n)$ source are dredged-up into the envelope and, hence, the spectroscopically accessible atmosphere: IM-AGB stars are s-process factories but, according to Busso *et al.*, not the dominant contributor to the interstellar medium. Why have those exciting papers of the 1970s been rejected in some quarters?

Busso *et al.*'s answer is in three basic parts:

• Operation of the $^{22}Ne(\alpha,n)$ source in IM-AGB stars results in a pulse of neutrons with a high peak neutron density ($N(n) \simeq 10^9$ to 10^{11} cm^{-3}) and a rapid decline of N(n) at the end of the pulse. Although the yields may closely resemble a solar system distribution for many s-process nuclides, the high neutron density leads to inconsistencies with the solar system distribution for nuclides in the neighborhood of several branches in the s-process path (Despain 1980). Classical analysis of the solar system abundances (see below) indicates a mean neutron density $N(n) \simeq 3 \times 10^8$ cm^{-3}. The freeze out is too rapid for the yields achieved at the peak neutron density to be shuffled in major ways, and so to reflect a lower density near the end of the He-shell flash. Busso *et al.* show that the s-process yields at several branches are far from the solar system abundance pattern.

• The neutron supply (and density) to run the s-process is controlled by several light elements that serve as "poisons". If the He-burning shell is rich in poisons, too few neutrons are made available for the synthesis of the heavy s-process elements. Among potential poisons is ^{22}Ne itself: $^{22}Ne(n,\gamma)^{23}Ne$ was considered by Truran and Iben (1977) who adopted a cross-section σ_{22} = 0.05 mb. Busso *et al.* note that new measurements (Almeida and Käppeler 1983) give a much larger cross-section: $\sigma_{22} = 0.9 \pm 0.7$ mb at kT = 30 keV. Busso *et al.*'s calculations done for σ_{22} = 0.9 mb show that ^{22}Ne's consumption of neutrons leaves too few available to synthesize the heavy elements in solar system proportions. A remeasurement of the $^{22}Ne(n,\gamma)$ cross-section (Beer *et al.*, 1989) has, however, led to $\sigma_{22} = 0.060 \pm 0.005$ mb at kT = 30 keV; *i.e.*, ^{22}Ne is not a crippling poison but, of course, the high neutron densities remain and lead to non-solar abundances at the branches along the s-process path.

• Exploration of the luminous stars in the Magellanic Clouds led to the striking result that the carbon stars were much less luminous than predicted by models of IM-AGBs that have experienced sufficient thermal pulses to convert the envelope from O-rich to C-rich. The carbon stars in the Clouds must be low mass (LM) AGB stars. What is the fate of the IM-AGBs? Busso *et al.* assert that the conclusion to be drawn from observations of the Magellanic Clouds is that the IM-AGBs "do not normally experience the H-shell reignition and the thermally pulsing phase". If true, this would be a strong reason for dismissing the IM-AGBs as a source of s-process nuclides. Wood, Bessell, and Fox (1983) showed that both Clouds contain long-period variables with enhanced ZrO band (*i.e.*, S stars) at absolute luminosities above those of the Cloud carbon stars but below the maximum luminosity for an AGB star. It is presumed that the luminous AGB stars are IM-AGBs, but this needs to be proven (see below). In short, the observations of the Magellanic Clouds presently suggest a weaker conclusion: IM-AGBs are possibly present with s-process overabundances signalling the operation of thermal pulses and dredge-up. There is evidence that the luminous AGB stars in the Clouds are losing mass at rates so high that many evolve early off the AGB; *e.g.*, the luminosity function of Hughes and Wood (1987) suggests that between $M_{bol} \sim -6$ and -7 stars are continuously leaving the AGB due to complete mass loss. A similar or even more drastic early termination is likely for the Galactic IM-AGBs. Therefore, the relative contributions of IM-AGB and LM-AGB stars to galactic enrichment of s-process nuclides remains an open question.

Observations of the Magellanic Cloud carbon stars clearly show that LM-AGB ($M \lesssim 3\ M_{\odot}$) dredge-up freshly synthesized ^{12}C from the He-burning shell. For such stars, the temperature in the He-burning is too low for $^{22}Ne(\alpha,n)$ to serve as the dominant neutron source. The neutron source is considered to be $^{13}C(\alpha,n)^{16}O$ where an adequate supply of ^{13}C must be assembled in the long interpulse interval as protons are mixed with or diffuse into the He-shell to react with the abundant ^{12}C nuclei [$^{12}C(p,\gamma)^{13}N(e^+,\nu)^{13}C$], and as long as the ^{12}C nuclei greatly outnumber the ^{13}C nuclei, an adequate supply of ^{13}C is maintained despite the three-times larger cross-section for $^{13}C(p,\gamma)$ relative to $^{12}C(p,\gamma)$. As a reading of the preceding papers by Iben and by Sackmann and Boothroyd will show (see also Lattanzio 1989),there is disagreement over the parameter space (mass, metallicity, mixing length) for which dredge-up is predicted to be successful in low mass stars. There is also disagreement over the occurrence of the semi-convection that is necessary to generate the ^{13}C supply from which neutrons are created at the next thermal pulse. Some LM-AGB models predict a dredge-up of ^{12}C from a He-shell in which the s-process did not run (Lattanzio 1989). The abstract of Sackmann and Boothroyd's review concludes by highlighting the "s-process mystery" - "only in a narrow range of mass and metallicity have theoretical models been found that encounter the semiconvective ^{13}C s-process mechanism". Or as the concluding sentence of the review declares, "The observed enrichment of s-process elements in low mass stars remains a puzzle". How can an observer resist the challenge to provide essential clues to unraveling the "s-process mystery"?

3. Chemical Composition and the s-Process

Perhaps the first step toward understanding how stars synthesize s-process nuclides is to pose a list of key questions that appear to be answerable through analyses of the chemical composition of stars. This list would surely include:

- Q1 - What is the neutron source?
- Q2 - What is the average neutron exposure and the average mixing fraction?
- Q3 - What is the mean neutron density?
- Q4 - What is the mean temperature at the site of s-processing?
- Q5 - When did the s-process occur?

https://doi.org/10.1017/S0074180900227459 Published online by Cambridge University Press

Since one of our goals is not only to understand how the s-process operates in individual stars but also to identify the types of stars (IM-AGB, LM-AGB, or ?) that provided the major share of the galactic s-process elements, I shall first summarize the answers to my list of key questions as provided by a classical analysis of the solar system abundances. Käppeler, Beer, and Wisshak (1989 ≡ KBW) provide an excellent review of the current status of the classical analysis.

A full accounting for the solar system abundances requires contributions from three components:

• the weak component (the dominant contributor to the lighter elements, $A \lesssim 85$). This component is generally identified as arising from He-core burning in massive stars ($M \gtrsim 10\,M_\odot$). I shall not consider it further here because such massive stars are outside the scope of my review and, in any case, estimates of few stellar abundances of the 'weak' elements (*e.g.*, Cu through Rb) have been reported, especially for the stars enriched in the s-process. Attention should certainly be paid to this gap in our knowledge.

