THE ROLE OF TECHNETIUM IN THE EVOLUTION OF RED GIANTS

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ABSTRACT Tc is detected in many AGB stars providing unambiguous proof that recent nuclear s-processing and mixing (the third dredge-up) has taken place. During this evolutionary episode the atmospheres of AGB stars are progressively enhanced with helium burning products (primarily ^{12}C) and s-process elements as they evolve from M->MS->S->SC->C stars. The increase in s-process elements can be traced most easily by the presence and increasing strength of the Tc I lines accompanying this progression. We also find that the third dredge-up phase is accompanied by an increase in the amplitude of light variation since no non-variable or low amplitude variable M, MS, SC, or S (with one exception) have Tc lines. M star Mira variables show Tc if P > 300^d (low mass Pop I stars). No Pop II star is known to have Tc. Nor do supergiants show Tc I lines. The significant fraction of MS, S and C stars that do not show Tc, are surmised to be cooler analogues to the Ba II stars, i.e. binaries. The source to provide the neutrons for the s-process is most likely the $^{13}C(\alpha,n)^{16}O$ reaction since most of the stars in which we observe Tc are thought to have masses less than 3 solar masses.

I. INTRODUCTION

The presence of Tc in the atmospheres of late type stars is an unambiguous tracer of recent s-process nuclear reactions in stellar interiors and subsequent outward mixing since all the isotopes of Tc are radioactive with half-lives much shorter than the lifetimes of stars. The longest lived isotope, ^{98}Tc, has a half-life of $4.2x10^6$ years, however, the only isotope produced by the s-process, ^{99}Tc, has a half-life of $2.1x10^5$ years. Both the s(slow) neutron capture and the r(rapid) neutron capture process are able to produce elements heavier than Fe by the addition of neutrons to the relatively abundant iron peak elements (Fe, Co, Ni). The r-process requires a large neutron flux (as for instance during a supernova explosion) so that successive neutron captures occur on the order of seconds to minutes; so fast that many radioactive daughter products do not have time to decay before the next neutron is captured. On the other hand, the s-process occurs under low neutron flux conditions. These low flux conditions can be found in the

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intershell region of thermally pulsing asymptotic giant branch stars, hereafter TP-AGB stars. The flux is so low that successive neutron captures occur on the order of days, allowing radioactive daughter products to decay before the next neutron capture takes place. The s-process proceeds along the neutron-rich edge of the valley of nuclear stability enhancing some isotopes relative to others. The process proceeds through the Tc region by a complex network of neutron captures and beta decays (Fig. 1) (Mathews et al. 1986) from ^{90}Zr through neutron captures and beta decays to Nb (where the only stable isotope ^{93}Nb is populated by the decay of ^{93}Zr) to Mo. Successive neutron captures on the stable isotopes of Mo, $^{95-98}$Mo, produce ^{99}Mo which decays with a half-life of 6^h to ^{99}Tc

$$^{98}\mathrm{Mo}(n,\gamma)^{99}\mathrm{Mo}(\beta^-\ \nu)^{99}\mathrm{Tc}(n,\gamma)^{100}\mathrm{Tc}(\beta^-\ \nu)^{99}\mathrm{Ru}.$$

