

s-PROCESS-ENRICHED COOL STARS WITH AND WITHOUT TECHNETIUM: CLUES TO  
ASYMPTOTIC GIANT BRANCH AND BINARY STAR EVOLUTION

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## ABSTRACT

High-resolution spectra at  $\lambda 4260$  have been obtained for 40 stars of type MS or S to search for the presence of Tc I. In addition, previously published Tc surveys provide an additional 18 stars for a total sample of 58 MS or S stars. Most of these stars have also been observed in the near-infrared near  $\lambda 7500$ , in a region which provides Zr I, Y II, La II, and Nd II lines. These lines allow us to determine that these stars do indeed show general *s*-process abundance enhancements. Of the total sample, we find that 38% (22 out of 58) of these *s*-process-enriched stars do not show Tc. This large fraction of Tc-poor, *s*-process-enriched stars is somewhat surprising as Tc (with a half-life of  $2 \times 10^5$  yr) produced during *s*-processing in an asymptotic giant branch (AGB) star should be visible in a star's atmosphere for  $\sim 10^6$  yr. This time is comparable to the maximum lifetime of a low-mass, thermally pulsing AGB star, and thus standard stellar evolution would suggest that virtually all *s*-process-enriched AGB stars should show Tc. However, we argue that the space density of these Tc-poor MS and S stars, relative to M giants, is comparable (within the uncertainties) to the space density, relative to normal G and K giants, of the barium stars, which also lack Tc and whose *s*-process enrichment is probably the result of binary mass transfer in the past. We suggest that the MS and S stars are composed of two major groups: (1) Tc-containing stars which are currently thermally pulsing AGB stars undergoing third dredge-up and (2) Tc-poor stars which represent the coolest members of the barium star class.

*Subject headings:* stars: abundances — stars: Ba II — stars: binaries — stars: late-type — stars: S-type

## I. INTRODUCTION

Merrill's (1952) discovery of technetium in the atmospheres of red giants is a landmark in the now extensive literature on observational inquiries into stellar nucleosynthesis and evolution. Although technetium is the outstanding indicator of recent and perhaps current nucleosynthesis in red giants, important aspects of its occurrence remain to be defined. In particular, quantitative estimates of the element's abundance are rarely provided. In this paper, we report on a search for technetium in a sample of 40 MS and S stars. The result that technetium is found in no more than half of these residents of the asymptotic giant branch (AGB) leads to the question, Why is technetium not omnipresent in a sample of stars enriched to similar levels in the heavy elements that are products of the same neutron capture *s*-process that is responsible for the synthesis of technetium?

Technetium is an especially important tracer of stellar evolution on the AGB because the isotope  $^{99}\text{Tc}$  that is produced by the *s*-process has a half-life ( $2 \times 10^5$  yr) comparable to the duration of the thermal pulsing (TP) stage. Simple, LTE spectrum-synthesis calculations by Smith and Lambert (1986), using the resonance Tc I lines near 4250 Å, show that if Tc is produced in expected quantities relative to its fellow *s*-process nuclei and then mixed into the MS and S stars at levels consistent with the observations, it should be detectable for about 6–7 half-lives. This translates to  $\sim(1-1.5) \times 10^6$  yr, which is very close to the TP-AGB lifetime of  $2 \times 10^6$  yr for a  $1 M_{\odot}$  ( $M_{\text{core}} \approx 0.6 M_{\odot}$ ) star as pointed out by Iben (1983). Thus, Tc might be expected to be present in stars of virtually all masses during the TP-AGB phase of evolution.

In low-mass stars, the *s*-process is probably driven by the neutron source  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  with the  $^{13}\text{C}$  produced by the mixing of protons in the  $^{12}\text{C}$ -rich He shell:  $^{12}\text{C}(p, \gamma)$

$^{13}\text{N}(\beta^+, \nu_e)^{13}\text{C}$ . Synthesis of  $^{13}\text{C}$  occurs prior to an He shell flash. In more massive AGB stars, the neutron source is expected to be the reaction  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  with the  $^{22}\text{Ne}$  produced naturally from the initial CNO nuclei in prior H burning and He burning; the CNO cycles convert CNO to (mostly)  $^{14}\text{N}$  and then  $^{14}\text{N}(\alpha, \gamma)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$ . At present,  $^{22}\text{Ne}(\alpha, n)$  is expected to be the dominant neutron source for stars of large core mass, i.e.,  $m_{\text{core}} \gtrsim 0.75 M_{\odot}$ . For lower core masses,  $^{13}\text{C}(\alpha, n)$  is presumed to be the neutron source.

An early concern (Cameron 1959) about the usefulness of Tc as a nucleosynthetic clock was restated recently. The half-life of  $^{99}\text{Tc}$  decreases from  $2 \times 10^5$  yr at low temperatures ( $T \lesssim 10^8$  K) to just 5 yr at  $T \approx 3 \times 10^8$  K, the expected temperature of the  $^{22}\text{Ne}$  neutron source (Cosner and Truran 1981; Schatz 1983). Smith and Wallerstein (1983) argued that Tc was more a thermometer for the AGB *s*-process site than a chronometer and that Tc's presence in TP-AGB stars could be understood only if the neutrons were supplied by the  $^{13}\text{C}(\alpha, n)$  reaction because this is ignited at a temperature ( $T \lesssim 1.5 \times 10^8$  K) where  $^{99}\text{Tc}$  has a moderately long half-life. This conclusion is not supported by detailed studies of *s*-processing during thermal pulses. Matthews *et al.* (1986) show that Tc is produced at the higher temperatures because higher neutron fluxes offset the higher  $\beta$ -decay rates of  $^{99}\text{Tc}$ . No longer can the absence of Tc in an *s*-process-enriched star be taken as strong evidence for a hot *s*-process site.