• the strong component (this is possibly needed to account correctly for the few s-process nuclides in the Pb-Bi region). The physical characteristics and location of the astrophysical site of this component are uncertain. It is even questioned whether this component is demanded by the solar system abundances (KBW).

• the main component. This component is widely identified as the product of AGB stars. Analysis of the abundances of nuclides affected by branches in the s-process path serves to define the mean physical characteristics of the s-process sites that contributed the main component. Clearly, the derived characteristics are not to be thought of as representative of a single star of a particular mass and metallicity, but as an average, over a few stellar generations of differing metallicity and over a mass range within each generation. Nonetheless, one would expect individual AGB stars of the type controlling galactic production of the s-process to overlap in their physical characteristics those of the main component. The latter characteristics must also reflect the assumptions of the classical model: principally, uniform temperature (T_s) and neutron density (N_n). Current estimates (Käppeler *et al.* 1990 ≡ KGMPR) for the main component are

$T_s = (3.3 \pm 0.5)\ 10^8$ K
$N_n = (3.4 \pm 1.1)\ 10^8$ cm^{-3}
$\tau_o = (0.306 \pm 0.010)\ [kT(keV)/30]^{1/2}$ mb^{-1}
$G = (0.057 \pm 0.004)$ %
$n_c(^{56}Fe) = 10.7 \pm 0.7$
$3 < \Delta t\ (yr) < 20$

where an exponential distribution of neutron exposures $\rho(\tau) = \dfrac{G N_\odot^{56}}{\tau_o} \exp(\tau/\tau_o)$

is assumed and τ is the time integrated neutron flux. An exponential distribution gives an excellent fit to the solar abundances. (For the weak component, it is unclear whether an exponential distribution is to be preferred to a single exposure.) G denotes the fraction of the observed ^{56}Fe abundance exposed to neutrons; n_c, the number of neutrons captured per ^{56}Fe nucleus, is computed from the s-process abundances and the fraction G. Δt is the pulse length as estimated from the branches at ^{151}Sm ($\Delta t > 3$ yr, Beer and Macklin 1988) and at ^{85}Kr ($\Delta t < 20$ yr, KGMPR).

Two of the questions (Q1 and Q5) in the above list cannot be answered by analysis of solar system abundances - see KBW for a discussion of chronometers, especially ^{205}Pb and ^{176}Lu. There is no obvious abundance signature that identifies the source of the neutrons: ^{22}Ne(α,n) or ^{13}C(α,n), presumably. The neutron density given by the classical analysis suggests that ^{22}Ne was not dominant, but the temperature T_s is that required to ignite ^{22}Ne in a He shell!

4. The s-Process Site in AGB Stars

4.1 INTRODUCTION

The data on the chemical composition of stars that provide answers to the key questions has come from AGB stars self-enriched in s-process products (spectral types MS, S, SC, CS, C) or from Barium stars (mostly G and K giants) where, as noted above, the s-process operated in the companion star now shrunk to a white dwarf.

Information on the galactic history of the s-process should be obtainable from detailed analyses of stars from the metal-rich to the metal-poor that are unpolluted by internal s-processing or by material donated by a neighbor. To date, apart from the resolution of the heavy element abundances into s-process and r-process contributions with different dependencies on metallicity [Fe/H], detailed exploration of the s-process has been largely neglected, *e.g.*, use of the Rb abundance to monitor the neutron density has been overlooked. In metal-poor stars, [Fe/H] $\lesssim$ -2, the heavy elements are the fruits of a r-process that operated in previous generations of stars which dispersed the products of the r and other nucleosynthetic processes in terminal supernova explosions (Sneden and Parthasarathy 1983; Gilroy *et al.* 1988). The delay in the appearance of s-process nuclides in the interstellar medium and stars is certainly consistent with operation of the s-process in AGB stars. In the standard model of the galaxy in which a gaseous sphere collapsed to a disk, IM-AGBs should be the first to provide their s-process products with lower mass AGB stars contributing later; massive stars (M $\gtrsim 10M_{\odot}$) will provide an earlier contribution of weak component nuclides. If, as seems likely, a quasi-r-process (high neutron density) operates in IM-AGBs and possibly in metal-poor LM-AGBs, the abundances of particular elements and nuclides (*e.g.*, Rb and ^{96}Zr, see below) should be enhanced in the moderately metal-poor stars whose parental clouds were contaminated with the s-process form IM-AGBs.

4.2 INTRINSIC AND EXTRINSIC AGB STARS

Technetium is the trademark of an AGB star that is experiencing thermal pulses in which the s-process runs in the He shell from which products are later dredged to the surface. As first highlighted by Scalo and Miller (1981), Tc is not detectable in about half of the observed MS and S stars (comparable statistics are unavailable for carbon stars). Brown *et al.* (1990) show conclusively that the MS/S stars without detectable Tc but clear enhancements of s-process elements are binary systems. Binarity is revealed by radial velocity variations and by the presence of strong He I 10830 Å absorption and/or emission due to an interaction between a white dwarf companion and the red giant's atmosphere or stellar wind. As first suggested by Iben and Renzini (1983), the MS/S stars without Tc may now be identified as more luminous counterparts (most probably descendants) of the Barium giants. Technetium has decayed completely in the long interval betwen the birth of the Barium star as a main sequence star or as a giant and evolution to luminosities expected of an AGB star; some MS/S non-Tc stars may be on the red giant branch (RGB) prior to the He-core flash and others may be on the AGB, but at luminosities too low for the occurrence of thermal pulses. Of course, when the MS/S non-Tc stars experience thermal pulses, Tc will be replenished at the surface. Brown *et al.*'s survey suggests, as expected from a consideration of the relative lifetimes, that evolved Barium stars with fresh Tc are rare. In this review, I shall assume that MS/S non-Tc stars are evolved Barium stars in which thermal pulses are not occurring. I consider these stars to be *extrinsic* thermally pulsing AGB stars and the MS/S star with Tc to be *intrinsic* AGB stars. The composition of an extrinsic star is presumably a mix of a portion of an AGB envelope with the envelope of the mass-gaining star.

4.3 THE NEUTRON SOURCE: ^{22}Ne OR ^{13}C?

The ^{22}Ne source cannot easily run the s-process and elude the stellar spectroscopist. Operation of

https://doi.org/10.1017/S0074180900227459 Published online by Cambridge University Press

the ^{22}Ne source is predicted to lead to a non-solar mix of Mg isotopes in the He-shell and in the atmosphere of an IM-AGB star (Truran and Iben 1977; Scalo 1978; Malaney 1987): *e.g.*, a star with a core mass of 1.16 $M_\odot$ and s-process elements enriched by a factor of 10 at the surface is predicted to have ^{24}Mg:^{25}Mg:^{26}Mg = 17:15:68 instead of the solar ratios 79:10:11 (Malaney and Lambert 1988). Since the Mg isotopic ratios are measureable through the MgH A-X lines, the predictions are testable for s-process enriched stars of spectral types K and later. The test has now been applied to about 10 classical Barium giants (Tomkin and Lambert 1979; McWilliam and Lambert 1988; Malaney and Lambert 1988), a few mild Barium stars (Tomkin and Lambert 1979; McWilliam and Lambert 1988) and several MS/S stars (Clegg, Lambert, and Bell 1979; Smith and Lambert 1986). To within the errors of measurement, the reported ratios are within a small interval of the solar ratio: ^{25}Mg and ^{26}Mg may be underabundant in the MS star HR363. Observations of main sequence stars and of normal giants show the Mg isotopic ratios to be close to the solar ratios except for metal-poor stars ([Fe/H] $\lesssim$ -1) where ^{25}Mg and ^{26}Mg are underabundant relative to their solar abundances (Tomkin and Lambert 1980; Barbuy 1985; McWilliam and Lambert 1988). There is no evidence in the published data on the s-process enriched stars for the ratios (*e.g.*, ^{26}Mg/^{24}Mg > 1) that would be expected from the ^{22}Ne source in an IM-AGB star.