The other two long-lived isotopes, ^{98}Tc and ^{97}Tc, are by-passed by the

Path of s-process through Tc Region

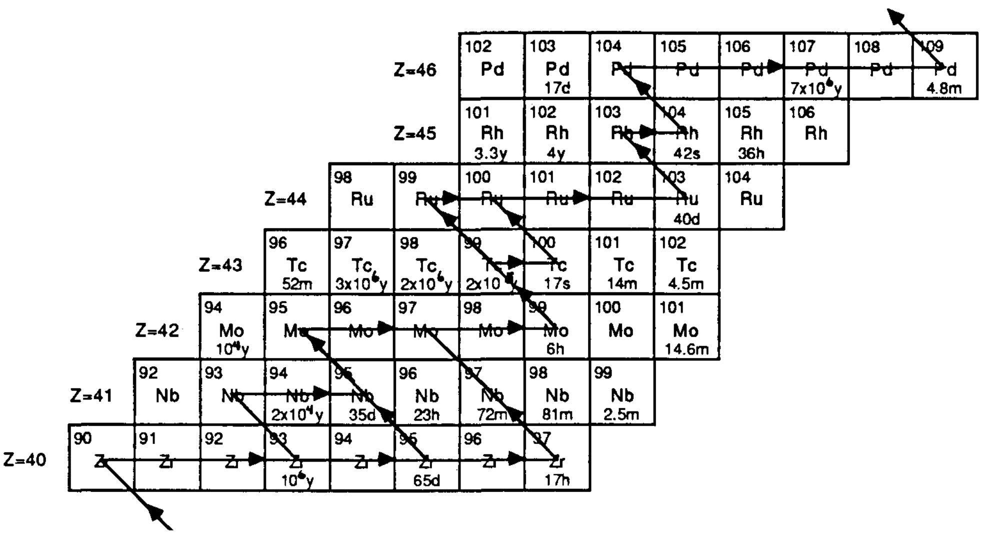

Figure 1 illustrates the s-process path in the Tc regions. The half-lives are listed for the radioactive isotopes of each element.

s-process. The isotope ^{98}Tc is shielded from beta and inverse beta decay and hence should only occur in very small quantities, and ^{97}Tc with a half-life of $2x10^6$ years, can only be produced by the p-process (whose mechanism and site are not well understood) when ^{97}Ru decays by an inverse beta process. The isotope ^{99}Tc can be produced both by the s- and the r-process. Since stars with Tc give no indication of a recent violent event it is assumed that the isotope of Tc that is observed in TP-AGB stars is ^{99}Tc. With time, neutron capture and beta decay transforms ^{99}Tc into Ru. The enhancements of the various s-process elements depend on the details of the s-process path through this region and on the integrated neutron flux. Hence, observed abundance ratios can be used to determine the neutron exposures in a given star (Smith and Wallerstein 1983; Smith and Lambert 1985; Beer and Walter 1985; Dominy and Wallerstein 1986; Smith, Lambert and McWilliam 1987).

In order for ^{99}Tc to be produced and to be observable in the outer layers, one needs both a neutron source and a mixing mechanism. Two neutron sources have been postulated a) the $^{22}Ne(\alpha,n)^{25}Mg$ source and b) the $^{13}C(\alpha,n)^{16}O$ source. The conditions under which these two sources operate are very different. The ^{22}Ne source comes into play during helium burning when successive α-particle captures on ^{14}N lead to the production of ^{22}Ne and free neutrons

$$^{14}N(\alpha,\gamma)^{18}F(\beta^-\ \nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg.$$

In order to be efficient the process requires temperatures of 2-3 x 10^8 K, the presence of α-particles and abundant ^{14}N. The released neutrons are then available to power the s-process. These conditions are found in the intershell region between the hydrogen and helium burning shells of intermediate mass stars (> 3 solar masses). In these double shell source stars a degenerate carbon-oxygen core is surrounded by a helium burning shell, a small intershell region (which contains mostly He) and a hydrogen burning shell in which most of the ^{12}C and ^{16}O is burned into ^{14}N by the CNO cycle. Periodic runaway nuclear reactions, called helium shell flashes, occur in the helium burning shell which can lead to mixing and dredge-up of ^{12}C and s-process elements after several helium shell flashing episodes and the eventual birth of a carbon star (Iben 1987). Earlier theoretical evolutionary models by Iben and collaborators and many others (see Iben and Renzini 1983) predicted that the third dredge-up ocurred in stars greater than about 5 solar masses but not in the lower mass stars. Since then it has been possible to produce dredge-up in lower mass models by modifying the input physics such as by taking semi-convection into account, by using improved carbon opacities, by considering mass loss and by changing the mixing length to scale height parameter (Iben 1988: this conference;Iben and Renzini 1982a,b; Wood 1980; Boothroyd and Sackmann 1988a,b,; Lattanzio 1986, 1987a,b, 1988:this conference). However, at the present time calculations of the third dredge-up have been confined to low metallicity models, i.e. those more appropriate to Pop II rather than Pop I stars.

