Nucleosynthesis and Mixing in Low- and Intermediate-Mass AGB Stars

David Hollowell and Icko Iben, Jr.
Astronomy Dept., University of Illinois
Urbana, Illinois
61801 U. S. A.

ABSTRACT. The existence of carbon stars brighter than $M_{bol}=-4$ can be understood in terms of dredge up in thermally pulsing asymptotic giant branch (AGB) stars. As a low- or intermediate-mass star evolves on the AGB, the large fluxes engendered in a helium shell flash cause the base of the convective envelope to extend into the radiative, carbon-rich region, and transport nucleosynthesis products to the stellar surface. Numerical models indicate that AGB stars with sufficiently massive stellar envelopes can become carbon stars via this standard dredge-up mechanism. AGB stars with less massive stellar envelopes can become carbon stars when carbon recombines in the cool, carbon-rich region below the convective envelope.

Neutron capture occurs on iron-seed nuclei during a shell flash, and the products of this nucleosynthesis are also carried to the stellar surface. The conversion of ^{22}Ne into ^{25}Mg can initiate neutron capture nucleosynthesis in large-core mass AGB stars, but only if these stars can survive their large mass loss rates. The current estimates of nuclear reaction rates do not allow for appreciable neutron capture nucleosynthesis via the ^{22}Ne source in lower mass AGB stars. The carbon recombination that induces dredge up in AGB stars of small envelope mass, however, also induces mixing of ^{1}H and ^{12}C in such a way that ultimately a ^{13}C neutron source is activated in these stars. The ^{13}C source can provide an abundant supply of neutrons for the nucleosynthesis of both light and heavy elements. While the existence of neutron-nucleosynthesis products in AGB stellar atmospheres can be understood qualitatively in terms of an active neutron source, the combination of nuclear reaction theory and evolutionary models has yet to provide quantitative agreement with stellar observations.

I. INTRODUCTION

In this review we wish to discuss how observations of AGB stars can be used to determine the manner in which heavy elements are created during a thermal pulse, and how these heavy elements and carbon are transported to the stellar surface. In particular we wish to study how the periodic hydrogen and helium shell burning above a degenerate carbon-oxygen (C-O) core forms a neutron capture nucleosynthesis site that may eventually account for the observed abundance enhancements at the surfaces of AGB stars. In section II we discuss the nucleosynthesis provided by stellar evolution models (for a general review see [1]). In section III we discuss the isotopic abundances provided by nucleosynthesis reaction network calculations (see [2, 3]). In section IV we discuss how observations of AGB stars can be used to discriminate between the neutron capture nucleosynthesis sources (see [4]). And in section V we note some of the current uncertainty in this work.

II. AGB EVOLUTION

A thermally pulsing AGB star spends ~80% of each pulse burning hydrogen in a thin shell above a hydrogen-depleted core. The H-burning shell remains at a radius ~0.01 R☉ and produces the AGB surface luminosity (~10^4 L☉) as it burns outward (in

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press

mass) through the star. The byproducts of CNO burning in this shell (principally ^{4}He, with some ^{14}N) are "dumped" onto the temporarily dormant helium shell (L_{He} ~ 10 L⊙) that surrounds the degenerate C-O core. Although the hydrogen-burning shell is not an active site of neutron capture nucleosynthesis, it is where raw materials for this nucleosynthesis, such as ^{4}He and ^{14}N, are created. This ^{4}He will be fuel for the following thermal pulse and the ^{4}He and ^{14}N may be reactants in the neutron capture nucleosynthesis reactions.

As the helium-rich shell below the hydrogen-burning shell becomes more massive, the temperature and density at the base of this shell increase until 3α burning begins. Due to the compact, thin-shell nature of this burning, a thermal runaway develops [5]; the maximum temperature in the helium-burning shell can reach $250 - 400 \cdot 10^6$ K and the luminosity of the shell can reach $10^7 - 10^8$ L⊙. The high temperatures and large luminosities cause a convective shell to form in the He-rich region. This hot convective shell first forms in the lower, He-burning regions and the temperature at the base of the shell, T_{csb}, is initially $\approx 100 \cdot 10^6$ K. The convective shell then grows inward with T_{csb} increasing to $250 - 400 \cdot 10^6$ K. It also grows outward and engulfs almost all of the products of hydrogen burning left behind by the advancing hydrogen-burning shell.