One qualification of the predictions must be noted. In the most luminous AGB stars the temperature at the base of the convective envelope may be so high that the excess ^{25}Mg and ^{26}Mg are removed by protons: ^{25}Mg(p,γ)^{26}Al and ^{26}Mg(p,γ)^{27}Al. Stars in which this and many other reactions occur are said to possess 'a hot-bottomed convective envelope' ($\equiv$ HBCE). The HBCE is the site for Li production and for the CN-cycle to process freshly dredged-up ^{12}C to ^{14}N. Attention has been drawn to the ^{25}Mg(p,γ) reaction as a source of both the radioactive ^{26}Al (half life = 740,000 yr) detected in the interstellar medium by the γ-ray spectrometer on the HEAO3 satellite (Mahoney *et al.* 1982) and the excess ^{26}Mg detected in inclusions in meteorites (Lee, Papanastassiou, and Wasserburg 1977). Identification of the site for ^{26}Al production with the HBCE of the most luminous AGB stars appears to have been made first by Nørgaard (1980) - see also Cameron (1984) and Frantsman (1989). Nørgaard's simplified models predicted thorough destruction of ^{25}Mg for $T_6 \gtrsim 70$ with ^{26}Al preserved unless $T_6 \gtrsim 90$ where $T_6 = T/10^6$ K. At the same temperatures, ^{26}Mg is converted to stable ^{27}Al. The discovery of low energy resonances in the ^{25}Mg(p,γ) reaction has led to higher reaction rates (Champagne, Howard, and Parker 1983) and, hence, to ^{25}Mg destruction and ^{26}Al production in cooler HBCE's than previously thought.

Thus, the HBCE alters the Mg isotopic ratios that are the expected signature of the ^{22}Ne-source. Unfortunately, no detailed calculations have been reported: Nørgaard remarked that, in his 7 $M_\odot$ model, the Mg isotopes are "essentially solar". Other characteristics of the model are necessarily a low ^{12}C/^{13}C ratio, thorough destruction of ^{18}O, and a high N/C ratio because the CNO-cycles must run in parallel with reactions such as ^{25}Mg(p,γ). With the enhanced (1983) rate for ^{25}Mg(p,γ), the expected excess of the neutron-rich Mg isotopes may be erased in AGB stars of lower base temperature (say $T_6 \gtrsim 40$). A low ^{12}C/^{13}C and a high N/C ratio are likely concomitants. Moreover, if $T_6 \gtrsim 50$, CNO-cycling leads to C/O > 1 and a carbon star results. Hence, it is unlikely that our interpretation of MgH analyses of intrinsic MS/S stars is compromised by destruction of ^{25}Mg and ^{26}Mg. Since models predict ^{26}Al/^{27}Al ~ 1 (Frantsman 1989), the ^{26}Al should be detectable in the atmosphere of the luminous AGB stars. Unfortunately, the separation of ^{27}Al from ^{26}Al in photospheric spectra of AGB stars is difficult: Branch and Peery (1970) set ^{26}Al/^{27}Al < 1/7 for R And, a S-type star with Tc. Bagrintseva and Strel'nitskii (1988) give ^{26}Al/^{27}Al < 1 for the circumstellar envelope of the carbon star IRC +10216. Perhaps vibration-rotation transitions of AlH or AlO may prove to be identifiable in infrared spectra.

The ^{13}C(α,n)^{16}O source does not generally leave a detectable signature; the yield of ^{16}O is insignificant relative to the small amount of ^{16}O produced by ^{12}C(α,γ)^{16}O and to the initial ^{16}O abundance. Moreover, the ^{13}C(α,n) source is not expected to result in observable distortions of the Mg isotopic ratios in the atmosphere. A slight enrichment of ^{25}Mg and ^{26}Mg with the ^{13}C source in operation was predicted by Jorissen and Arnould (1986), but this assumed the high (σ_{22} = 0.9 mb) cross-section for ^{22}Ne(n,γ). When the new low value of σ_{22} (= 0.06 mb) is adopted, production of ^{25}Mg and ^{26}Mg is unimportant (Jorissen 1990).

The stars examined to date have shown no evidence of excess ^{25}Mg and ^{26}Mg and, hence, are presumed to be LM-AGBs. Although the sample needs to be enlarged, one might suppose LM-AGBs to be the principal contributors to galactic s-process enrichment. Further spectroscopic examination of these stars shows that the operation of the s-process in these stars has led to neutron exposures at mean neutron densities that are compatible with the results of the classical analysis of solar system abundances. An observer with even a modicum of curiosity will seek to extend the spectroscopic examinations to IM-AGBs in order to test models of these stars. Such an extension raises the question: How are IM-AGBs to be identified? For galactic field stars, the question is not obviously answerable because distances to individual stars and, hence, absolute luminosities are notoriously uncertain so that for this and other reasons estimates of the stellar masses are also quite uncertain. One could and certainly should expand the MgH analyses to larger samples of s-process enriched stars in order to identify some stars rich in ^{25}Mg and ^{26}Mg.

A more direct possibility is to examine AGB stars in the Magellanic Clouds where reliable absolute luminosites and approximate (relative) masses may be assigned. Our study (Smith and Lambert 1989, 1990a) of the most luminous AGB stars in both Clouds has shown that stars within about 1 magnitude of the limiting luminosity ($M_{bol} \simeq -7.1$) for an AGB star (*i.e.*, the core mass is equal to the Chandrasekhar limit) are remarkably rich in lithium which is presumed to be synthesized at the base of a HBCE by the chain of reactions $^{3}He(^{4}He,\gamma)^{7}Be(e^{-},\nu)^{7}Li$ - see Cameron and Fowler (1971). The HBCE converts ^{12}C to ^{14}N and inhibits the star's conversion to a carbon star unless $T_6 \gtrsim 50$. The Li-rich Cloud stars are the long-period variables (LPVs) first recognized as luminous AGB stars by Wood, Bessell, and Fox (1983). These stars may be IM-AGBs (see Sec. 5.3) and as suspected in 1983 on account of strong ZrO bands, are s-process enriched to levels found for many Galactic S stars (Smith and Lambert 1989). Lithium-rich Galactic S and C stars are rare and *may* also be IM-AGBs. Unfortunately, these stars are so cool that strong molecular bands dominate their spectra and, therefore, certain aspects of the s-process in IM-AGBs (*e.g.* determination of the neutron exposure) can probably not be probed. Less evolved IM-AGBs have a higher effective temperature and, hence, a spectrum less blanketed by molecular lines: spectral types equivalent to early to mid M. These stars are presumably not Li-rich because HBCEs are predicted to exist only for $M_{bol} \lesssim -5.5$ (Scalo, Despain, and Ulrich 1975). In the Clouds, these stars are just accessible to high resolution spectroscopy. In the Galaxy, these stars, if they could be identified, would offer spectroscopic insights into the operation of thermal pulses on IM-AGBs. It would seem that ^{25}Mg and ^{26}Mg must betray these stars.

