TECHNETIUM IN STELLAR ATMOSPHERES

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ABSTRACT. The quantitative determinations of technetium abundances are discussed. Up to now Tc abundances were found for nearly 30 stars which all are thermally pulsing AGB stars. The technetium abundance values for these AGB stars atmospheres, where it was found to be present, cluster around -1.0 ÷ 1.7. The fact that Tc is not omnipresent in the atmospheres of AGB stars, which are highly enriched in other heavy elements produced in s-process, is discussed.

1. INTRODUCTION

Technetium was first produced and chemically proved to exist in 1937. The only Tc isotope, found in terrestrial minerals, is ^{99}Tc, originated in spontaneous fission of ^{238}U.

The spectrum of Tc was first described by W. Meggers and B. Scribner in 1950, and the most unexpected discovery was made in 1952, when P. Merrill of the Mount Wilson Observatory announced that he had identified technetium in the spectra of several S-type long-period variables. Soon his list contained 14 stars, most of which were long-period variables or Miras of the spectral type S and M.

Technetium is believed to be produced in stars by the so-called s-process, in which nuclear reactions take place starting with the nuclei near iron in the periodic table and successively adding neutrons. Tc has no stable isotopes and ^{99}Tc, the only Tc isotope involved in the s-process, has a half-life of $2.1 \cdot 10^5$ y. The ^{99}Tc half-life is even shorter at high temperatures, when its isomeric state of half-life 6 h becomes substantially populated. The stars, in which this process is believed to be active, are asymptotic red giant branch stars (AGB) with masses less than 8 $M_{\odot}$. In low mass AGB stars the s-process is probably driven by the neutron source $^{13}C(\alpha, n)^{16}O$ with ^{13}C produced by mixing of protons into the ^{12}C-rich He shell. In more massive AGB stars, the neutron source is

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expected to be the reaction $^{22}Ne(\alpha, n)$ ^{25}Mg with ^{22}Ne produced from the initial CNO nuclei prior to H and He burning.

The detection of Tc in the atmospheres of these stars provides unambiguous proof that recent s-processing and subsequent mixing with the outer layers has taken place. During the so called third dredge-up the atmospheres of AGB stars are progressively contaminated with helium burning products which consist mainly ^{12}C and s-process elements.

The half-life of ^{99}Tc is comparable to the duration of the thermally pulsing stage on AGB. If Tc is produced in expected quantities relative to its fellow s-process elements, it should be detectable for about 6-7 half-lives as Smith and Lambert (1986) estimated from a comparison of synthetic and observed spectra. This is very close to TP-AGB lifetime of $2 \cdot 10^6$ y for a 1 M_0 star. Thus Tc should be present in stars of all masses during the TP-AGB phase of evolution. This expectation is in conflict with observations and the question is - why is technetium not omnipresent in a sample of stars enriched to similar levels in other heavy elements produced in s-process.

2. OBSERVATIONS OF Tc IN STARS

Our knowledge about the presence of Tc in late-type stars is mainly due to a work by Little, Little-Marenin and Bauer (LLB)(1987). They made an extensive survey and a compilation of earlier data on about 300 late-type giants and supergiants for the presence of TcI lines in the violet part of the spectra, where three most intense TcI lines are at $\lambda\lambda$4297, 4262, 4238. They report that nearly 100 stars from their sample probably contain technetium in their atmospheres. In following I refer the results obtained by LLB.

No TcI lines have been detected in any BaII star regardless of the fact that these stars show s-process element enhancements. The binary nature of these stars could provide an explanation. However, these stars are too hot for TcI to be the major form of Tc in these stars. The search for the resonance lines of TcII in the UV spectral region with the IUE for several classical BaII stars has also proved to be negative.

M stars

1. Nonvariable M stars do not show Tc (with one exception: o' Ori).
2. Supergiant M stars do not show Tc.

3. Irregular Lb variables do not show Tc like as semiregular SRb giants, if $P<100^d$ and $P>150^d$ with some exceptions.

4. M type Mira variables do show TcI lines, if their periods are longer than 300^d. All those stars have spectral types later than M2.

MS, S and SC stars

In those groups there are stars, which do show TcI lines and which do not show TcI lines.