The $^{13}C(\alpha,n)^{16}O$ source operates at much lower temperatures (around 10^8 K). In order to produce enough ^{13}C atoms, it is necessary first to mix hydrogen into a carbon-rich region in order to produce ^{13}C by proton capture [$^{12}C(p,\gamma)^{13}N(\beta^-\ \nu)^{13}C$], and second to mix the ^{13}C down into a helium burning region in order to activate the neutron source. These conditions should exist during and after helium flashing episodes in stars with masses between 0.7 and 2 solar masses. In a few models it has been shown that hydrogen from the convective envelope can be carried inward into a region in which He burning has previously taken place. ^{12}C will then be burned into ^{13}C during quiescent He shell burning. During the next He shell flash, the convective He burning shell grows outward in mass eventually engulfing the region of high ^{13}C and activating the ^{13}C source (Iben 1987; Hollowell 1987). The models by

Hollowell have not yet been able to dredge-up material from the intershell region after the ^{13}C source has been in operation.

The interpulse period for low mass stars is on the order of 10^5 years (it decreases to $<10^4$ years for intermediate mass stars) and the total duration of the thermal pulsing (TP) stage is only a few times 10^6 years for low mass stars (Iben 1983). From the observed abundances of Tc relative to other s-process elements in MS and S stars Smith and Lambert (1986) estimate that ^{99}Tc should be detectable for 6-7 half-lives or about 1-1.5 x 10^6 years after being mixed to the surface. Hence, it is expected that Tc should be observable in almost all TP-AGB stars.

At the temperatures of the intershell region in intermediate mass stars (2-3 x 10^5 K), Cosner and Truran (1981) and Schatz (1983) have found that the half-life of ^{99}Tc decreases to < 40 years due to much shorter decay time of ^{99}Tc from an excited nuclear state. However, Mathews et al. (1986) have shown that by carefully considering the network of nuclear reactions that are responsible for the production and destruction of Tc that the thermally enhanced beta decay rate of ^{99}Tc at the higher temperatures is more than offset by the increased efficiency of the ^{22}Ne source at these temperatures leaving the Tc abundance almost unchanged. Hence, the ratios of Tc/Nb and Tc/Mo are a good indicator of the time a star has spend in the third dredge-up phase and these ratios are fairly independent of the temperature in the s-processing region. Mathews et al. (1986), Dominy and Wallerstein (1986), Winters and Macklin (1987) and Wallerstein and Dominy (1988) have used the observed abundance ratios in four M, MS and SC stars to estimate the time scale since processing as 10^5 - 10^6 years.

Stars experiencing the third dredge-up, as expected, show an increasing amount of helium burning products, primarily ^{12}C, and s-process elements in their atmosphere with successive dredge-up episodes. During this time the stars evolve from being M stars into C stars. The location of stars on the AGB in intermediate age globular clusters in the Magellanic Clouds are observed to show a progression of spectral type from M->MS->S->(SC)->C with increasing luminosity (Wood 1985) providing direct support for this scenario. The SC stars are enclosed in parentheses in order to indicate that this stage may be by-passed since it requires a near-equality of C and O in the atmosphere and enough C may be dredged up during one helium shell flash episode to allow this phase to be bypassed.