4.4 NEUTRON EXPOSURES

The abundances of the s-process elements in an AGB star's atmosphere are a record of the neutron exposure received by the material in the He shell. If AGB stars were the primary source for the solar system's main s-process component, one expects the stellar abundances to resemble the solar s-process abundances: *i.e.*, the neutron exposures in a star follow an exponential distribution with $\tau_0 \simeq 0.3$ for kT = 30 keV. For cool AGB stars, the spectrum is so heavily blanketed by molecular bands that one must search for the rare lines of heavy elements in windows between the bands. As a result, the selection of lines suitable for an abundance analysis is restricted. Too few elemental abundances in a single star are obtained to permit a clear definition of the form of the distribution function for the neutron exposure. For the warmer extrinsic (Barium) stars, the selection of lines and elements is not seriously compromised by molecular bands and it is possible to check the form of $\rho(\tau)$. In general, it has been assumed that an exponential distribution is appropriate and the stellar abundances are used to determine τ_0 and a mixing fraction giving the relative masses of s-processed material from the He-shell and unprocessed envelope material. An exponential distribution has a theoretical justification. Ulrich (1973) showed that an exponential distribution is expected for AGB stars undergoing a series of third dredge-ups.

Smith and Lambert (1990b) present heavy element abundances for a sample of M giants and intrinsic and extrinsic MS and S stars. The observed and predicted abundances are compared in Figure 1 where the ordinate, the average Y and Zr overabundance (relative to the metals M) is a measure of the total s-process enrichment or mixing fraction and the abscissa, which measures the relative overabundance of a heavy s-process element (Nd) to light s-process elements (Y and Zr), is an indicator of the neutron exposure (*i.e.*, τ_0). The predictions for $\tau_0 = 0.1$ to 1.0 mb^{-1} and mixing fractions $M_s/M_e \leq 10^{-2}$ were computed from tables given by Malaney (1987). Inspection of Figure 1 shows that the s-process added to MS/S stars has $\tau_0 = 0.3 \pm 0.1$ with surprisingly few stars having a τ_0 outside this range. There is a continuous spread in mixing fractions up to $m_s/m_e \simeq 0.004$ with TV Aur having $M_s/M_e \simeq 0.02$ as the extreme case. Extrinsic (no Tc) and intrinsic (Tc present) MS/S stars are indistinguishable by their location in Figure except for a hint that τ_0 is slightly higher for extrinsic AGB stars.

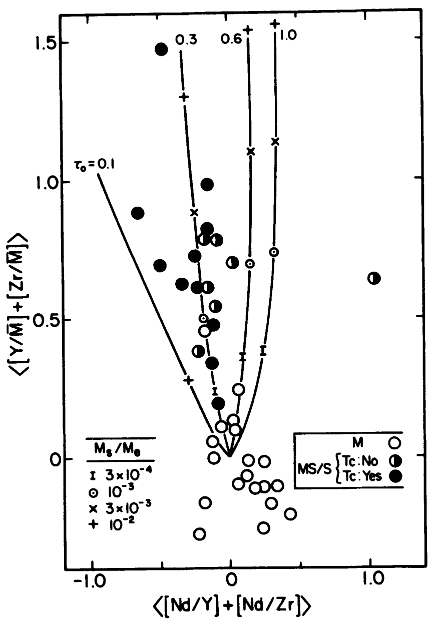

Figure 1. - The s-process averabundance index <[Y/$\bar{M}$] + [Zr/$\bar{M}$]> vs. <[Nd/Y] + [Nd/Zr]> for a sample of M, MS, and S stars where [M/H] is the mean metal abundance. The predicted abundances (solid lines) are given for a range of τ_0 and M_s/M_e (see text). (From Smith and Lambert 1990b).

As ^{12}C is dredged up following each pulse, the C/O ratio in the envelope increases and the star evolves along the sequence M → MS → S → SC → CS → C in which the $^{12}C/O$ ratio and the s-process overabundance [s/Fe] increase monotonically. (A HBCE will change the C/O ratio and may prevent the star from becoming C-rich.) Examination of the s-process abundances in carbon stars shows how the nature of the s-process changes as a star evolves along the AGB. A comparison with published abundances for the M/MS stars must recognize that an interpretation is compromised by the lack of reliable estimates of the masses of MS, S, and C stars. A reasonable assumption is that galactic MS, S, and C stars come from stars of similar low (1-3 $M_\odot$) initial mass.

Few investigations of s-process abundances for carbon stars have been published; the visible and near-infrared spectra have proven to be an effective deterrent! Fortunately, Utsumi

https://doi.org/10.1017/S0074180900227459 Published online by Cambridge University Press

(1985) has undertaken a curve of growth analysis of lines from 4400 to 5000 Å in "windows" between C_2 bands. For the 12 stars considered, the results are quite similar and the mean abundances are y_s = <[Y/Ti] + [Zr/Ti]> = 1.7 and x_s = <[Nd/Y] + [Nd/Zr]> = -0.8; Utsumi used Ti I lines to determine metallicity and, in merging his abundances with those in Figure 1, I make the reasonable assumption that [Ti/M] = 0. Utsumi states that the accuracy of his abundances is about 0.4 dex and, hence, the mean abundances should be reliable to ± 0.2 dex unless systematic errors are present. The latter would appear to be small because, as generally concluded from inspection of line strengths (Dominy 1985), the J-type (= ^{13}C-rich) carbon stars in Utsumi's sample show no s-process enrichment (y_s = -0.1; x_s = -0.2). When placed in Figure 1, the cool carbon stars are seen to be more s-process enriched than the MS/S star sample and characterized by $\tau_0 \simeq 0.2$ mb^{-1}. The extreme star in Figure 1 is TV Aur with y_s = 1.45 and this is the extreme S star in Smith and Lambert's (1990b) sample. Since such extreme S stars and, in particular, the coolest examples such as LPVs were excluded from their sample, I think it likely that the stars in the M → S → C sequence span the range from $y_s = 0$ to $\simeq 2$.

Classical Barium giants and their relatives are contaminated with s-process products that closely resemble those seen in the atmospheres of the more luminous MS/S stars. The chemical composition of the Barium stars was reviewed by Lambert (1985). Smith (1984), who analysed seven Barium stars, noted that the abundance patterns corresponded to τ_0 = 0.3-0.4; when his stars are plotted on Figure 1, they occupy the same area as the majority of the MS/S stars. A detailed analysis of one star, HR 774 with y_s = 1.2, by Tomkin and Lambert (1983) gave $\tau_0 \simeq 0.6$. Smith's abundances correspond to τ_0 = 0.3 with the difference attributable to his lower abundance for Ba and heavier elements. The s-process enrichment of the mild Barium star o Vir with y_s = 0.6 corresponds to $\tau_0 \simeq 0.8$ (Tomkin and Lambert 1986). These hints that the Barium stars indicate a higher τ_0 than the MS/S stars should be subject to additional observational tests.