C stars

Most C stars show Tc lines. However, a significant fraction (about 25 %) of C stars and all J stars do not show these lines.

The main conclusion reached from the LLB analysis is that the onset of the third dredge-up occurs in M stars on the AGB and is accompanied by the onset of variability. For Miras the third dredge-up appears to correlate very strongly with period.

Miras form a fairly well defined group. Kinematic studies show that the short period ($150-200^d$) Miras tend to be old (pop. II), low mass ($M \sim 1\ M_o$) objects, while the long period ones ($300-400^d$) are younger (pop. I) with masses 1.5-2.5 M_o. Most C stars tend to have F5 main sequence progenitors with masses around 1.2 M_o.

The LLB data seem to indicate that Tc is mixed to the outer layers during the third dredge-up of 1.5-2.5 M_o pop I stars and not in less massive and older objects. These data indicate that the luminosity of stars, which have experienced the third dredge-up, is M_{bol} =-4.4÷-4.9. However, current evolutionary models do not predict the third dredge-up in this mass, luminosity and metallicity range.

3. TECHNETIUM ABUNDANCES IN STARS

Our knowledge about the technetium abundance in quantitative terms is too scarce yet. Up to now nearly 30 stars have been analyzed in order to determine the Tc abundance. In the following a table will be presented, in which all determinations, available to the author, are collected together with references. It is interesting to note some oscillations in time of Tc abundance values from very small to quite large ones. As the methods of analysis are improving, the abundance values seem more and more to stabilize.

Star	Sp	lg ε(Tc), references
W Cyg	M4-9	1.5 [1]
TU CVn	M5	2.0 [1]
T Cep	M5-9e	1.5 [1]
R Cas	M7e	-0.5 [2]
R Aur	M7-9	2.0? [1]
o Cet	M5-9	0.6±0.3 [3]; 0.2 [2]
χ Cyg	M5-6+, S	1.7+0.3 [3]; 0.7 [2]
RS Cnc	M6IIIS	-1.5 [4]; 3.0[1]; 0.6±0.2 [5]
OP Her	M5IIIa(S)	-2.0 [2]; -1.0 [2]
R Ser	M6.5e	-0.1 [2]
T Cet	M5-6IIeS	-1.5 [4]
HR 8062	M4IIIS	-0.4 [6]
R Hya	M6-9e,S	-2.0 [4]
HR 6702	MS	-0.8 [6]
S UMa	S2/6e	<2.8 [7]; <0.0 [8]
o' Ori	S3.5/1-	2.0 [1]; 0.1 [6] 0.5+0.1 [5]; 0.1 [2]
HR Peg	S4+/1+	-0.5 [6]
R And	S6/5e	3.4 [9]; 1.5 [4]; 1.2±0.2 [5]
W And	S8/2e	0.4 [2]
CY Cyg	SC2/7.5	2.6 [7]; 0.9 [8]
RZ Peg	SC6/9e	0.4 [8]
RR Her	SC5/10e	0.9 [8]
R CMi	SC4/10e	1.9 [7]; 1.2 [8]
VY UMa	C6,3	3.0? [1]
TX Psc	C6,5	0.5 [10]
U Hya	C6.5,3	-2.0 [4]
UX Dra	C7,3	-1.5 [4]

1. Kipper and Kipper (1984)
2. Kipper (1990)
3. Dominy and Wallerstein (1986)
4. Orlov and Shavrina (1983)
5. Wallerstein and Dominy (1988)
6. Smith and Lambert (1986)
7. Smith and Wallerstein (1983)
8. Smith and Kipper (1988)
9. Garstang et al. (1983)
10. Kipper (1987)

Most of the analyses rely on the three TcI resonance lines located at $\lambda\lambda$4297, 4262, 4238. Due to the weakness of late-type stars in this spectral region it is very difficult to observe those spectra with high resolution, but high resolution is badly needed, as the crowding of the lines in the late-type spectra is enormous. Each of the Tc lines is near other blending features. For instance, the strongest line at λ 4297.06 is blended with a combination of a CeII line, the Raie Ultime of SmI, a weak ZrII line and a CrI line. With other lines the situation is not better. Therefore, it is extremely important to have good line lists with precise wavelengths and atomic constants for all lines near the Tc lines in order to compute the synthetic spectra, which can be compared with observations. The parameters of stellar atmospheres should also be given with high precision. In earlier works the hyperfine broadening, which, incidentally, is very large for TcI lines, was not taken into account. This is the reason for the quite large abundance values, found in earlier works, particularly in our paper from 1984. The proper value of the velocity parameter is also important, and evidently the too large value for the microturbulent velocity adopted by Orlov and Shavrina (1983) leads to great underestimation of the Tc abundances.