A number of observers have conducted searches for the presence of Tc in stellar atmospheres, using primarily the three strong resonance lines of Tc I lying in the violet part of the spectrum (4238, 4262, 4297 Å). All observations to date have been summarized and new data presented most recently by Little, Little-Marenin, and Hagen-Bauer (1987, hereafter LLB). We present a survey of a sample of stars selected primarily

from the catalog of S stars by Stephenson (1984). Whereas the survey by LLB contains a large number of Mira-type variables classified as pure M spectral type, our sample contains only stars classified generally on the strength of ZrO, which usually indicates an abundance enhancement of Zr (as well as other *s*-process elements) as demonstrated by Boesgaard (1970) and Smith and Lambert (1985, 1986). The purpose of this study was to isolate a sample of stars which show evidence of *s*-process enhancement. Many of the pure M-type Miras observed by LLB do show Tc I in their spectra, yet seem to exhibit no other indications of *s*-process dredge-up. In an abundance analysis of Mira (*o* Cet), Dominy and Wallerstein (1986) detected Tc but found none of the other *s*-process elements to be enhanced measurably. Such stars are not included in our survey, but probably represent the earliest phases of TP-AGB dredge-up before the amount of dredged-up, stable *s*-process elements has exceeded the initial abundances in the star's atmosphere.

An expectation that Tc should be seen in all TP-AGB stars is at odds with the observations. Scalo and Miller (1981) first pointed out that of 30 stars of type MS, S, SC, and C in an earlier survey and compilation of Tc observations by Little-Marenin and Little (1979), nine stars did not contain Tc. These spectral types exhibit, in general, *s*-process and  $^{12}\text{C}$  enrichment (Boesgaard 1970; Smith and Lambert 1985, 1986; Utsumi 1985; Dominy, Wallerstein, and Suntzeff 1986). The absence of Tc in some 30% of these stars led Scalo and Miller (1981) to suggest two possible explanations, both of which would involve radical changes in the accepted picture of AGB evolution: (1) The mixing of *s*-processed material to the surface does not occur at every shell flash. If many consecutive flashes occur without mixing into the envelope, the surface Tc decays steadily until it is replenished by a flash in which mixing occurs. (2) Some stars above a certain core mass (say  $M_{\text{core}} \gtrsim 0.8 M_{\odot}$ ) never mix. Scalo and Miller's (1981) explanations depend on how long the Tc I lines are considered to remain observable. Scalo and Miller adopted a limiting Tc abundance of 0.1 times the initial abundance; this corresponds to about 3.3 half-lives, or approximately  $7 \times 10^5$  yr. As mentioned earlier, Smith and Lambert (1986) estimated from a comparison sample of synthetic spectra and modern spectra a limiting age of about twice the Scalo and Miller (1981) estimate. With this longer estimate, the suggestions by Scalo and Miller (1981) would have to be modified as only the stars of very low core mass ( $M_{\text{core}} \lesssim 0.6 M_{\odot}$ ;  $M \lesssim 1 M_{\odot}$ ) exist as TP-AGB stars for longer than  $1.5 \times 10^6$  yr.

Iben and Renzini (1983) criticized Scalo and Miller's (1981) conclusions and suggested three alternatives: (1) Some stars may not be *s*-process enhanced; low-resolution classification spectra may not be sufficient to be an adequate basis from which to claim a definitive *s*-process enhancement. Indeed, we (Smith and Lambert 1986) found that four out of nine stars classified as MS from Yamashita's (1967) catalog did not exhibit measurable *s*-process enhancements ( $[s/\text{Fe}] \lesssim +0.2$  relative to solar). (2) Some stars may be cooler (or evolved) examples of the G and K giant barium stars, which also exhibit *s*-process enrichments yet contain no Tc. Such cooler barium stars could have acquired their *s*-process enhancements long ago that the Tc has decayed. These stars have not yet entered the TP stage when fresh additions of *s*-processed material including Tc may be expected. The remarkable discovery by McClure, Fletcher, and Nemeč (1980) and McClure (1983) that probably all barium stars are binaries and may have white dwarf companions (Böhm-Vitense 1980; Böhm-Vitense,

Nemeč, and Proffitt 1984) has led to the hypothesis that the barium stars are the result of a transfer of mass from a TP-AGB star (now, the white dwarf) to a donor (now, the barium star) (Lambert 1988). This mass transfer could have easily happened long enough ago to have allowed any Tc that once existed in the system to have decayed away. (3) The third explanation promoted by Iben and Renzini (1983) invoked the temperature sensitivity of the Tc lifetime. The work by Mathews *et al.* (1986) would seem to refute this explanation.

In order to clarify the claims that Tc is not detectable in a significant fraction of MS and S stars, we made a new survey of the Tc I resonance lines. Here, we discuss observations of 40 stars classified as MS or S and test for the presence of Tc I in their spectra. Most of these stars have also been observed by us in the near-infrared at 7500 Å where we detect clean spectral lines of Zr I, Y II, La II, and Nd II (Smith, Lambert, and McWilliam 1987). These spectra provide some confirmation of true *s*-process enhancement, and thus these spectra, as a whole, can provide some estimate of the fraction of *s*-process-enriched stars that do not contain Tc. This fraction should show whether the *s*-process-enhanced stars without Tc may be the cooler and evolved members of the barium stars or whether radical changes in the *general* picture of AGB evolution are needed.

## II. OBSERVATIONS AND ANALYSIS

The majority of the spectra presented here were obtained with the McDonald Observatory's 2.1 m telescope and the coudé spectrograph equipped with an RCA CCD detector. The dispersion on the CCD was  $0.06 \text{ \AA pixel}^{-1}$  which, with a three-diode slit width, gave a resolution of  $0.18 \text{ \AA}$ . A few spectra were taken with the McDonald Observatory's 2.7 m telescope and the coudé spectrograph equipped with a Reticon detector at very nearly the same dispersion and resolution as the 2.1 m spectra. Spectra of stars observed with both telescope and detector combinations showed no measurable differences between the two systems.