The form of $\rho(\tau)$ may be examined using the large number of elements available through spectroscopy of Barium stars. Tomkin and Lambert (1983) considered 19 elements with $Z \geq 37$ and concluded that "s-processing by a single burst of neutrons may be rejected". An exponential distribution with τ_0 = 0.6 fitted the stellar abundances of these same elements to within 0.1 dex (except for Mo). Cu and Zn are more abundant than predicted, but the addition of a weak component (τ_0 = 0.08) can account for their abundances.

4.5 NEUTRON DENSITY

In the limit that the neutron density, N(n), tends to zero, the s-process takes a unique path along the valley of stability. The uniqueness results from the fact that all unstable nuclei decay rather than capture a neutron. At the neutron densities expected in an AGB's He-burning shell, a competition arises at certain unstable nuclei between decay and neutron capture. These nuclei serve as branch points in the s-process path - note the path at N(n) → 0 is not unbranched. For each branch point, there is a critical value of the neutron density $N(n)_c$: if $N(n) << N(n)_c$, the unstable nuclide at the branch decays but, if $N(n) >> N(n)_c$, the unstable nuclide captures a neutron. The magnitude of $N(n)_c$ is set by the ratio of the unstable nuclide's rate of decay (usually, β-decay) and its neutron capture cross-sections. The switch of a branch from the $N(n) << N(n)_c$ to the $N(n) >> N(n)_c$ paths occurs over a factor of about 1000 in N(n). For $N(n) \sim N(n)_c$, the two possible branches are open.

Classical analysis of several branches yields $N(n) \simeq 3 \times 10^8$ cm^{-3} of the main component of solar system material. Just two branches are available for use with AGB stars:

- the branch at ^{85}Kr that determines the Rb abundance relative to its neighbors Sr and Y.
- the branch at ^{95}Zr that controls production of the stable isotope ^{96}Zr.

The ^{95}Zr Branch: The s-process path near ^{95}Zr is shown in Figure 2. For N(n) → 0, ^{96}Zr is not produced by the s-process. For N(n) → ∞, ^{96}Zr is produced with an abundance $N(^{96}Zr)/N(^{94}Zr) \simeq 1.8$ for $\tau_0 \simeq 0.3$. The ratio $N(^{96}Zr)/N(^{94}Zr) = 0.05$ for $N(n) \simeq 2 \times 10^8$ cm^{-3} and 0.50 for $N(n) \simeq 3 \times 10^9$ cm^{-3} (Toukan and Käppeler 1990). Neutron densities within AGB stars are measureable via the ^{95}Zr branch provided that ZrO bands are present with an appropriate strength. Initial determinations of the Zr isotopic ratios used photographic spectra of the γ 0-0 ZrO band near 6370 Å (Schadee and Davis 1968; Peery and Beebe 1970). Zook (1978, 1985) used the B-X 0-1 6930 Å band. We have obtained Reticon and CCD spectra of the B-X 0-1 and γ 1-2 R_1 6923 Å heads for a sample of S stars. Isotopic ratios are obtained from a comparison of synthetic and observed spectra (Smith 1988). Inspection of our spectra shows no evidence for a high abundance of ^{96}Zr. For two LPVs - R And and R Gem - examined in some detail, we estimate $N(^{96}Zr)/N(Zr) \lesssim 0.05$ or $N(n) \lesssim 5 \times 10^8$ cm^{-3} (Toukan and Käppeler 1990). According to Malaney (1986), who discussed the Zr isotopic ratios expected from AGB models of various core masses, the observations are incompatible with the high N(n) predicted for IM-AGBs. This conclusion remains valid when current estimates of the neutron capture cross-sections are adopted.

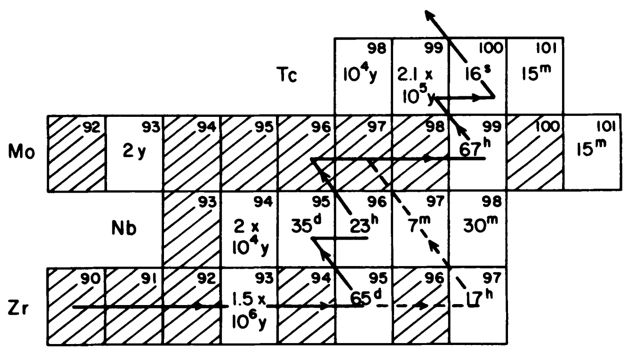

Figure 2. - The main-s-process flow through the Zr-Tc region of nuclei. Stable isotopes are indicated by cross-hatching.

Inspection of Figure 2 shows two additional interesting aspects of the s-process path near ^{95}Zr. First, ^{93}Zr is produced; this isotope is effectively stable at the s-process site. ^{93}Zr, which like Tc measures the time elapsed since s-processing, decays to ^{93}Nb, the sole stable isotope of Nb. Second, ^{93} Nb is effectively absent from the He-shell at the time of s-processing once the p-process nuclide ^{92}Mo is flushed out by ^{92}Mo(n,γ)^{93}Mo(e,ν)^{93}Nb(n,γ). Dominy and Wallerstein (1986) report the presence of Tc in the LPV o Cet in association with normal abundances for other s-process elements (*e.g.*, Zr and Mo) and an underabundance of Nb. This odd combination of heavy element abundances is approached with a recent mild exposure to neutrons: Dominy and Wallerstein suggest that a large fraction of the envelope has been exposed to the level $\tau_0 \simeq 0.005$. However, the observed upper limit on the Nb abundance is less than predicted.

The ^{85}Kr Branch: Figure 3 shows the s-process paths around ^{85}Kr. This branch is not as simple as that at ^{95}Zr because a short-lived isomeric state is populated and reduces the effectiveness of the branch at the ^{85}Kr ground state. Thanks to the latter's 'long' lifetime, the products following the ^{85}Kr branch are sensitive to the duration (Δt) of the s-processing in the thermal pulse: KGMPR suggest that Δt is not a critical factor. The potential branch point at ^{86}Rb plays a minor role. Beer and Macklin (1989), who provide accurate measurements of the ^{85}Rb and ^{87}Rb neutron capture cross-sections, discuss the operation of the ^{85}Kr branch in AGB models and the interpretation of solar and stellar abundances of affected nuclides.

Application of the branch to cool stars must rely on its effect on the Rb abundance. In the limit $N(n) \rightarrow 0$, the dominant path is through ^{85}Rb, ^{86}Rb to ^{86}Sr. In the high density limit, the path through ^{86}Kr to ^{87}Rb and ^{88}Sr is opened and, thanks to the isomeric state of ^{85}Kr, runs in competition with the path through ^{85}Rb. The elemental abundance of Rb (relative to Sr and Y) is sensitive to the neutron density because the neutron capture cross-sections of ^{85}Rb and ^{87}Rb differ by a factor of about 10. (Note the Sr abundance, but not that of Y, is also sensitive to the ^{85}Kr branch.) The Rb/Sr ratio varies by more than an order of magnitude between the low and high density limits.