It is this hot convective shell that can be an active site of neutron capture nucleosynthesis in a thermally pulsing AGB star [6]. Convection mixes the nucleosynthesis raw materials for α capture and for neutron producing reactions to the hot base of the convective shell. The material mixed to the base contains heavy elements that originally were in the stellar envelope (perhaps in a solar system distribution), as well as heavy elements from previous thermal pulses (perhaps in a neutron-rich distribution). Processed material is simultaneously mixed away from the shell base to cooler outer regions of the shell, and this material contains α-burning byproducts and a rearranged heavy element distribution (if neutron capture nucleosynthesis has occurred).

When the temperature at the base of the convective shell becomes $\geq 250 \cdot 10^6$ K, the ^{14}N in the convective shell is rapidly converted to ^{22}Ne by two α captures and a β^- decay. If the base temperature is in excess of $300 - 350 \cdot 10^6$ K, the Coulomb barrier between ^{22}Ne and ^{4}He can be overcome and the ^{22}Ne$(\alpha,n)^{25}$Mg reaction acts as a neutron source in the convective shell. Extant evolutionary models, however, suggest that only the high-core mass ($M_{core} \geq 0.8$ M⊙, $M_{bol} \leq -6.0$) AGB stars can attain these high convective shell temperatures long enough to produce a sufficient number of neutrons for substantial neutron capture nucleosynthesis. Models of low-core mass AGB stars ($M_{bol} \geq -6.0$) do not strongly activate the ^{22}Ne source since their convective shells are too cool. A possible source of neutrons in the low-metallicity, low-core mass AGB stars is the ^{13}C$(\alpha,n)^{16}$O reaction [7]. We will shortly discuss how ^{13}C can be formed in an AGB star just after a thermal runaway.

As the energy from the pulse escapes from the hot convective shell (now C and He rich), the region between the H and He shells becomes radiative. As the pulse energy flows through the base of the convective envelope, the convective envelope moves inward in mass. If the luminosity is large enough (i.e. if the AGB core mass is large enough) the convective envelope will extend into the region that was previously occupied by the hot convective shell [6, 8, 9]. The convective envelope then mixes the nucleosynthesis byproducts (particularly ^{12}C, and perhaps neutron irradiated material) to the stellar surface in the "classical" dredge-up mechanism.

When this dredge-up phase occurs, the extinct hydrogen shell (which marks the discontinuity between the H-rich envelope and the C- and He-rich interior) has expanded to ~ 1 R⊙ due to the thermal pulse heating. During this phase the carbon nuclei will begin to recombine with free electrons in those regions of the AGB star that are cooling to temperatures $\leq 10^6$ K [10, 11]. In AGB stars with a large envelope (M_{env} ~ 1 M⊙) temperatures below 10^6 K only occur in the H-rich, C-poor, convective envelope, and carbon recombination has little effect. In AGB stars with a small envelope (M_{env} ~ 0.1 M⊙) these temperatures will be found in the C- and He-rich interior just below the H-rich envelope. In these stars carbon recombination will increase the local opacity, due to the bound-bound and bound-free transitions of carbon and a convective region forms that mixes hydrogen downward to the carbon/helium rich region and mixes carbon upward toward the hydrogen-rich region. Our calculations show that if enough carbon is transported upward into sufficiently cool regions, the convective envelope will mix with these recombination regions and

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press

carbon will be dredged up to the surface. Independent of whether or not carbon is mixed to the stellar surface, the hydrogen mixed downward will form a region ~ 10^{-4} M⊙ in size which is .1% H (by mass) in a ~ 20% C, 80% He mixture.