With the CCD detector, only about 30 Å of spectra are contained in a single exposure, so it is not possible to observe all three strong Tc I resonance lines (4238, 4262, 4297 Å) simultaneously. We chose to center the spectra on the 4262 Å line; the 4238 Å line lies within the wings of the strong 4226 Å Ca I line and the 4297 Å line is blended quite strongly with a Ce II line. The 4262 Å is itself blended with a feature that is primarily Gd II and Nb I, with a weaker contribution from Cr I. This composite feature is much weaker than the Tc I resonance line at its maximum strength and is also separated from the Tc I line by  $0.1 \text{ \AA}$  to the blue. As we shall show, a wavelength shift of this much is easily detectable in our spectra. Unlike its companion resonance lines, the 4262 Å line is amenable to a quantitative abundance analysis. Indeed, some of our spectra have been used to provide quantitative Tc abundances (Smith and Lambert 1986; Smith 1988).

In Figure 1, we illustrate three typical CCD spectra of the 4262 Å region. These spectra are plotted to the same relative intensity scale but are shifted by arbitrary amounts. Differences of 0.1 times the intensity of the local "continuum point" are indicated. The major spectral features in this short spectral interval are also shown. The first spectrum is the normal M giant  $\mu$  UMa which does not show the Tc I line; the arrow indicates the expected position of the 4262 Tc I line. Next is HD 49368, an S star with large *s*-process abundance enhancements and no visible Tc line. The wavelength of the feature

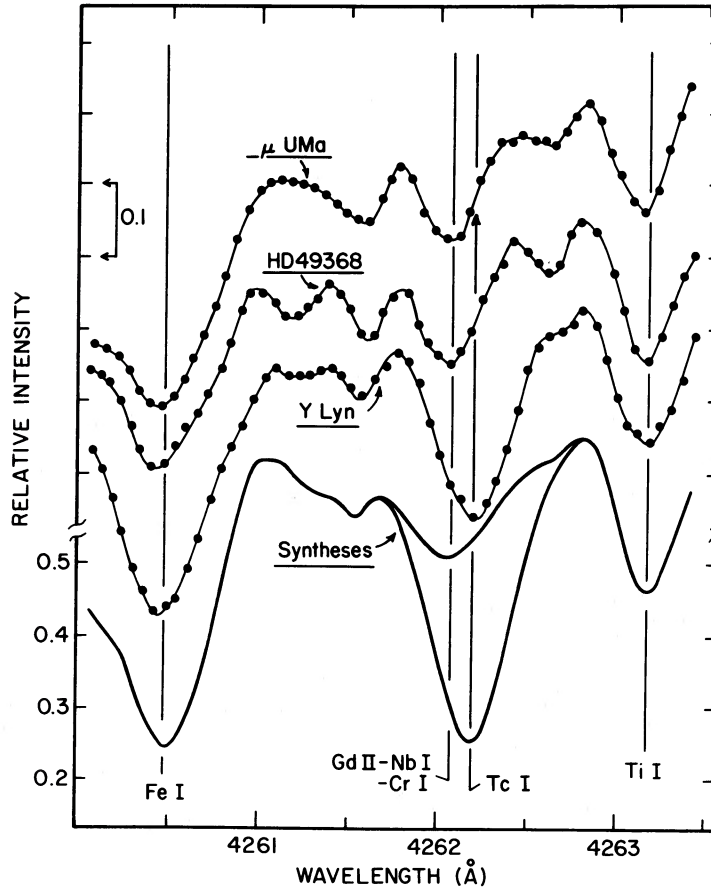


FIG. 1.—Sample spectra of three stars and two syntheses near the Tc I line. The stellar spectra are shown normalized to the same scale but shifted in relative intensity. The M giant  $\mu$  UMa and the *s*-process-enriched S star HD 49368 do not show Tc I, while the *s*-process-enriched MS star Y Lyn clearly does contain Tc I. One synthetic spectrum contains no Tc, while the other contains approximately the maximum Tc abundance expected for observed MS/S stars.

closest to the Tc I wavelength is shifted to the blue by over two diodes ( $\sim 0.12$  Å) from the expected position of Tc I and the line depth of this feature is not much different from  $\mu$  UMa. The wavelength of this feature corresponds with the expected wavelength of the Gd II-Nb I-Cr I blend. Next we show Y Lyn, an MS star with *s*-process overabundances and a strong spectral feature at the proper wavelength for Tc I, which swamps the much weaker Gd II-Nb I-Cr I blend. Finally, we illustrate two synthetic spectra of this region; one spectrum with Tc and one without to illustrate the expected line shift between stars with and without Tc. The abundance of Tc used in the synthesis with Tc was  $\log \epsilon(\text{Tc}) = 1.0$ , on the usual scale where  $\log \epsilon(\text{H}) = 12.0$ ; this is near the maximum expected for the abundance of Tc based upon observed *s*-process enhancements in MS and S stars (Boesgaard 1970; Smith and Lambert 1985, 1986) and theoretical *s*-process predictions from Cowley and Downs (1980). For the synthetic spectrum we show the relative intensity scale based upon the same normalization point as that used for the real spectra. This provides some indication of the actual line depths of the spectral features in this region.

In order to decide whether Tc I can be considered to be present in these spectra, we measured the wavelength of this feature in the 40 MS and S stars and in a “control group” of 10 M giants. We adopted an internal stellar wavelength scale. Eight nearby ( $\lesssim 5$  Å to either side), apparently unblended, stellar features, which correspond to known atomic wavelengths, were chosen as the wavelength standards. In stars that

are this cool, no spectral feature is truly unblended; however, the chosen features are dominated by a single atomic transition. Second-order polynomial fits to the centroids of these features provide rms differences between actual and fitted wavelengths of  $\pm 0.02$ – $0.03$  Å. These fits are then used to determine the wavelength of the feature that either corresponds to the Tc I line or the nearby blend.