Whereas stars in the Magellanic Clouds allow for the determination of good luminosities of AGB stars, the stars are so faint that it is not yet possible to obtain the high dispersion spectra needed to measure high quality abundances. Hence abundance analyses are confined to relatively few galactic AGB stars whose luminosities are not well known. With very few exceptions the stars analyzed for abundances have been non-Mira variable M, MS, S, and C stars since good atmospheric models are available for them. As expected the C/O ratio increases and the s-process elements are enhanced along the M->C sequence (Boesgaard 1970; Smith and Lambert 1985, 1986; Utsumi 1985; Dominy, Wallerstein and Suntzeff 1986; Lambert et al. 1986). M stars show marginal if any enhancements of s-process elements (Smith and Lambert 1985; Dominy and Wallerstein 1986), MS stars show enhancements from 2 to 5 (Smith and Lambert 1985, 1986) and S stars show enhancements by a factor of 3-8 (Smith and Wallerstein 1983; Smith and Lambert 1986). Therefore, the s-process enhancements correlate well with the increase of the ^{12}C abundance as predicted (Smith 1987). In SC stars Zr and Nb are enhanced by a factor of 5-10 with Mo and Ru being enhanced by about a factor of 50-100 over solar abundances (Smith and Wallerstein 1983). The C stars show s-process enhancements by factors of 10-100 (Utsumi 1985). The early R-type C stars apparently do not belong on this sequence being neither luminous enough to be AGB stars nor showing s-process enhancements (Dominy 1984). The carbon enrichment needed to make them C stars must have been produced by another mechanism than the third dredge-up, possibly an off-center He core flash.

II. OBSERVATIONS

Merrill's (1952) discovery of the resonance lines of the radioactive element technetium (Tc I) in several S, MS and Mira variable M stars at 4297 A, 4262 A and 4238 A, marked the beginning of our ability to provide observational tests of nucleosynthesis schemes. Merrill showed that the Tc I lines tended to be stronger in stars with more pronounced S-type characteristics. Since none of the isotopes are stable, Merrill was correct to suspect that the S stars (and MS stars) represent a transient stage of stellar evolution. In 1956 Merrill detected Tc in the carbon star TX (19) Psc, and this was followed by Peery's 1971 discovery of four more N-type C stars with Tc. The discovery of technetium stars has continued, and now the total number of stars known to have technetium stands at 86 with an additional 19 possible technetium stars out of a total of 301 stars searched (Little, Little-Marenin and Bauer 1987 and references therein, hereafter LLB; Smith and Lambert 1988). All types of AGB stars are represented in this sample of technetium stars: 34 M stars, 17 MS stars, 20 S stars, 3 SC stars and 12 C stars.

Stars with Tc have been identified primarily from the presence of the three resonance lines of Tc I in their spectra at 4297.06 A, 4262.27 A and 4238.19 A which have an intensity ratio of 5:4:3. The identification of the lines is by no means unambiguous since all three lines are blended at the cool temperatures found in AGB stars. The primary blending contributors to the 4297 A line are the lines of three s-process elements Zr II, Sm I and Ce II at about 4296.7 A; those blending the 4262 A line are Gd II, Cr I and AlH; and the 4238 A line lies in the wing of the Ca I 4227 A line (Little-Marenin and Little 1979). Many of the blending contributors are s-process elements and they strengthen as the Tc lines strengthen making identification even more difficult. Our analyses (done in conjunction with my husband and various other collaborators) measured precise wavelengths of the spectral lines on coudé spectra which usually had a resolution of about 0.2 A. Others, primarily Verne Smith and his collaborators, have calculated synthetic spectra in the 4262 A region in order to identify

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the lines and to determine abundances. We reached the same conclusions as Verne Smith about the presence of Tc for the stars in common to our analyses. Our search concentrated on variable stars, especially the Mira variables. These stars are estimated to be AGB stars and good atmospheric models are not yet available making spectrum synthesis calculations difficult.

The presence and absence of Tc in various types of stars can be summarized as follows. Individual categories are expanded in greater detail below.

(1) Nonvariable M stars do not show Tc.

(2) M supergiants do not show Tc.

(3) Irregular variable (Lb) M giants do not show Tc. In general these are low-amplitude variables (mean $\Delta m \sim 0.2$ mag).

(4) M star Mira variables tend to show the Tc I lines if their periods are longer than 300 days. The percent of Miras with Tc and P < 300 days is almost 0% (three Miras with possibly very weak Tc lines have periods of 229 days, 238 days and 264 days). It rises to 100% for Miras with 370 < P < 400 days (Figure 2). Too few Miras with P > 400 days have been observed in order to establish a firm pattern, but it is clear that some of the long period Miras do not show Tc.