In all AGB stars, as the dredge-up phase ends and as helium burning (now in a radiative structure) above the C-O core decreases, the C/H discontinuity will contract to ~ 0.01 R⊙. Hydrogen will begin to burn again, and will continue to burn until conditions are ready for the next thermal pulse. If a low-envelope-mass AGB star has a "pocket" of .1% hydrogen and 20% carbon as previously described, the pocket will also contract and the hydrogen will burn with ^{12}C in the CNO cycle. It will, however, only burn to form ^{13}C as there is too little ^{1}H and too much ^{12}C for further CNO burning. In this way a low-envelope-mass AGB star forms a pocket of ^{13}C which eventually will be engulfed by a hot convective shell during the following thermal pulse. Since the pulse temperature is always high enough ($>150 \cdot 10^6$ K) to overcome the Coulomb repulsion between ^{13}C and ^{4}He nuclei, the $^{13}C(\alpha,n)^{16}O$ reaction will readily convert this ^{13}C matter into ^{16}O and neutrons - the only requirement is that the AGB star produce a sufficient quantity of ^{13}C.

III. AGB NEUTRON CAPTURE NUCLEOSYNTHESIS

While stellar evolution models describe neutron production, the calculations must be supplemented with nucleosynthesis calculations to determine what abundances of heavy elements the ^{13}C or ^{22}Ne neutron sources will produce. While analytic theory can approximate the production of heavy elements [3], numerical modelling of ~ 500 isotopes is used for detailed comparison of stellar evolution theory and observation. In general, the destruction of an isotope between Fe and Bi occurs due to that isotope capturing a neutron or β^- decaying, while the creation of an isotope will be due to the neutron capture or β^- decay of lighter elements.

The neutron capture rate in the AGB convective shell is primarily dependent upon the neutron density N_n. Higher neutron densities tend to build up the neutron-rich isotopes. The β^- decay rate of an unstable isotope can, in some instances, be sensitive to the temperature at the base of the convective shell, T_{csb}. Higher temperatures mean greater excitation of low-lying nuclear levels from which β^- decay may proceed much more rapidly than from the nuclear ground state. In addition, the lifetime of the convective shell describes how long the nucleosynthesis will occur – a larger shell lifetime allows more light elements to be transmuted into heavy elements. In this review we will consider how N_n and T_{csb} differ between the ^{13}C and ^{22}Ne neutron sources, and how this difference affects the heavy element nucleosynthesis.

The ^{22}Ne source, as we recall, operates at a significant rate only in AGB stars of large core mass. These stars have high maximum shell temperatures and hence have more rapid neutron production and large neutron densities [12, 13, 14]. Since the ^{22}Ne reaction rate is temperature dependent, N_n will vary as the shell temperature varies. A gradual temporal change in N_n during a pulse will be found in models with a gradual temporal change in T_{csb} during a pulse. The maximum shell temperature during a thermal pulse and the maximum value of N_n during a thermal pulse are both functions of core mass. For an AGB star with a 0.8, 1.0, or 1.2 M⊙ C-O core, the maximum neutron density in the convective shell would be 10^8, 10^{10}, or 10^{11} n/cm^3 respectively, and thus the ^{22}Ne source can provide an s-process nucleosynthesis environment or an environment intermediate between those which produce s- and r-process distributions [16]. Of course, high maximum shell temperatures can, in many instances, accelerate the conversion of nuclear neutrons to nuclear protons by β^- decays, and thus with the ^{22}Ne source there is a coupling between the neutron capture nucleosynthesis and the β^- decay of the isotopes.

The ^{13}C source liberates neutrons as soon as the ^{13}C pocket is mixed into the hot convective shell (typically at $T_{csb} \approx 150 \cdot 10^6$ K). The release of neutrons is essentially immediate, depending only upon the abundance of ^{13}C in the shell and not on shell temperature. The abundance of ^{13}C in the shell is a function of the small amount of ^{1}H that was mixed into a ^{12}C-rich region (which occurred ~ 10^5 years earlier) and thus N_n from the ^{13}C source is mixing dependent, not temperature

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press

dependent. This ^{13}C source provides a "pulse" of neutron irradiation that lasts until all the ^{13}C is incorporated into the convective shell (~ 1 year). After this, no more neutrons are released, and N_n drops rapidly as neutrons are captured on the elements. However, after neutron production from the ^{13}C source has ceased, the β^- decay rates that control the conversion of nuclear neutrons to nuclear protons become temperature sensitive when the pulse temperatures approach their maximum values (250–300•10^6 K in low-core mass stars). Hence, for the ^{13}C source there is not the same kind of coupling between neutron release and β^- decay as occurs with the ^{22}Ne source. Our calculations show the ^{13}C source always produces a neutron density ~ 10^{12} n/cm^3 in the convective shell, and thus the ^{13}C source always provides a nucleosynthesis environment intermediate between the classical s-process and r-process environments.