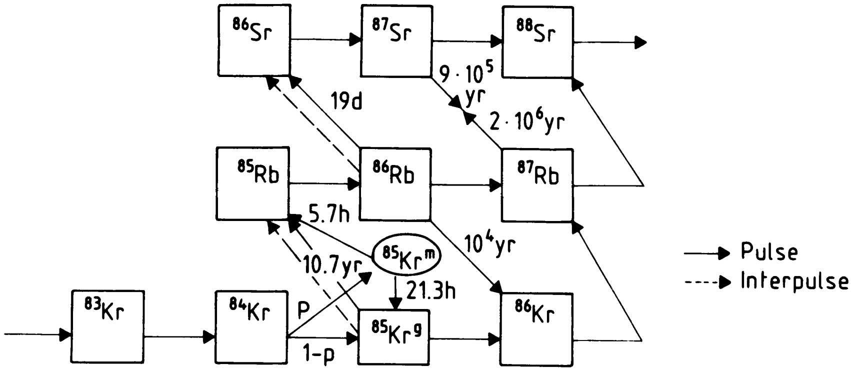

Figure 3. - Synthesis of Kr, Rb, and Sr isotopes during a thermal pulse (solid line) and in the interpulse phase (dashed lines) when the ^{85}Kr and ^{86}Rb which are built up decay. The population P of the isomeric state in ^{85}Kr is generated by neutron capture on ^{84}Kr (P = 0.49 ± 0.06). The time scales for ^{87}Rb and ^{87}Sr beta decay during the pulse are too long to be of any significance for the synthesis. The branching of ^{86}Rb to ^{86}Kr can be neglected too. (From Beer and Macklin 1989.)

The ^{85}Kr branch via the Rb abundance was exploited first by Tomkin and Lambert (1983) for the Barium star HR 774. Later analyses of three other Barium stars (Smith and Lambert 1984; Malaney and Lambert 1988) gave similar results: all values are close to the low density limit. Determinations of the Rb isotopic ratio have not been attempted. An analysis of the Rb I lines in Arcturus (Lambert and Luck 1976) suggests that such a determination is very unlikely to be a more accurate indicator of neutron density than the Rb/Sr and Rb/Y ratios. At present we are examining Rb in a sample of bright M, MS, and S stars. Preliminary analyses of several stars and inspection of spectra of the entire sample show that the Rb/Sr ratios are solar-like in all cases. Of especial interest are HR8714 with a high Li abundance and TV Aur, the most s-process enriched star of our sample.

These results show that the neutron density at the s-process site did not exceed about 10^8 cm^{-3}. The derived limit may depend on the form adopted for the neutron pulse since the abundances are partially determined by the neutron densities during the "freezeout". Beer and Macklin (1989) predicted Rb/Sr ratios for neutron pulses appropriate for IM-AGB models having C-O cores of mass 0.65 to 1.16 $M_\odot$. As expected for pulses having a peak density $N(n) \gtrsim 3 \times 10^9$ cm^{-3} and a rapid freezeout, the predictions exceed the ratios observed for Barium and MS/S stars by a large margin. Beer and Macklin show that pulses with a peak density $N(n) \sim 10^8$-10^9 cm^{-3} and pulse lengths $\Delta t \sim 30$-3 yr are required to fit the observations.

In summary, observations of ^{96}Zr and Rb in s-process enriched stars show that $N(n) \leq 10^9$ cm^{-3}. Such a limit is in conflict with models of IM-AGBs where the neutron source is ^{22}Ne(α,n). I comment below on whether LM-AGBs are predicted to satisfy the limit. The simplest conclusion is that none of the stars yet analysed is an IM-AGB.

4.6 OTHER CHARACTERISTICS

Questions Q4 and Q5 remain to be addressed; the latter is discussed by Dr. Kipper (this volume). Of the several branches that are now used in the classical analysis (KGBPM) to give an estimate of the temperature (T_s) at the s-process' site of the main component, none seem to be of potential use for cool stars. Just possibly, the potential of these branches may be realized through spectroscopy of warm extrinsic AGB stars (*e.g.*, main sequence Barium stars of type F or G) where high-resolution spectra may yield isotopic abundances from atomic lines of elements affected by the branch.

At present, T_s is inferred indirectly. Absence of excess ^{25}Mg and ^{26}Mg implies that the stellar s-process site was cooler than the minimum temperature $T \sim 3 \times 10^8$ K required to ignite the ^{22}Ne neutron source. By default, ^{13}C(α,n) is taken to be the neutron source and its ignition does not occur below $T \sim 1.5 \times 10^8$ K. The inferred T_{s*} is between (1.5-3) 10^8 K and so just at or below the temperature $T_{s\odot} = (3.3 \pm 0.5)\ 10^8$ K given by the classical analysis of solar system material. I comment below on reasons why T_{s*} and $T_{s\odot}$ may differ.

5. Observations vs. Models of IM and LM AGBs

5.1 COMPOSITIONS AND AGB MODELS

To the stellar spectroscopist, the chemical composition of a star is but the beginning of the chase. I have sketched in the preceding section how some of the physical characteristics of the s-process site (the He shell) of AGB stars may be deduced from elemental and isotopic abundances. Two additional fundamental questions require answers before the chase is ended. The first question concerns the source of galactic s-process enrichment: are LM-AGBs the major contributor to the solar system's and the local interstellar medium's mix of s-process elements? This question I leave to pandits anxious to tackle the slippery questions of galactic chemical evolution.

The second question is: do the observations of chemical composition provide support for theoretical models of IM and LM-AGB stars? Earlier, I showed that the absence of evidence for the ^{22}Ne source suggests that the galactic AGB stars run the s-process with the ^{13}C source and, hence, are LM-AGBs. Then, the question may be replaced by the following two questions:

• Do current models of LM-AGBs reproduce the observed compositions of intrinsic and extrinsic AGB stars?

• Where are the IM-AGB stars?

5.2 MODELS OF LOW MASS AGB STARS

There is substantial observational evidence that the galactic AGB stars examined so far are not replicas of current models of IM-AGB stars. In terms of the chemical composition, the two main pieces of evidence are:

• the predicted excesses of ^{25}Mg and ^{26}Mg from the running of the ^{22}Ne source have not been found.

• high neutron densities predicted during the s-processing in IM-AGBs driven by the ^{22}Ne source lead to high Rb and ^{96}Zr abundances that have not been found.

Scrutiny of the IM-AGB models may uncover some areas requiring reconsideration; *e.g.*, an envelope reduced by mass loss may lead to lower neutron densities in the He shell; the ^{12}C(n,γ)^{13}C reaction may serve as a moderator and reduce the neutron densities (see below); the neutron yield from ^{22}Ne(α,n) may be reduced through competition with ^{22}Ne(α,γ) - see Arnould (this volume) who remarks that both these reaction rates are subject to large experimental errors. However, it may be very difficult to reduce the neutron density to the observed limit and to maintain an adequate supply of neutrons to generate the observed s-process enrichments. Such investigations seem most unlikely to reconcile the predicted and observed compositions. Moreover, the evidence (mainly from the Magellanic Clouds) that the majority of the stars that have experienced the third dredge-up have the low luminosities expected of LM-AGBs is another difficulty facing identification of the IM-AGB models with the typical AGB star.