In Table 1 we present the wavelengths determined for the feature in the 10 control M giants. Listed are the HR number and name of the star along with the spectral type from Hoffleit (1982) and the measured wavelength,  $\lambda_x$ , of the blend that may

TABLE 1  
THE CONTROL SAMPLE OF M GIANTS

Star	Spectral Type	Wavelength $\lambda_x - 4200$ (Å)
HR 259 .....	M4 IIIab	62.10
HR 867, RZ Ari .....	M6 III	62.06
HR 921, $\rho$ Per .....	M4 II	62.10
HR 2286, $\mu$ Gem .....	M3 IIIab	62.04
HR 4069, $\mu$ UMa .....	M0 III	62.10
HR 4483, $\omega$ Vir .....	M4 III	62.11
HR 6146, 30 Her .....	M6 III	62.03
HR 6406, $\alpha^1$ Her .....	M5 Ib-II	62.08
HR 7405, $\alpha$ Vul .....	M0 III	62.07
HR 8775, $\beta$ Peg .....	M2.5 II-III	62.06

include Tc I and which we now dub "feature X." As can be seen, the wavelengths of feature X range from 4262.03 to 4262.11 Å, with a mean of 4262.08 Å and a standard deviation of 0.03 Å. This mean wavelength is within 0.01 Å of the expected Gd II–Nb I–Cr I blend, and the standard deviation of the mean is close to the typical rms deviations of the fitted dispersion solutions.

In Table 2 we list the data for the 40 MS and S stars. Either the HR, HD, or BD numbers are given along with the variable star designation or name, if any. The spectral type is from Stephenson's (1984) compilation, unless noted otherwise. The wavelength for feature X is then given followed by our decision as to whether Tc I is present (Y = yes) or not (N = no); we discuss below the criterion governing this decision. Finally, we note whether the star is listed in LLB's compilation and their verdict on Tc in the star. There is good agreement between the two surveys: stars considered by us to have Tc are labeled as

"yes" or "prob" by LLB, and stars considered by us to have no Tc are labeled as "dbfl" or "no" by LLB. (In part, the agreement is due to the fact that LLB's compilations draws on our earlier discussion of Tc in several stars now listed again in Table 2 [Smith and Lambert 1986, 1987].) It might be noted that different Tc I resonance lines most heavily influence the decisions regarding the presence of Tc. LLB's decision about the presence of Tc is based largely on the 4297 Å line that is blended with a Ce II line. Ours is based exclusively on the 4262 Å line.

As the first step in the analysis, we compiled frequency histograms (Fig. 2) for three classes of stars: the M, MS, and S stars. The wavelength bins were 0.02 Å wide. Inspection of Table 2 and especially Figure 2 shows that some of, but by no means all, the MS and S stars contain Tc.

For the M stars, the histogram is approximately peaked at 4262.08 Å. This sample includes four stars (the cross-hatched

TABLE 2  
THE SAMPLE OF MS AND S STARS

STAR		Spectral Type	Wavelength $\lambda_x - 4200$ (Å)	Tc		Notes
HR, HD, or BD Number	Name			This Paper	LLB <sup>a</sup>	
BD +18°145	...	M25	62.07	No	...	1
HR 363	...	S3/2	62.06	No	No	
HD 14028	W And	S7/1e	62.20	Yes	Yes	
HR 1105	BD Cam	S4/2	62.07	No	dbfl	
BD +23°654	...	S	62.16	Yes	...	
HR 1556	<i>o</i> <sup>1</sup> Ori	M3S	62.17	Yes	Prob	
HD 35155	...	S3/2	62.04	No	No	
HD 37536	...	M2S	62.14	Yes	...	
HD 49368	V613 Mon	S3/2	62.05	No	...	
HR 2508	...	M1 Ib-IIa	62.06	No	...	2, 3
HD 54587	AA Cam	M5S	62.18	Yes	Prob	
HD 58521	Y Lyn	M6S	62.19	Yes	Prob	
HR 2967	NZ Gem	M3 II-III	62.11	No	dbfl	2, 3
HD 63733	...	S4/3	62.14	Yes	...	
HD 64332	NQ Pup	S5/2	62.23	Yes	...	
BD +06°2063	...	M3S	62.08	No	...	
HR 3639	RS Cnc	M6S	62.24	Yes	Yes	
HR 4088	DE Leo	M3 IIIabS	62.10	No	dbfl	2, 3
BD -10°3156	...	M3S	62.04	No	...	
HD 96360	...	M3S (wk)	62.07	No	...	
HR 4647	...	M4S	62.17	Yes	...	4
HD 110813	S UMa	S3/6e	62.20	Yes	Yes	
BD -02°3726	...	M1S (wk)	62.05	No	...	
HD 142143	ST Her	M6.5S	62.14	Yes	Prob	
BD -13°4495	...	M2S	62.10	No	...	1
BD -18°4320	...	S (wk)	62.10	No	...	
HR 6702	OP Her	M5 IbS	62.19	Yes	Prob	3
BD +16°3426	...	M4S (wk)	62.12	No	...	1
HD 170970	...	S3/1	62.14	Yes	...	
HD 177175	V915 Aql	S5/2	62.25	Yes	Yes	
HR 7442	...	M5S	62.07	No	dbfl	2, 3
BD -18°5539	...	S2*3	62.08	No	...	
HD 189581	...	S4*2	62.09	No	...	
HD 191226	...	M3S	62.01	No	No	
HD 191589	...	S	62.09	No	...	
HD 199799	...	MS	62.23	Yes	...	
HR 8062	...	M4S	62.15	Yes	Yes	
BD -11°5880	...	M4S	62.05	No	...	1
BD +33°4573	...	S (wk)	62.03	No	...	
HR 8714	HR Peg	S4/1	62.20	Yes	Prob	

<sup>a</sup> Presence of Tc as described by LLB: dbfl = doubtful and prob = probable.