For S stars, and especially for SC stars, in the spectra of which the TiO bands are weak or absent, it is possible to use the intercombination line of TcI at λ5924. This line is also severely blended and quite often only an upper limit of the Tc abundance can be derived. The λ 5924 line was first used by Smith and Wallerstein (1983) to study some S and SC stars. This line was also used by the author when determining the Tc abundance for TX Psc (Kipper, 1988) and for several SC stars together with V.V. Smith (Smith and Kipper, 1988).

4. DISCUSSION

Now, let us return to the point that a great number of MS and S stars do not show TcI lines, regardless of the fact that their spectral type indicates the enhancement of other s-process elements' abundances.

The suggestion by Smith and Wallerstein (1983), that the Tc production is highly temperature sensitive due to drastically shorter half-lives of ^{99}Tc at higher (T ≥ 10^8K) temperatures and therefore Tc presence in TP-AGB stars is possible only if neutrons were supplied by ^{13}C(α, n) reaction and consequently Tc is expected to show up only in low-mass stars, was revised by Matthews et al. (1986) who showed that Tc can be produced also at higher temperatures due to much higher neutron fluxes.

Some of the stars not showing Tc lines are known to be binaries, and hence the s-process enhancements may be related to mass transfer. Smith and Lambert (1988) have recently conducted an additional survey of MS and S stars with definitely enhanced s-process elements for the presence of Tc. They found that 38 % of these s-process enhanced stars do not show Tc lines confirming an earlier contention that Tc-poor and s-process rich AGB stars are common. They suggest that MS and S stars are composed of two groups:

1. Tc-containing stars which are currently thermally pulsing AGB stars undergoing the third dredge-up;
2. Tc-poor stars, which represent the coolest members of the barium star class.

The possibility of an evolutionary link between barium and S stars has been first suggested by Burbidge and Burbidge (1957) and then by many authors simply on the ground of spectroscopic similarities between them.

As a class the classical BaII stars were first isolated by Bidelman and Keenan (1951). But only recently some consensus was reached concerning their origin. The barium stars are not nearly luminous nor cool enough to be thermally pulsing AGB stars yet their atmospheres show ^{12}C and heavy s-process elements' overabundance closely resembling the abundances found for AGB stars. The typical BaII giant has a luminosity $M_{bol} \sim 0$, but some more luminous BaII stars are known (ζ Cap, $M_{bol} \sim -3.7$). The surprising discovery by McClure et al. (1980) and McClure (1983) that probably all BaII stars, or at least the extreme ones, are members of spectroscopic binaries with low mass secondaries, leads to the conclusion that binarity should be of some importance in the development of the BaII star anomaly. The radial velocity data by McClure are of 0.4 kms^{-1} accuracy. Analyzing the known and probable orbital elements McClure concluded, that for primary masses around 1.5 $M_{\odot}$, the secondaries have masses of 0.2 - 0.6 $M_{\odot}$ and are probably white dwarfs. For several systems there are direct detections in UV spectral region of white-dwarf companions of BaII stars (Dominy and Lambert, 1983).

Two events which can lead to BaII stars are the He-core flash or the He-core-burning phase. The paucity of BaII stars compared with ordinary

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G and K giants (0.5 - 1 %) indicates to some selection effect. This selection can be introduced by binarity (Tomkin and Lambert, 1983). Dominy and Lambert (1983) rejected the hypothesis of mass-transfer origin of BaII stars by McClure et al. (1980) on the basis of the white-dwarf's minimum age ($t_{WD} > 8 \cdot 10^{8}$ y) and the lack of obvious progenitors of BaII stars among main-sequence and subgiant stars, which means that the mass-gaining star should be on giant branch.