IV. AGB OBSERVATIONS

The existence of radioactive ^{99}Tc seen in many AGB stars is strong evidence that AGB stars are active sites of neutron capture nucleosynthesis. With a half life of < 2•10^5 years, the technetium must have been created and mixed to the stellar surface within the last ~ 10^6 years [4, 15, 17, 18] (a time equal to or longer than a thermal pulse time). Although the lifetime of ^{99}Tc is only 10 years at the 350•10^6 K at which the ^{22}Ne source operates [19], it has been found [20] *that ^{99}Tc can always be made by the ^{22}Ne source. The coupling between N_n and T_{csb}* always allows more ^{99}Tc to be created by neutron capture nucleosynthesis than can be destroyed by β^- decay. The ^{13}C source, on the other hand, operates at relatively low temperatures, where ^{99}Tc always decays more slowly than neutrons are captured. We note, however, that neutron capture nucleosynthesis and β^- decay are not tightly coupled in the ^{13}C source, and thus the ^{99}Tc created in the convective shell at an early, cool period of a thermal pulse (via the ^{13}C source) may be destroyed by β^- decay at a later, hotter portion of a pulse.

From the observations of ^{99}Tc in Mira type AGB stars and from assumed period-luminosity relations [21] for such stars, it is concluded that ^{99}Tc may be observed in AGB stars as dim as $M_{bol} \approx -4.0$ ($M_{core} \approx 0.6$ M⊙). As current AGB evolution models show that the ^{22}Ne neutron source is only active in AGB stars with $M_{bol} \leq -6.0$ ($M_{core} \geq 0.8$ M⊙), one concludes that the ^{13}C source must be the nucleosynthesis source in the low-core mass objects.

If the observed absence of ^{99}Tc lines in a significant percentage of C stars [21] is not due to the difficulties in Tc line identification, the absence must be due to a lack of atmospheric Tc. This would imply that all of the surface material in these evolved AGB stars was irradiated at a time long ago compared with the ^{99}Tc decay lifetime. If the ^{13}C source is active in these stars, then the thermal pulse temperatures may have become high enough to insure the destruction of any ^{99}Tc that is created during the ^{13}C source neutron capture nucleosynthesis. Another possibility is that during dredge up the convective envelope may reach deep enough into the star to mix the C- and He-rich pocket (containing .1% hydrogen) to the surface, creating the observed C star. Since the pocket is destroyed, the ^{13}C neutron source will not exist, and no ^{99}Tc will be formed during the following thermal pulse. Finally, independent of the nucleosynthesis properties of C stars, some AGB models do show that dredge up can "turn off" during an advanced AGB stage [8], such that neutron irradiated material is no longer transported to the surface. In this case the surface abundance of Tc (brought to the surface during previous dredge-up episodes) would drop as the envelope ^{99}Tc slowly β^- decays.

While observations of ^{99}Tc suggest the occurrence of neutron capture nucleosynthesis, isotopic observations can be used to probe more deeply the conditions in the hot convective shell during this nucleosynthesis. In particular, the observations of the ZrO bands in S stars can be used to study the neutron flow through the Zr isotopes, ^{90}Zr – ^{96}Zr. The existence of ^{93}Zr (with a half life of ~10^6 years) at the surface of these stars confirms that they contain an active site of neutron capture nucleosynthesis in their interiors. Abundance measurements of the stable isotope ^{96}Zr have been used to determine the physical conditions that