Rejection of IM-AGB stars is done with some reluctance because the s-process run by the ^{22}Ne source in these stars appears well constrained; for example, the ^{22}Ne supply is set by the star's initial composition. By sharp contrast, many uncertainties compromise our understanding of the operation of the ^{13}C source and the third dredge-up in LM-AGB stars. These uncertainties are so considerable that Sackmann and Boothroyd (this volume) focus attention on the "s-process mystery". Before we resolve this mystery, observers and theoreticians must exchange observational results and theoretical ideas. Observers will test models that make specific predictions about the s-process (and other) abundances. One such test against the solar system abundances was described by KGBPR - see also Gallino (1989).

In the thermal pulses of the LM-AGB, the primary neutron supply comes from a small pocket of ^{13}C formed during the interpulse intervals when a semiconvective zone at the top of the He shell mixes a small amount of hydrogen from the convective envelope into the C-enriched He shell and later, as these layers are heated, the hydrogen through $^{12}C(p,\gamma)^{13}N(e^+,\nu)^{13}C$ produces the ^{13}C; some ^{13}C is processed to ^{14}N by $^{13}C(p,\gamma)^{14}N$. At the next pulse, the pocket of ^{13}C is engulfed by the convective region in the He shell and $^{13}C(\alpha,n)^{16}O$ releases neutrons provided that the temperature at the base of the convective region (T_b) reaches $T_b \sim 1.5 \times 10^8$ K. The ^{13}C supply is exhausted before the convection ceases. Calculations show that a second burst of neutrons is released as the convective shell reaches its maximum size and $T_b \simeq 3$ is attained; this burst from the ^{22}Ne source is weak ($\tau \sim 0.001$ mb) relative to the burst from the ^{13}C source ($\tau \sim 0.3$), but it plays a role in explaining the solar abundances of a few nuclides.

The physics of the development of the ^{13}C pocket is an unsettled issue as are the details of the third dredge-up (mixing of the base of the outer convective envelope with the quiescent top of the He-shell). KGBPR discuss a LM-AGB model chosen to give a fit to the solar system abundances. Recipes for the formation of the ^{13}C pocket and its ingestion into the convective shell were taken from Hollowell and Iben (1988, 1989) - these recipes and the composition of the He shell control the duration, peak neutron density, and the decline of the neutron burst. The composition also influences the neutron density ($N(n) \propto Z^{-1}$; Hollowell and Iben 1989). Another factor influencing the peak neutron density is the moderating influence of ^{12}C as $^{12}C(n,\gamma)^{13}C$ removes neutrons that are released later in the burst via $^{13}C(\alpha,n)^{16}O$. This role for ^{12}C was introduced by Gallino *et al.* (1988) but, with the present low estimate for σ_{12} (Arnould, this volume), the calculations reported by Hollowell and Iben (1990) suggest that $^{12}C(n,\gamma)$ plays a minor role in shaping the neutron burst.

KGBPR show that one of their LM-AGB models for an initial composition $Z \simeq 5.5 \times 10^{-3}$ gives a "best fit" to the solar abundances. The predictions refer to the envelope composition reached asymptotically in the series of thermal pulses. Almost all the s-process elements are overabundant by approximately the same factor ($\simeq$ 1300 times); *i.e.*, this material when diluted would give the solar abundances (with respect to lighter elements). The predicted overabundance is typical of that found for the MS/S stars. The predicted abundances of pure s isotopes unaffected by branches match the solar values with a dispersion of about 5%; *i.e.*, $\tau_o = 0.30$ mb^{-1} for the composition of the model LM-AGBs envelope. KGBPR conclude that their calculation "demonstrates that thermal pulses in the helium shell of LMSs [$\equiv$ LM-AGBs] are a suited astrophysical site for producing solar s-process abundances" and remark that "it constitutes a significant improvement with respect to previous predictions" for IM-AGBs.

When the comparison of predicted and observed abundances is extended to nuclides affected by branches, the agreement is less satisfactory. In particular, ^{87}Rb and ^{96}Zr are overproduced relative to their solar abundances. However, the predicted $^{96}Zr/^{94}Zr$ ratio of about 0.2 is approximately consistent with our preliminary estimates of the Zr isotopic abundances for R Gem and R And. The predicted Rb/Y ratio is higher than the solar ratio by a factor of about 1.5 (0.2 dex). This too is approximately consistent with the Rb abundances of the Ba and MS/S stars. KGBPR give an extended discussion of the nuclides affected by those branches exploited by the classical analysis including those that are temperature as well as neutron density sensitive. The brief second neutron burst fed by the ^{22}Ne source has a major influence on setting the nuclides controlled by the temperature sensitive branches at abundances appropriate to $T_s \sim 3 \times 10^8$ K, but the major processing occurred at $T_s \sim 1.5 \times 10^8$ K. The ^{22}Ne miniburst may reconcile the apparently conflicting clues provided by the classical analysis: N(n) → LM-AGBs but T_s → IM-AGBs. In summary, the particular model studied by KGBPR does have an envelope with s-process abundances similar in all the observed details to the typical S star.

This stunning theoretical success must be set in context. Debate rages over how the ^{13}C-pocket develops and the conditions need to ensure dredge-up. On a more practical level, the theory of LM-AGBs must yet show

• why the ^{13}C neutron burst supplemented by the ^{22}Ne mini-burst results in s-process abundances for AGB S stars that cover only a small range in neutron exposure: $\tau_0 \simeq 0.3$ mb^{-1}.

• how do the s-process enrichment in the He shell and the third dredge-up combine to give s-process overabundances at the surface in the observed range. Mass loss from the envelope has to be included.

In parallel, observers must establish more securely the range and nature of the s-process abundances in AGB stars and strive to obtain improved estimates of the mean neutron density for Rb and ^{96}Zr.

5.3 WHERE ARE THE THERMALLY PULSING, IM-AGB STARS?

The AGB population of the Magellanic Clouds extends to the limiting luminosity set by the Chandrasekhar limit for the core mass. Are these luminous AGB stars the missing IM-AGBs? Within 1 mag. of the limiting luminosity, the Cloud stars are Li-rich as well as s-process rich (Smith and Lambert 1990a). For the Li-rich stars, Wood, Bessell, and Fox (1983) estimate the *present* masses as M ~ 4-8 $M_\odot$ or M ~ 2-4 $M_\odot$ depending on whether these LPVs are pulsating in the fundamental or first-overtone modes respectively. Estimates of the corresponding initial stellar masses and indeed the masses in the early phases of thermal pulsing when the s-process enrichments may have been established depend on the unknown rates of mass loss. Sackmann and Boothroyd (this volume) claim that stars of initial mass greater than 3-4 $M_\odot$ suffer such extensive mass loss that they leave the AGB without experiencing thermal pulses: *i.e.*, there are NO thermally pulsing (TP) IM-AGBs!