(5) The semi-regular (SRb) M giants do not show Tc if P < 100 days or P > 150 days (except for TU CVn (50 days), RT Hya (290 days), and T Mic (347 days)). The SRb's in the 130-150 day range that show Tc may be stars which are the evolutionary equivalent to the Miras but pulsating in the first overtone rather than in the fundamental mode (Willson 1982). Only seven SRa's have been observed. In general the longer period SRa's show Tc and the shorter period ones do not. SRc variables are thought to be supergiants and do not show Tc.

(6) M stars with Tc have spectral types later than M2.

(7) The MS stars should be divided into two groups:

(7a) about 60 % of evolutionary MS stars show Tc. (Evolutionary MS stars are defined by LLB to be in an intermediate evolutionary phase between M and S stars. They show the spectroscopic peculiarities defined by Keenan (1954) as well an overabundance of s-process elements and usually show Tc).

(7b) spectroscopic MS stars do not show Tc. (Spectroscopic MS stars are defined by LLB as having the spectroscopic peculiarities defined by Keenan (usually weakly) but no overabundance of s-process elements can be determined (Smith and Lambert 1985, 1986, 1988))

(8) S stars should be divided into two categories:

(8a) Single S stars show Tc (usually very strongly).

(8b) binary S stars without Tc but other s-process enhancements (except for o^1 Ori (Johnson and Ake 1986)).

(9) SC stars show the resonance lines of Tc (but only three have been analyzed to date).

(10) Twelve out of 16 C stars (75%) show Tc. All 16 analyzed are N-type C stars. The four N-type C stars without Tc are SS Vir, UU Aur, X Cnc and Y CVn. In general J-type C stars do not show any s-process enhancements so that the absence of Tc in the J-type star Y CVn is not surprising.

(10a) All four irregular variable (Lb) C stars show Tc. The Lb C stars have larger amplitudes of light variation ($\Delta m \sim 1$) than the M star Lb's mentioned in (3).

(10b) Early R-type C stars were not observed but are known to have no s-process enhancements (Dominy 1984), hence no Tc is expected to be present.

(13) Ba II stars do not show either Tc I or Tc II lines.

(14) As expected two A stars (Vega and Sirius), one subgiant (HD 176021) and three K giants and supergiants do not show Tc I. These stars are neither AGB stars nor cool enough to have neutral Tc lines.

III. DISCUSSION

The pattern that emerges from the above data is the following: (A) the production and mixing of Tc with atmospheric material during the third dredge-up is associated with large amplitude light variation. Non-variables and low-amplitude variables are not observed to have Tc. The only exception known to date is the S star BS 8062. Possibly this star is temporarily in a quiescent phase. (B) Even when large light amplitudes are observed such as in Miras, the presence of Tc appears to occur only for stars with $P > 300$ days (Fig. 2). (C) The large percentage of MS, S, SC and C stars with Tc supports the scenario that M stars evolve into C stars. (D) Tc is a very sensitive indicator of s-processing. Its presence is detected in the atmospheres of stars even when it is not possible to measure the slight overabundances of other s-process elements either by spectrum synthesis calculations or by spectroscopic classification criteria i.e. the stars are classed as M stars rather than MS stars. Dominy and Wallerstein (1986) detected and determined abundances for Tc in Mira (o Ceti) but could not measure an enhancement of other s-process elements. (E) Not all TP-AGB stars show Tc. Roughly 40% of the MS and S stars (Smith and Lambert 1988) and about 25% of the N-type C stars (LLB) show no Tc.