NOTES.—(1) Near-infrared spectra suggest that this star may not be *s*-process enhanced. (2) Stars studied by Smith and Lambert (1986) that are not *s*-process enhanced but classified MS by Yamashita (1967). (3) Spectral type from Hoffleit (1982). (4) Found by us in a survey of M Giants from Hoffleit (1982).

areas of Fig. 2) classified previously as MS, but that do not show measurable enhancements of the *s*-process elements on our spectra. This quartet comprises HR 2508, HR 2967, HR 4088, and HR 7442. This histogram is, we assume, representative of measurements across a sample of Tc-free stars; the wavelength matches the wavelength of the blend in our synthetic spectra when the Tc I line is excluded from the line list.

In the lower two panels of Figure 2, we show the histograms for the MS and S stars. For the former sample, the cross-hatched areas identify four stars for which the *s*-process enrichment is apparently very small or even nonexistent on our near-infrared spectra of this quartet (BD +18°145, -13°4495, +16°3426, and -11°5880); the equivalent widths of Zr II, Y II, La II, and Nd II suggest little or no strengthening with respect to normal M giants. We suspect that this quartet may include M rather than MS stars, but pending the results of a quantitative abundance analysis, we retain the assumption that the stars are MS stars.

When the Tc I line contributes to the spectrum, the wavelength of feature X will be shifted to the red. In the middle

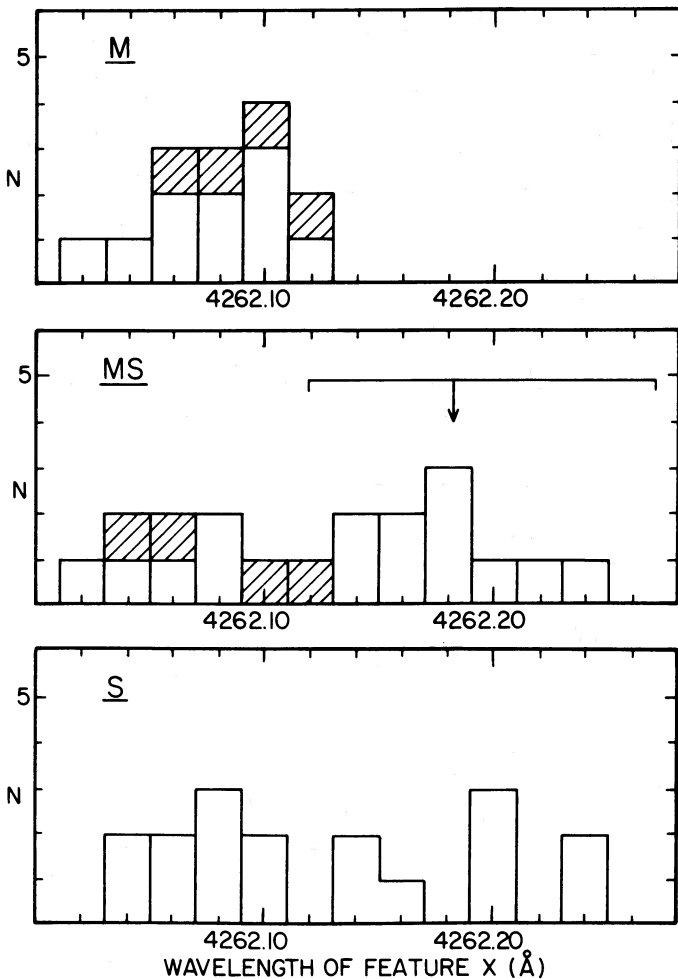


FIG. 2.—Frequency histograms of the wavelength of spectral feature X for the M, MS, and S stars. The horizontal bar and vertical arrow in the MS panel indicate the extent of hfs in the Tc I line and the approximate centroid of the feature, respectively. The cross-hatched boxes indicate stars that have been classified as MS, but either definitely do not have *s*-process enhancements based upon an abundance analysis (the M panel), or probably do not have *s*-process overabundances based upon equivalent-width measurements, but with a proper abundance analysis still needed (the MS panel).

panel of Figure 2, where we show the histogram for the MS stars, we indicate with the horizontal bar the extent of the hyperfine splitting of the 4262 Å Tc I line (Wendlandt, Bauche, and Luc 1977), and, with the arrow, the centroid of this feature as measured from our synthetic spectra; the typical wavelength of this broadened line is 4262.18 Å with the total hfs splitting extending from 4262.11 to 4262.27 Å. Clearly a large fraction of the MS and S stars group around the wavelength corresponding to the Tc I line, but a sizable fraction also cluster around 4262.08 Å, the wavelength of the Gd II-Nb I-Cr I blend. As a criterion for deciding whether Tc I is present or not, we choose the wavelength of 4262.14 Å. No M stars are found with this value of  $\lambda_x$ , and, for values larger than this, feature X is dominated by Tc I as demonstrated by our synthetic spectra. Below 4262.14 Å feature X is dominated by the Gd II-Nb I-Cr I blend.