Webbink's (1986) finding that the average eccentricity for seven BaII stars with known orbits is much less than that of normal G and K spectroscopic binaries and that the distribution of their mass functions are also different, provides a strong observational evidence in support of mass-transfer which is now the most favourable scenario for Ba star origin. The current white dwarf companion was once a cool, luminous AGB star which after losing its envelope became a white dwarf transferring ^{12}C - and s-process-rich mass to the now BaII star.

If S stars are in some ways related to BaII stars, that class should also contain a high proportion of binaries. Jorrissen and Mayor (1988) were the first to directly estimate the proportion of binaries among S stars from radial velocity monitoring, probably owing to the confusion that pulsations could introduce (a substantial fraction of S stars are indeed Mira, SR or Lb variables). Jorissen's and Mayor's observations confirm the fact that binarity is a key property of both BaII and S stars. They observed 27 BaII and 9 S stars with the radial velocity spectrometer CORAVEL and found that a very high (89 %) number of stars have variable radial velocities. At least 5 S stars are found to be binaries and for 3 stars the Mira-type pulsations cannot be excluded. These observations support to some extent the BaII - S evolutionary scheme.

Canonical evolutionary models of single, thermally pulsating AGB stars predict that S stars should belong to the M-MS-S-SC-C evolutionary sequence. These models relate the heavy element synthesis to the thermal pulses occurring in these double-shell burning stars, either during hot pulses (for the most massive stars in the intermediate mass range) or during the period between pulses (for low-mass, low metallicity stars, according to the semiconvection theory). The detailed mechanism, by which a M star can transform into a S star, it yet not well understood, although there is some observational evidence supporting it. For example, the CNO elemental abundances, the $^{12}C/^{13}C$ ratio and the O isotopic ratios show a continuous trend from M to S stars.

The difficulty of explaining the extremely high ratios of $^{16}O/^{17}O$ and $^{16}O/^{18}O$, amounting to 2000 for the cool carbon stars, in the frame of the simplest working hypothesis supposed by Lambert et al. (1986), that the dredge-up on the AGB adds ^{12}C but not ^{13}C and ^{16}O, was partially removed by new observations (Lambert, 1988).

The observations of M, S and C giants along the AGB of intermediate age globular clusters in Magellanic Clouds by Bessell, Wood and Lloyd Evans (1983) and Lloyd Evans (1984) reveal that at low luminosities $M_{bol} \geq -4$ the giants are all pure M type. Going to higher luminosities in the interval of 0.4 mag the S stars can be found with the S star characteristics increasing in strength with increasing luminosity. The interpretation of these results is that dredge-up of C and s-process elements has begun. The main problem here is that the M to C star transition is found to occur at luminosities significally below the luminosities at which the dredge-up of carbon has been expected to occur according to standard stellar models. On the contrary, luminosity functions of the field AGB stars in LMC and SMC reveal that the stars at the tip of the AGB are by no means C stars as predicted by models (Reid and Mould, 1985). These observations also reveal that S stars are too numerous with respect to C stars in the view of the short duration of the S star stage. Hot bottom burning (HBB), leading to conversion of some ^{12}C to ^{13}C and ^{14}N in the envelope by CN-cycling at the base of the convective envelope, could be invoked in order to reconcile those observations with current models. Observations by Lambert et al. (1986) in 30 cool carbon stars of the $^{12}C/^{13}C$ ratio, which would be brought closer to its CN-cycle equilibrium values in the presence of HBB, and of N abundance do not show any evidence in favour of HBB.

Conclusion from this discussion is that the binarity and mass-transfer is not needed to produce an S star and the M-S-C evolutionary scheme can produce S stars. On the other and, the evolution of a barium star up the AGB should also take place regardless of the barium star origin. This scenario may account for too large total number of S stars.

To summarize we can conclude that the idea by Smith and Lambert (1985) explaining the Tc-poor S stars as coolest members of the barium star class is the most favourable hypothesis up to now. The estimate of M, MS and S star space densities by Smith and Lambert (1988) also does not contradict with this idea. The sample of stars studied by Jorissen and Mayor (1988) is, however, too small to state that all Tc-poor S-stars are binaries.

So, here we have a wide and fascinating field of research.

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