I will discuss in greater detail some of the categories defined above starting with the M stars. The M supergiants searched for Tc do not appear to be experiencing the third dredge-up since they do not show the Tc I lines. They are likely to be in the core helium burning phase rather than the TP-AGB phase. No supergiant of any spectral class is known to have Tc. This may in part be due to that fact that it is very difficult to classify MS, S and C stars correctly as supergiants because reliable luminosity criteria have not yet been established for s-process enriched atmospheres. Non-variable M stars are not TP-AGB stars. Judging by the lack of Tc in low-amplitude variables and its presence in larger amplitude variables, I estimate that Miras are thermally pulsing AGB stars and that several He shell flashes are needed before a star becomes a long period Mira. However, only Miras with $P > 300$ days are able to dredge-up s-process elements as can be seen in Figure 2. The trend of Miras with Tc as a function of period can be seen easily in 2(a) where the percent of Miras with Tc is plotted in 15 day intervals. The number of stars analyzed in each 15 day interval can be seen in 2(b) and 2(c).

Miras form a well-defined group. Kinematic studies of Miras show that the shorter period Miras P ~ 150-200 days tend to be old Pop II, low mass objects with masses typically around 1 solar mass, whereas the longer period Miras P~300-400 days are somewhat younger (intermediate Pop I) stars with masses between 1.5 to 2.5 solar masses (Feast 1963; Clayton and Feast 1969). The analysis of Dean (1974) shows that C stars on the average have 1.2 solar mass progenitors and confirms the kinematic studies of Feast and Clayton and Feast since thermally pulsing M stars are expected to develop into C stars.

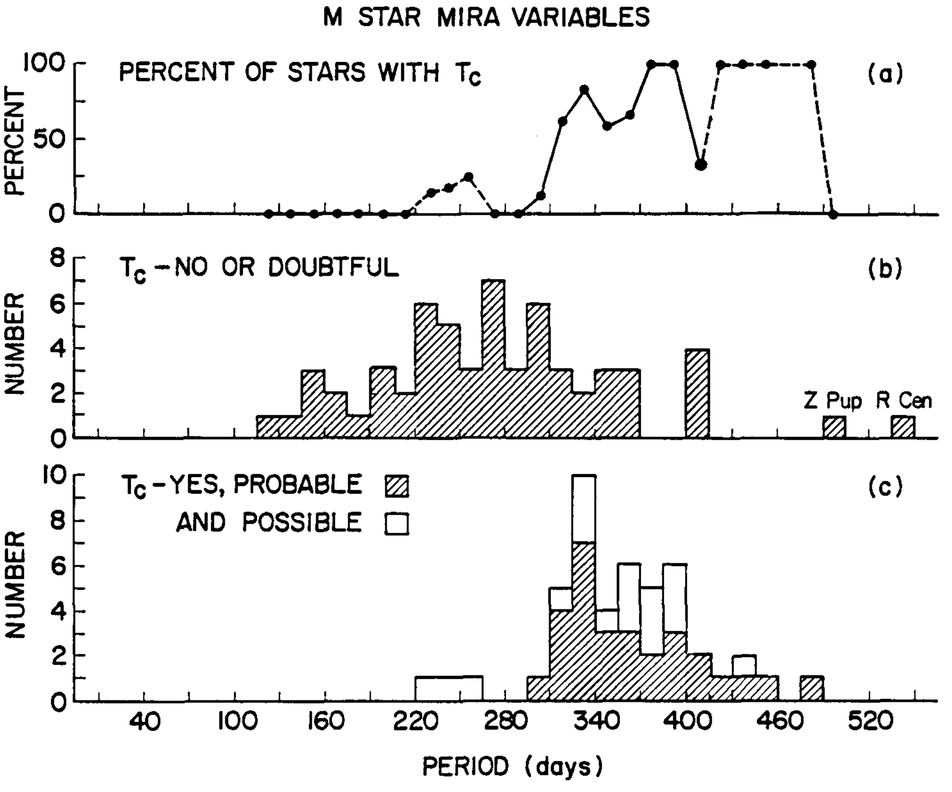

Figure 2. Histogram of M Mira variables with and without Tc. Reprinted from the Astron. J, 94, 981, (1987).