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press

existed during neutron capture nucleosynthesis. The A=90 to 94 isotopes of Zr will capture neutrons and form ^{95}Zr, but ^{95}Zr is unstable and decays with a lifetime of ≈2 months. Only when neutron irradiation occurs with a high neutron flux ($N_n > 10^{10}$ n/cm^3) will the ^{95}Zr capture a neutron and form the stable ^{96}Zr before β^- decaying. For lower neutron densities ($N_n < 10^{10}$ n/cm^3) the ^{95}Zr will β^- decay before any ^{96}Zr can be formed. Since observations suggest little or no ^{96}Zr exists in these S stars [4, 22, 23], the nucleosynthesis source must be a mild one. Malaney [13] finds that the ^{13}C source and the high-core mass ^{22}Ne source always produce large amounts of ^{96}Zr, and only a low-core mass ^{22}Ne source ($M_{core} \approx 0.8$ M⊙, $N_n \sim 10^8$ n/cm^3) is able to match the low ^{96}Zr abundance.

In order to match the observed overabundance of atomic zirconium with the relatively small enhancement of atomic zirconium that a low core mass ^{22}Ne source provides, the observed stars must have a small envelope mass - we may be seeing almost pure irradiated matter in the envelope [13]. If the stellar surface consists largely of irradiated matter, and if the ^{22}Ne$(\alpha,n)^{25}$Mg reaction was the source of neutrons, one would expect the ^{25}Mg (or ^{26}Mg, the neutron capture daughter) to be enhanced relative to ^{24}Mg at the stellar surface [24, 25]. However no significant ^{25}, ^{26}Mg enhancements are seen in S stars [26], which suggests that the ^{22}Ne source is not responsible for the Zr enhancement. Unlike the ^{22}Ne source, the daughter nuclei of the ^{13}C source could never be noticed in an AGB atmosphere. The increase in ^{16}O abundance from the ^{13}C$(\alpha,n)^{16}$O reaction is always negligible compared to the increase from the ^{12}C$(\alpha,\gamma)^{16}$O reaction.

V. DISCUSSION

Why do some observations, when compared with theoretical calculations, suggest ^{22}Ne is the active neutron source, and other observations suggest ^{13}C is the source? If a change in reaction theory were to allow the ^{22}Ne source to produce neutrons at a lower temperature, all low-mass, low-luminosity AGB stars (independent of metallicity and envelope mass) could be active sites of neutron capture nucleosynthesis. This would require, however, a modification in our understanding of light element nucleosynthesis, which must explain why ^{25}Mg and ^{26}Mg are not enhanced in some AGB stars. Similarly, if further stellar evolution calculations show AGB stars with $M_{bol} = -4.0$ develop convective shells that are hot enough to activate the ^{22}Ne source, we will still have to understand how heavy elements can appear neutron enriched, while ^{25}, ^{26}Mg does not appear enriched. The ^{13}C source, on the other hand, is dependent upon the stellar mixing, and hence our current understanding of this source may simply reflect our use of the mixing-length theory of convection in 1-D, quasistatic modelling.

It should also be realized that we have considered ^{13}C source nucleosynthesis independently from ^{22}Ne source nucleosynthesis. The final element distribution that would result if both sources are active during the same thermal pulse in an AGB star may be different than the distributions created by the sources separately. We note that, even with current reaction rates, the ^{22}Ne source is activated at about the 1% level in the convective shell in low-core mass AGB models [8, 28], long after the ^{13}C source has been exhausted. Although the effect on elemental distribution of neutron irradiation from a two neutron source model has not been studied, it is known that the time evolution of neutron density does effect the resultant isotopic distribution [3, 27]. It has also been shown [13] that the ^{96}Zr abundance is only sensitive to the maximum value of N_n during a pulse, and hence the large neutron flux provided by the ^{13}C source should always produce a large amount of ^{96}Zr, whether or not the ^{22}Ne source is active during a thermal pulse.