Our synthetic spectra were computed in order to show how the wavelength  $\lambda_x$  shifts to the blue as the Tc abundance declines. The initial (i.e., maximum) abundance was estimated using the *s*-process predictions prepared by Cowley and Downs (1980):  $\log [N(\text{Tc})/N(\text{Zr})] \approx -2.2$  to  $-2.5$  for a wide range of neutron exposures. The Zr enhancement for many S stars is  $[Zr/Fe] \approx +1.0$ , thus the Tc abundance is  $\log \epsilon(\text{Tc}) = 1.0$  on the usual scale where  $\log \epsilon(\text{H}) = 12.0$ . Of course, as the dredge-up phase progresses, Zr is enriched progressively, but some of the Tc from the earliest episodes of dredge-up will have decayed. With an abundance close to the estimated maximum, the Tc I 4262 Å line is quite severely saturated. Consequently, the wavelength of feature X from synthetic spectra remains constant for several (here 5) half-lives [assuming simple decay from the initial abundance of  $\log N(\text{Tc}) = +1.0$ ], but begins to shift blueward at 6 half-lives and by 7 half-lives is essentially undetectable. Of course, these estimates are somewhat dependent upon the model atmosphere parameters; at cooler temperatures the Tc I line is stronger, but, however, line-blending is also stronger. The above calculations were done with a model atmosphere corresponding to  $T_{\text{eff}} = 3400$  K and  $\log g = 1.0$ , typical of a spectral type M4. The synthetic spectra suggest that Tc, as monitored by the observed wavelength  $\lambda_x$ , is detectable for  $(1.0-1.5) \times 10^6$  yr if its initial abundance is close to the maximum or  $\log \epsilon(\text{Tc}) = 1.0$ . At the fairly sharp transition from  $\lambda_x = 4262.18$  Å to  $\lambda_x = 4262.08$  Å, the Tc abundance is  $\log \epsilon(\text{Tc}) \approx -0.8$ , or  $\log [\epsilon(\text{Tc})/\epsilon(\text{Zr})] \approx -4.4$  for  $[Zr/Fe] = +1.0$ . We adopt this limiting abundance in our discussion of the Tc-free (“no” in Table 2) and Tc-containing (“yes” in Table 2) stars.

The striking observation highlighted by Figure 2 is that many MS and S stars do not contain a detectable amount of Tc. These stars are enriched in carbon and the *s*-process elements such as Zr. If the four possible M giants (see the cross-hatched areas in Fig. 2) are excluded, five of the 15 MS stars show no evidence of the Tc I line. Nine of the 17 S stars similarly lack the Tc I line. Until quantitative analyses are completed, the distinction between the MS and S spectral types contains a degree of arbitrariness. If the samples are combined, we find that 14 of 32 or 44% of the MS/S stars show no evidence of the Tc I line. If the four questionable MS stars are included, the Tc I is lacking in spectra of 50% of the MS/S stars. These striking results are combined with LLB’s survey and compilation as we attempt an interpretation in terms of stellar evolution and nucleosynthesis.

### III. DISCUSSION

Our statistics on MS and S stars with and without Tc can be extended with stars in LLB’s list. This compilation based on

their own spectra and published searches for Tc contains 41 MS and S stars, but 18 of these are included in our survey. Hence, the combination of the two surveys provides a sample of 58 MS and S stars; we remove from the total sample of 63 stars the five stars classified as MS, but showing no detectable *s*-process enhancements on our spectra—these five misclassified or very mild MS stars are HR 2508, HR 2967, HR 4088, HR 7442, and 57 Peg (Smith and Lambert 1986). For the 18 stars in common, we and LLB are in perfect agreement as to whether Tc I lines are detectable or not. The combined sample of 58 stars consists of 24 MS and 34 S stars. The statistics on Tc are as follows: 11 (or 46%) of the 24 MS and 11 (or 32%) of the S stars do not show the Tc I lines. Of the total sample, 38% (22 of 58 stars) do not have Tc I lines, but a large fraction (perhaps all) have significant enrichments of the *s*-process elements. Our more extensive survey confirms Scalo and Miller's (1981) contention that Tc-poor *s*-process-rich AGB stars are common. As the § I illustrates, a variety of scenarios may be envisaged to account for the Tc-poor MS and S stars. Here we attempt a systematic summary of these scenarios and discuss in detail the one that appears to account for the majority of the Tc-poor stars.

In the cool atmosphere of an AGB star, an appreciable fraction of an element may be associated into molecules: Is Tc present in Tc-poor stars as TcO? The competition for free oxygen atoms among various monoxides of metal atoms is largely responsible for the appearance in the spectra of MS and S stars of ZrO, LaO, and other monoxides at the expense of the TiO molecules whose bands dominate the spectra of the M stars. Although the enhancement via the *s*-process of Zr, La, and other heavy elements is a contributing factor, the key factor behind the rise of ZrO and the other monoxides is that their dissociation energies ( $D_0$ ) exceed that of TiO so that, as the C/O ratio approaches unity and the number of O atoms not associated into CO decreases, oxygen atoms are associated with ZrO and other monoxides rather than with TiO:  $D_0(\text{ZrO}) = 8.00 \pm 0.14$  eV, but  $D_0(\text{TiO}) = 6.92 \pm 0.14$  eV (Pedley and Marshall 1983). However, technetium is most unlikely to reside in a molecule rather than remain as a free atom or ion. The most abundant molecule is likely to be the monoxide TcO. There are no experimental data on  $D_0(\text{TcO})$ . With Pedley and Marshall's (1983) estimate of  $D_0(\text{TcO}) = 5.6 \pm 0.9$  eV, we can expect no appreciable loss of free atomic Tc to TcO. Even in the case of ZrO, Zr I lines are prominent in spectra of MS and S stars. In short, an absence of Tc cannot be blamed on the association of the Tc atoms with TcO or another molecule. This conclusion is in agreement with the absence of TcO bands in S stars as observed by Sanner (1978).