Miras define a period-luminosity relationship which is given by (Glass and Lloyd Evans 1981; Robertson and Feast 1981) as

$$M_{bol} = 0.76(+/- 0.11) - 2.09 \log P$$

for galactic Miras. This relationship indicates that M_{bol} lies between -4.4 to -4.9 for the Miras with Tc. Hence the data lead to the conclusion that stars showing Tc I lines are Pop I stars (Z ~ 0.01-0.02) with masses predominately in the 1.5 - 2.5 solar mass range and luminosities in the 5-6 x 10^3 L_o range. These stars have experienced s-processing and subsequent mixing. However, the third dredge-up can occur in higher mass stars, for example UV Aur has Tc and has an estimated mass of > 4 solar masses. The lack of Tc in the Mira variable V1 in the globular cluster 47 Tuc lends support to the conclusion that the third dredge-up operates mainly in low mass Pop I stars. No theoretical evolutionary model has yet been able to show a successful dredge-up in this mass, metallicity and luminosity range.

The stars without Tc are as intriguing as the stars that show Tc. Ba II stars are known to have s-process enhancements; however, no Tc I lines and more importantly (since Tc is estimated to be mainly ionized at the temperatures of the Ba II stars) no Tc II lines have been detected (Little-Marenin and Little 1987). Hence, the observed s-process enhancements must have occurred more than 10^6 years ago. The discovery by McClure, Fletcher and Nemec (1980) and McClure (1983;1988 this conference) that all Ba II stars appear to be binary led to the suggestion that the s-process enrichment is related to the binary nature of the system. Even though the exact mechanism is not yet well defined, the most likely suggestion is that a previous TP-AGB star, now a white dwarf, transferred part of its envelope more than 10^6 years ago onto the present day Ba II star transferring over both the s-process and ^{12}C enrichments (McClure 1984). The discovery of white dwarf companions for some Ba II stars by (Bohm-Vitense 1980; Bohm-Vitense, Nemec and Proffitt 1984; Bohm-Vitense and Johnson 1985) makes this scenario more plausible. Largely unsuccessful searches for white dwarf companions to technetium stars (Smith and Lambert 1987; Ake and Johnson 1988) except for o^1 Ori (Johnson and Ake 1986) diminish the possibility that Tc as well as the s-process enhancements observed in MS and S stars resulted from mass transfer from a more highly evolved TP-AGB star. But if does demonstrate that if any such mass transfer occurred, it happened very long ago (so that the companion is no longer detectable) at a time when the present day red giant was still on the main sequence. Therefore the MS and S stars with Tc do represent examples of thermally pulsing AGB stars in which the third dredge-up is operating.

The data listed in LLB and the careful abundance analyses of Smith and Lambert (1986, 1988) clearly show that not all stars estimated to be TP-AGB stars show Tc. Specifically about 40% of the evolutionary MS and S stars and about 25% of the C stars do not have Tc I lines but show other s-process enhancements and ^{12}C enrichments. This confirms the suggestions of Scalo and Miller (1981) that among the AGB stars about 30% of the stars are enriched by s-process elements but are without Tc. From the fact that the estimated space densities of M giants to MS/S stars without Tc is very similar to the ratio of G/K giants to (G/K) Ba II stars, Smith and Lambert (1988) conclude that the s-process-enriched MS/S stars without Tc are evolved Ba II stars, i.e. are members of binary systems in which the s-process enrichment occurred more than 10^6 years ago allowing for the decay of Tc. A search for radial velocity variations among Ba II and S stars (largely those without Tc) by Jorissen and Mayor (1988) finds that at least 5 out of 9 S stars (over 50%) show radial velocity variations indicative of orbital motion and hence are likely to be members of a binary system. Hence, the work of

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Jorissen and Mayor lends support to the conclusion that only single S and MS stars show Tc in their spectrum. I have not included in the discussion the MS stars defined by LLB as spectroscopic MS or as very mild MS stars by Smith and Lambert (1988) which show neither Tc nor have measurable s-process enhancements. Their mild MS characteristics seen on spectrograms must be produced by another mechanism than enhanced abundances of Zr and Ba.