If M ~ 4-8 $M_\odot$ is the range for the present masses, the stars are IM-AGBs and provide testbeds for IM-AGB models. One would suppose that some of the Li-rich galactic S stars may also be IM-AGBs. Currently, we are determining Rb and ^{96}Zr abundances to search for the high neutron densities predicted for IM-AGBs. The Mg isotopic abundance may betray the ^{22}Ne source: a HBCE may partially erase the excesses of ^{25}Mg and ^{26}Mg, but will likely then convert the S star to a carbon star.

If M ~ 2-4 $M_\odot$ is the appropriate mass range, some of the stars may be LM-AGBs at an advanced age. Luminous LM-AGBs are expected to develop a HBCE too, but seem unlikely to run the ^{22}Ne source because their envelopes are of insufficient mass. The galactic intrinsic S star HR 8714 is Li-rich, but has a solar Rb/Y and Mg isotopic ratios: *i.e.*, it would appear to be a LM-AGB. A search for galactic IM-AGBs must be made using the Mg isotopic abundances.

(Stop press! Examination of our spectra shows that the Li-rich S stars in the Clouds are not enriched in ^{96}Zr and the Rb abundance is that expected for low neutron density, not the high neutron density predicted for IM-AGBs.)

5.4 IS THE THIRD DREDGE-UP ALWAYS NECESSARY?

The extrinsic and intrinsic MS/S and the cool carbon (non-J type) stars show overabundances of both ^{12}C and s-process elements which signal clearly that the third dredge-up is (or has) operated in an AGB star. There remain stars of high absolute luminosity that do not exhibit the full range of the abundance anomalies expected from the third dredge-up. I conclude with brief discussions of two kinds of stars where anomalies exist that may not be attributable to the He-shell and a third dredge-up.

Malaney (1989) proposed that Tc may be produced in detectable amounts via γ-ray induced fission of ^{232}Th, ^{235}U, and ^{238}CU in the H-burning shell of an AGB star with the γ-rays provided by the $^{13}C(p,\gamma)^{14}N$ and $^{14}N(p,\gamma)^{15}O$ CN-cycle reactions. The base of a HBCE is also a likely site. Further calculations (Lattanzio and Malaney 1989) show that Tc produced by this photofission process reaches detectable amounts for AGB stars with low envelope masses ($M_e \lesssim 0.2\ M_\odot$) and masses on the AGB of 1-2 $M_\odot$. These stars have the luminosities of LPVs ($M_{bol} \sim -4.5$ to -6). It should be noted that the predicted Tc abundances, though detectable, are about 10^{-3} of those expected from the s-process. As noted earlier, o Cet and other LPVs do show Tc but no evidence for overabundances of the stable s-process elements: is the Tc a product of photofission? Smith (1989) notes that the Tc abundance is approximately consistent with production by the s-process, but not photofission.

The J-type (^{13}C-rich) cool carbon stars are obviously enriched in carbon, but the s-process elements have near-normal abundances. It is unclear whether these stars are thermally pulsing TP- AGB stars: Lattanzio (1989) notes that his calculations show some model LM-AGBs enriched in ^{12}C but not the s-process elements. Similar stars - the warm carbon (R-type) stars - exist at the much lower luminosities appropriate to He-core burning giants. Occam's razor suggests that the J-type cool carbon stars have evolved from the R stars which may have been created when the He-core flash unleashed extensive mixing (Dominy 1984). Thanks to the brief life of a TP-AGB star relative to the time spent on the AGB at lower luminosities, samples of the J-type cool-carbon stars are likely to be dominated by stars that have not yet begun thermal pulses. When pulses commence, the surface composition is likely to show s-process overabundances including Tc.

5.5 SiC GRAINS FROM METEORITES

Preserved interstellar grains of SiC were discovered recently in meteorites (Tang and Anders 1988). The isotopic ratios of C, N, and Si (Tang *et al.* 1989; Zinner, Tang, and Anders 1989) and the presence of rare gases with isotopic ratios expected for the s-process suggest that the grains have come from the circumstellar envelopes of several carbon stars. Lewis, Amari, and Anders (1990) present isotopic ratios for all five rare gases from a number of SiC grains. Gallino *et al.* (1990) compare these ratios with predictions for LM-AGBs. The brief summary that must suffice here may convince stellar spectroscopists of the enormous significance of recent remarkable work on meteorites.

The isotopic ratios of the rare gases clearly show evidence of s-processing, as first proven for the Xe isotopes (Srinivasan and Anders 1978). With the new measurements, it is possible to extract information of the s-process site's physical characteristics using isotopes affected by a branch in the s-process path. For example, the $^{80}Kr/^{82}Kr$ ratio is influenced by the temperature (and neutron density) sensitive branch at ^{79}Se. Gallino *et al.* show that "only the ^{13}C source acting at relatively low temperature ($T \simeq 1.5 \times 10^8$ K) (and not the ^{22}Ne one, requiring $T \geq 3 \times 10^8$ K) can reproduce the low $^{80}Kr/^{82}Kr$ ratios extrapolated for the pure-s component". The predictions for LM-AGBs reproduce the observed scatter in the $^{86}Kr/^{82}Kr$ ratio which is influenced by the branch at ^{85}Kr: the $^{86}Kr/^{82}Kr$ observations "require a range of neutron exposures, up to $\tau = 0.3$ mb^{-1}". The SiC grains are enriched in ^{22}Ne, as predicted. Their ^{3}He content gave the first estimate of the $^{3}He/^{4}He$ ratio for an AGB star; the ^{3}He was synthesized in the main sequence star well outside the H-burning core.

In short, the composition of the SiC grains is quite consistent with predictions about the envelope models of LM-AGBs. In providing data on the rare gases, the grains complement the stellar abundance analyses.

6. CONCLUDING REMARKS

On both the observational and theoretical fronts, the s-process is under intense and productive scrutiny. A concensus is emerging:

• Low mass AGB stars ($M \lesssim 3 M_\odot$) in which the s-process is driven by the $^{13}C(\alpha,n)$ source were responsible for the s-process abundances in solar system material as well as the interstellar (circumstellar by birth) SiC grains recently discovered in meteorites;

• Galactic intrinsic and extrinsic MS, S, and most probably C stars are LM-AGB stars.

The fate of intermediate mass ($3 \lesssim M/M_\odot < 8 M_\odot$) stars on the AGB is uncertain. Evidence has yet to be found for their s-process products from a He-shell in which $^{22}Ne(\alpha,n)$ contributed the neutrons. Luminous AGB stars that are Li-rich *may* be IM-AGB stars, but a convincing spectroscopic test has yet to be made. These tests include overabundances of ^{25}Mg and ^{26}Mg (relative to ^{24}Mg), and Rb and ^{96}Zr excesses resulting from the high neutron densities expected from ignition of the ^{22}Ne source. The possibility remains that the IM stars lose mass so extensively that they are unable to evolve to the stage of thermal pulses.

In writing this review, I have benefited considerably from discussions with Drs. D. S. P. Dearborn, A. Jorissen, J. C. Lattanzio, and V. V. Smith. I thank Drs. E. Anders, and R. Gallino for sending me very stimulating preprints. My research into AGB stars is supported in part by the National Science Foundation (grant AST89-02835) and the Robert A. Welch Foundation.

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