If the hypothesis that the Tc-poor stars are active TP-AGB stars is to be retained, one (or both) of the following scenarios must be entertained:

1. The yield of Tc from the *s*-process site is reduced to very low levels because  $^{99}\text{Tc}$  decays very quickly at high temperatures. Since the characteristics of the site surely vary with stellar (core) mass and luminosity, this proposal might provide Tc-poor and Tc-rich MS and S stars in a similar area of the HR-diagram. However, as noted in § I, the reduced half-life of  $^{99}\text{Tc}$  at high temperatures may be offset by a higher production rate (Mathews *et al.* 1986).

2. Tc was synthesized and mixed to the surface, but has decayed to low levels in the Tc-poor stars. The required delay of about  $10^6$  yr between the last episode of mixing and the present might arise in one of several ways. Perhaps the most

recent pulses have not ignited the neutron source so that the carbon added to the envelope has not been mixed with *s*-products. Hollowell and Iben (1988) speculate on how  $^{13}\text{C}$  production and, hence, the neutron source  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  may be inhibited in low-mass TP-AGB stars. It has been widely advertised that mixing between the He shell and the envelope is difficult to attain in models of low-mass TP-AGB stars. If this difficulty is reflected in nature's TP-AGB stars, one might suppose that mixing may be interrupted for many thermal pulses. An extremely simple scenario would suggest that the interval between thermal pulses which replenish the Tc supply is so long that Tc decays to low levels prior to a pulse. This is, however, unlikely as the time between pulses,  $\Delta t_{\text{ip}}$ , is only about  $10^5$  yr for a  $1 M_{\odot}$  star with a core mass of  $0.6 M_{\odot}$  (Iben and Renzini 1983) and decreases to a mere  $10^4$  yr for a core mass of  $0.8 M_{\odot}$ . Using the core-mass- $\Delta t_{\text{ip}}$  relation from Iben and Renzini (1983), an interpulse time of  $\geq 10^6$  yr would require an unrealistically low core mass of  $M_c \leq 0.35 M_{\odot}$ . Such a low core mass for a substantial fraction of AGB stars would not agree with the white dwarf mass distribution derived by Koester, Schulz, and Weidemann (1979), which has a rather sharp peak near  $0.6 M_{\odot}$ .

Finally, we discuss the scenario which requires no radical surgery on current models of TP-AGB stars and which appears to account for the observed frequency of the Tc-poor MS and S stars. The preferred scenario rejects the supposition that these stars are TP-AGB stars and assigns their enrichment of *s*-process elements including Tc to an event not directly linked to their present evolutionary stage. If, for example, the He core flash in a low-mass star were responsible for the *s*-process enrichment, Tc would not be expected in the M giant descendant because about  $2 \times 10^8$  yr is required to evolve from the core flash through He core burning to the AGB. We prefer to link the Tc-poor MS and M stars to the barium G and K giants. If the latter evolve into the former, all of the Tc present at the formation of the barium star will decay long before the star evolves up the AGB. Evolution of a barium star up the AGB is not in question; some of the Tc-poor MS and S stars must be evolved barium stars. This assertion is probably independent of the method by which a barium star is created. Earlier, we noted that mass transfer across a binary is an attractive hypothesis. If this is the case, the *s*-process enrichments originated in a TP-AGB star, i.e., a star like the Tc-rich MS and S stars in our sample.

Is our sample of MS and S stars seriously contaminated by evolved barium stars? After all, the barium G and K giants are estimated to account for only about 1% of all G and K giants (MacConnell, Frye, and Uggren 1972). Yet the Tc-poor MS and S giants compose 38% of the observed sample. (A few of the MS and S stars may have been created directly cool as luminous barium giants.) The question may be answered by comparing the space densities of barium and MS/S stars.

Stephenson's (1984) catalog of Galactic S stars may be used to estimate the space density of MS and S stars. He lists 178 such stars brighter than  $V \approx 9.9$  mag. We assume that the catalog is complete to this limit. The absolute magnitude is needed in order to convert the star count to a space density. Keenan (1954) quotes  $M_V \approx -1.0$  from a statistical parallax based on 17 S stars. Keenan (1954) points out an observation by Feast (1953) of a common radial velocity companion to  $\pi^1$  Gru (an S star with Tc I LLB) of spectral type G0 V at a projected separation of  $2''$ . The radial velocities suggest a physical association, and, with an assumed  $M_V$  for the G0 V

companion, Feast (1953) estimates  $M_V \approx 0$  to  $-1$  for  $\pi^1$  Gru. In addition, Dominy and Wallerstein (1986) have measured the reversal width of the Ca II K line for the S star HR 1105 and derive  $M_V = -0.4$ . Lloyd Evans (1983) provides photometry of MS, S, and C stars in the Magellanic Clouds, and his sample of S stars have  $M_V$  in the range of  $-1.5$  to  $-2.5$ . A study of the volume distribution of a sample of S stars by Yorke and Wing (1979) concludes that the mean value of  $M_V$  at maximum light is  $\langle M_V \rangle = -1.5$  to  $-2.0$ . These various determinations indicate that  $M_V \sim -1$  to  $-3$  would include the great majority of MS and S star absolute magnitudes. Using their derived absolute visual magnitudes, both Stephenson (1984) and Yorke and Wing (1979) estimate  $z$ -direction scale heights of 465 pc and 200 pc, respectively. These two determinations represent the extremes of MS and S star scale heights.