Four N-type C stars do not have any observable Tc in their spectrum. This is surprising since the progenitors of N-type C stars are TP-AGB M stars. Utsumi (1985) has found that C stars rich in ^{13}C (type J) show no s-process enhancements. Hence, the origin of the carbon enrichment in the J-type carbon star Y CVn, which shows no Tc, and its low $^{12}C/^{13}C$ ratio of 3.5 implies a compositional change during an earlier evolutionary phase and not the third dredge-up. Unfortunately, no other J-type C star has been searched for Tc. The carbon isotope ratio increases during the third dredge-up as can be seen from Figure 2 of LLB. Stars with stronger s-process enhancements show progressively larger $^{12}C/^{13}C$ ratios. UU Aur and X Cnc do show s-process enhancements but no Tc. If these are cooler analogues to the Ba II stars and are more evolved than the MS and S stars without Tc is not yet known. We were surprised to find the carbon Mira variable SS Vir without Tc lines in its spectrum since it is a prime candidate for the third dredge-up. No information about s-process enhancements in this star is known. None of the three stars have not been searched for radial velocity variations.

IV. CONCLUSIONS

Stars with Tc trace the onset and continuation of thermal pulses in asymptotic giant branch stars. These stars experience the third dredge-up and are predicted to show increasing amounts of carbon and s-process elements in their atmospheres with successive helium shell flashes as a star evolves from being an M->MS->S->(SC)->C star. Observations of stars in globular clusters in the Magellanic Clouds lend support to this evolutionary spectral sequence and detailed abundance analyses of M, MS, SC and C stars confirm the increasing trend of s-process enhancements and carbon abundances along this sequence. Tc is a very sensitive tracer of the mixing of recent s-processed material with the atmosphere of a star since it can be detected before increases in the abundances of other s-process elements can be measured. The mere detection of Tc is enough to establish that s-processing and mixing have occurred and is more easily accomplished than the determination of abundances by spectral analyses. The third dredge-up is accompanied by an increase in the amplitude of light variation since neither non- nor low-amplitude variables show the Tc I lines. In the Mira variables Tc is observed almost exclusively in stars with P > 300 days, indicative of 1.5-2.5 solar mass Pop I stars. Tc is not observed in Pop II stars.

A surprisingly large percent (25%-40%) of the C, S and MS do not show Tc even when other s-process elements are enhanced. Based on the space density of evolved stars, Smith and Lambert (1988) argue that

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MS and S AGB stars without Tc are the cooler, more evolved analog of the Ba II stars. The observed s-process enrichments are estimated to have been produced by mass transfer from a companion so long ago that Tc has had time to decay away.

V. RECOMMENDATIONS

Our understanding of the late stages of evolution have progressed greatly during the last decade. High quality, high dispersion spectra have become available making it possible to establish the presence of Tc in a large cross-section of stars; better model atmospheres have allowed the determination of abundances of Tc and other s-process elements; more detailed stellar evolution models are able to match many of the observed characteristics; precise measurements of radial velocity variations has discovered many new binary systems and established that probably all Ba II stars and many MS and S stars are members of binary systems. Spacecraft observations have detected binary white dwarf companions to some of these systems. With all these accomplishments what problems are left unsolved?

1. More carbon stars need to be searched for technetium in order to define a statistical basis for the number of C stars with and without Tc.
2. Similarly more Miras with P > 400 days need to be analyzed in order to define the percentage of stars that show Tc in this category.
3. No Pop II stars have yet been found to have Tc even though evolutionary models indicate that dredge-up is more easily accomplished in these lower metallicity stars. Known TP-AGB stars of Pop II should be searched for Tc.
4. More s-process abundance determinations of SC and C stars are needed in order to allow detailed comparisons between predictions of evolutionary models and the observations.
5. Model atmospheres for the coolest stars and Mira variables are not yet available making it difficult to perform spectral synthesis calculations on these important objects.
6. The stellar evolutionary models are not yet able to produce the observed abundances of Tc and s-process elements in Pop I stars in which they are observed.

The usefulness of Tc is not confined to the late stages of stellar evolution. A new proposal has been made to use Tc occurring naturally in ores on earth as a way of detecting the ever elusive solar neutrinos!

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