While significant uncertainty exists in determining the absolute stellar abundances of the heavy elements, the relative isotopic abundance of an atomic species can be determined somewhat independently of the atmospheric modelling uncertainties [4, 29]. Observations of different ZrO bands in a star do produce slightly different surface abundance values, but the uncertainty this introduces into our analysis of stellar nucleosynthesis is small compared to other uncertainties we have already discussed. In addition, the heavy element

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press

enhancements in the AGB stars may be due to nucleosynthesis that occurred before the AGB phase (particularly during the helium core flash) [24, 30]. If such pre-AGB nucleosynthesis occurs, our analyses of these abundances in terms of AGB evolution may be faulty.

This work has been supported in part by the U.S. National Science Foundation, grant AST 84-13371, by the U. S. Department of Energy, and by the National Center for Supercomputing Applications.

REFERENCES

[1] Iben, I., Jr. and Renzini, A. 1983, Ann. Rev. Astr. Ap., 21, 271.
[2] Mathews, G. J., Takahashi, K., Ward, R. A., and Howard, W. M. 1986, Ap. J., 302, 410.
[3] Käppeler, F., Beer, H., Wisshak, K., Clayton, D. D., Macklin, R. L., Ward, R. A. 1982, Ap. J., 257, 821.
[4] Smith, V. V. 1987, preprint, to appear in Proceedings of the ACS Symposium on the Origin and Distribution of the Elements.
[5] Schwarzchild, M. and Härm, R. 1965, Ap. J., 142, 855.
[6] Iben, I., Jr. 1975, Ap. J., 196, 549.
[7] Iben, I., Jr. and Renzini, A. 1982, Ap. J. Lett., 263, L23.
[8] Iben, I., Jr. 1983, Ap. J. Lett., 275, L65.
[9] Lattanzio, J. 1987, Ap. J., 313, L15.
[10] Sackmann, I.-J. 1980, Ap. J. Lett., 241, L37.
[11] Iben, I., Jr. and Renzini, A. 1982, Ap. J. Lett., 259, L79.
[12] Iben, I., Jr. 1977, Ap. J., 217, 788.
[13] Malaney, R. A. 1987, preprint, to appear in Proceedings of the 2nd IAP Rencontre on Nuclear Astrophysics.
[14] Howard, W. M., Mathews, G. J., Takahashi, K., and Ward, R. A. 1986, Ap. J., 309, 633.
[15] Smith, V. V. and Wallerstein, G. 1983, Ap. J., 273, 742.
[16] Clayton, D. D. 1968, Principles of Stellar Evolution and Nucleosynthesis (U. Chicago Press: Chicago), 546.
[17] Merrill, P. W. 1952, Ap. J., 116, 21.
[18] Mathews, G. J., Takahashi, K., Ward, R. A., and Howard, W. M. 1986, Ap. J., 302, 410.
[19] Takahashi, K., Mathews, G. J., and Bloom, S. D. 1986, Phys. Rev. C, 33, 296.
[20] Takahashi, K., Mathews, G. J., Ward, R. A. and Becker, S. A. 1986, Nucleosynthesis and Its Implications on Nuclear and Particle Physics, ed. J. Audouze and N. Mathieu (Reidel: Dordrecht), 285.
[21] Little, S. J., Little-Marenin, I. R., and Bauer, W. H. 1987, Astr. J., 94, 981.
[22] Zook, A. C. 1978, Ap. J. Lett., 221, L113.
[23] Peery, B. F., Jr., and Beebe, R. F. 1970, Ap. J., 160, 619.
[24] Truran, J. W. and Iben, I., Jr. 1977, Ap. J., 216, 797.
[25] Almeida, J. and Käppeler, F. 1983, Ap. J., 265, 417.
[26] Smith, V. V. and Lambert, D. L. 1986, Ap. J., 311, 843.
[27] Cosner, K., Iben, I., Jr. and Truran, J. W. 1980, Ap. J. Lett., 238, L91.
[28] Becker, S. A. 1981, Physical Processes in Red Giants, ed. I. Iben, Jr. and A. Renzini (Reidel: Dordrecht), 141.
[29] Johnson, H. R. 1985, Cool Stars with Excess of Heavy Elements, ed. M. Jaschek and P. C. Keenan (Reidel: Dordrecht), 271.
[30] Pilachowski, C. 1987, this volume.

https://doi.org/10.1017/S0252921100093374 Published online by Cambridge University Press