Using the range of estimated scale heights,  $M_V$  of either  $-1$  or  $-3$ , and a  $0^{m.5}$  correction for absorption, we derive the following crude space densities for the MS and S stars from Stephenson's (1984) catalog: for  $M_V = -1$  the space densities are  $N(\text{MS/S}) = 5.0 \times 10^{-2} (10^6 \text{ pc}^3)^{-1}$  and  $1.1 \times 10^{-1} (10^6 \text{ pc}^3)^{-1}$  for the two scale heights of 465 and 200 pc, respectively, and  $N(\text{MS/S}) = 6.7 \times 10^{-3} (10^6 \text{ pc}^3)^{-1}$  and  $1.6 \times 10^{-2} (10^6 \text{ pc}^3)^{-1}$  for  $M_V = -3$ . We suppose that these space densities consist of two components: the TP-AGB Tc-rich stars (62%) and (evolved barium?) Tc-poor stars (38%). For M giants of comparable luminosity ( $M_V \lesssim -1$ ), Mihalas and Binney (1981) quote a space density of  $N(\text{M}) \sim (3-3.5) (10^6 \text{ pc}^3)^{-1}$ . The ratio of space densities of the luminous M giants to the technetium-poor MS and S stars ranges from 72 to 1375—a factor of 20 in the extreme estimates! Clearly the space densities of the MS and S stars are not well known; however, this range of ratios of M giants to Tc-poor MS and S stars encompasses the ratio of G and K giants to barium stars of  $\sim 100$ .

Due to the large uncertainty in our estimate of the space densities of the MS and S stars, we discuss other estimates. Scalo and Miller (1979) derive space densities of the MS and S stars of  $N(\text{MS/S}) = (1-6) \times 10^{-2} (10^6 \text{ pc}^3)^{-1}$ , which leads to ratios of M giant to Tc-poor MS and S stars (38% of the total) in the range of 130–920: again, these ratios are not greatly different from the ratio  $N(\text{GK})/N(\text{barium GK}) \sim 100$ . Recently, Jura (1988) has estimated that the surface density of S stars is  $\gtrsim 10 \text{ kpc}^{-2}$  with a  $z$  scale-height of 200 pc. This number does not include the MS stars and thus represents a lower limit to  $N(\text{MS/S})$ . Using Jura's (1988) density, however, we derive ratios of  $N(\text{M})/N(\text{Tc-poor S}) \sim 300-370$ , which represents ratios that are too large due to not including the MS stars. Both Wing and Yorke (1977) and Scalo and Miller (1979) conclude that, relative to the S stars, the MS stars should be "numerous"; hence, the ratios of 300–370 derived from Jura's (1988) S star density must be lowered by some factor of 2 or more, which again places the range of M giant to Tc-poor MS and S star densities within the value for  $N(\text{GK})/N(\text{barium GK})$ . Claussen *et al.* (1987), using a flux-limited sample of carbon stars, derive a space density of  $N(\text{C}) \approx 1 \times 10^{-1} (10^6 \text{ pc}^3)^{-1}$ , while Wing and Yorke (1977) estimate that the ratio of the space densities  $N(\text{C})/N(\text{S}) \approx 2$ . The value of  $N(\text{S}) \approx 5 \times 10^{-2} (10^6 \text{ pc}^3)^{-1}$  thus derived would lead to ratios of  $N(\text{M})/N(\text{Tc-poor S}) \sim 160-185$  with no inclusion of the MS stars. Including the MS stars would lower these ratios by a factor of  $\sim 2$  or more, close to the range of  $N(\text{GK})/N(\text{barium GK})$ .

All of the above studies and estimates demonstrate that,

although the ratio of M giant to MS and S star space densities is uncertain, the limits on this ratio encompass the value of  $N(\text{GK})/N(\text{barium GK})$ . This close correspondence and our expectation that the barium GK giants should retain their abundance peculiarities as they evolve up the AGB encourages us to identify the majority of the Tc-poor MS and S stars as evolved barium giants. This identification has been proposed before (Smith and Lambert 1985, 1987; LLB), but the comparison of the space densities provides novel evidence that suggests that Tc-poor, but active, TP-AGB stars must be quite rare.

Our identification of the Tc-poor MS and S stars as evolved barium stars is supported by the correlation between the presence of Tc and the period of the light variations of the long-period variable stars. Little-Marenin and Little (1979) and LLB have shown that the presence of Tc is correlated with the period: Tc is present in the longest period stars and absent from the shortest period stars. The former are considered to be further evolved along the AGB than the latter (Wood, Bessell, and Fox 1985). Since the amplitude of the light variations also increases with increasing period (Whitelock, Pottasch, and Feast 1987), a division of our sample into variables and non-variables will be an approximate separation by absolute luminosity. When we divide the combined sample of 58 stars into those with variable star designations and those without, a striking difference emerges: only five out of 35 stars with variable star names do not show Tc (14%), whereas 17 out of 23 stars without variable star designations do not (74%). Admittedly, some stars that are not known to be variable may, in fact, be undetected variables; however, the most obvious variables to be found would be the ones with large amplitudes and, hence, highly evolved. Stars that have acquired  $s$ -process enrichments via mass transfer could appear anywhere along the AGB as MS and S stars and would not need to be nearing the advanced, luminous, long-period-variable state of evolution. At these latter stages, one might expect Tc to be seen in all stars because even the evolved barium stars should enter the phase of active TPs and, hence, synthesize Tc.

Fortunately, our identification of the Tc-poor MS and S stars as evolved Barium stars is open to the simple test of searching for the radial velocity variations characteristic of those shown by all barium stars. Of course, the velocity variations arising from semiregular pulsations of the MS and S stars will complicate the search for the small amplitude orbital variations, but a thorough program of radial velocity measurements and photometry should permit the two effects to be separated. Jorissen and Mayor (1987), from a survey of nine S stars with the radial velocity spectrometer CORAVEL, found that at least five stars are binaries. The Tc-poor S star HD 35155 (Table 2) is one of these five. The remaining four stars have yet to be examined for Tc. Jorissen and Mayor note that the search for spectroscopic binaries may be used to discriminate between evolved barium stars and the intrinsically enriched TP-AGB single stars. Only if a large fraction of the Tc-poor MS and S stars are discovered not to be binaries shall we be forced to entertain radical changes to the current picture of TP-AGB evolution.

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