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A search for Technetium in semiregular variables[*]

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Abstract. We searched for the lines of Tc in the spectra of Semiregular variables (SRVs) in the wavelength region from 4180 to 4300 Å using high resolution spectroscopy. Tc as an s-process element is produced on the thermally pulsing AGB and is therefore a good indicator for the evolutionary status of Semiregular variables. Combining our results with previous investigations we get a database large enough for a statistical study.

Tc is not found in SRVs with periods below 100 days, spectral types earlier than M5 and photospheric IRAS colours. These objects are 'blue' SRVs in the classification system of Kerschbaum & Hron (1994). Among the 'red' SRVs (periods longer than 100 days) the fraction of stars showing Tc in their spectra is about 15 % with a probably lower fraction among the stars with periods above 150 days. This is significantly lower than for the typical Miras. Taking into account the probable conditions for the occurence of the third dredge-up and the expected behavior of the Tc abundance along an evolutionary track on the AGB, our results support an evolutionary scenario from 'blue' SRVs (early AGB) to 'red' SRVs (early TP-AGB) and on to long period Miras. Only the most massive (masses above $2M_{\odot}$) stars show Tc during the SRV stage. The luminosities of the Tc-rich SRVs and Miras are compatible with theoretical estimates of the minimum core mass required for the third dredge-up.

Key words: stars: late-type – stars: AGB and post-AGB – stars: evolution – stars: abundances – stars: variables: general

1. Introduction

During the last decade our understanding of Mira variables has considerably improved. However, the group of Semiregular variables (SRVs) was hardly studied, and its role within stellar evolution is much less clear. Kerschbaum & Hron (1992, 1994 in the following KH92 and KH94) tried to improve the existing classification of SRVs, which was solely based on light curve parameters, by including IRAS data and JHKLM photometry. Based on number densities and luminosities relative to Miras and the presence or absence of carbon stars, they divided the SRVs into two groups: the 'blue' SRVs were suggested to be early AGB, i.e. non thermally pulsing, objects while the 'red' SRVs are apparently TP-AGB stars although it is not clear whether this stage precedes the Mira phase or if TP-AGB stars switch between Mira- and SRV-like behaviour. SRc and SRd variables were excluded from these works as these objects seem to be not on the AGB. Furthermore we want to concentrate on oxygen rich objects (spectral type M and MS).

The presence of Tc in the spectrum of a star is strong evidence for the third dredge-up and hence for thermal pulses (Busso et al. 1992). Tc was observed for the first time in stellar spectra of late type stars by Merrill (1952). Technetium has no stable isotope, and the half life time of the two longest living isotopes, ^{97}Tc and ^{98}Tc, is only about 3–4$\cdot 10^6$ years, therefore much shorter than the typical main sequence life time of an AGB star's progenitor. The third isotope of Tc with a considerable half life time, ^{99}Tc, is thought to be produced via the s-process (but ^{97}Tc and ^{98}Tc are not, see e.g. Little-Marenin 1989). In the following we will therefore always mean the isotope ^{99}Tc, when we speak about the occurence or absence of Tc-lines in stellar spectra. Since this isotope has a half life time of only $2\cdot 10^5$ years, only freshly produced material will be seen in the stellar atmosphere. Therefore it represents a better indicator for the recent occurrence of thermal pulses than the enrichment of other s-process elements which can also be caused by mass transfer in binary systems as shown already by several authors (e.g. Smith & Lambert 1988). Tc thus also allows an independent check of the above evolutionary sequence from 'blue' to 'red' SRVs and possibly on to Miras.

Tc is observable in three lines in the blue region of the spectrum at 4297 Å, 4262 Å and 4238 Å, respectively. However, these lines are all rather weak and partly or completely blended, making an identification difficult and only possible at very high resolution. This difficulty can also be seen by comparing the results of different investigations on the same star. We will discuss this problem and its impact on our data below.

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A number of investigations has been done on this field before. The largest sample of late type stars in this context has been observed by Little et al. (1987, hereafter LLMB) using an intermediate spectral resolution and detecting Tc by the shift of the center of the blends. The result of their investigation was that nonvariable stars, SRVs and stars classified as irregular variables typically show no Tc, while Miras with periods of more than 300 days do show Tc. They searched and collected data on 43 oxygen rich SRVs of type a and b. However, their sample of SRVs is still much too small to allow any definite conclusions as these variables appear in a large variety (e.g. covering a period range from 30 to 1000 days). Further investigations were done by Wallerstein & Dominy (1988), Vanture et al. (1991), Dominy & Wallerstein (1986) and Smith & Lambert (1988, 1990). However, these investigations include only data for very few objects, but as the observations therein were obtained at very high resolution they provide a source of reliable measurements.

A recent study of S stars was done by Van Eck & Jorissen (1999, and references therein), Carbon stars have been investigated by Barnbaum & Morris (1993). According to these results, a large fraction of S and C stars shows Tc, while those without Tc can be explained as results of mass transfer in binaries.

In Tables 1, 2 and 3 all previous observations of O-rich SRVs are indicated. As most of the authors use only two classifications for the presence or absence of Tc (Yes/No) we merged the LLMB classes Yes and Probable and Doubtful and No, respectively. From the SRVs investigated by LLMB we excluded the stars α Sco, AH Sco and VX Sgr due to their extremly long period (more than 700 days), DE Leo due to a lack of period, and T Cen due to its very early spectral type (K5) and the uncertainty in the determination of its Tc contents (as noted by LLMB).

The aim of this paper is to extend the previously observed sample of SRVs taking into account the new classification scheme for SRVs suggested by KH92 and KH94. From this larger database we will try to find further information on the evolutionary status of SRVs. Furthermore we want to check the difference in classification between spectra of intermediate and high resolution.

2. Observations

The data for this paper have been taken primarily during three observing runs using the Coudé spectrographs at the ESO-CAT, Chile, (Feb 10 to Feb 15, 1995) and the 2.2 m telescope at Calar Alto Observatory, Spain (Aug 19 to Aug 22, 1994). A second run with the ESO-CAT (Aug 20 to Aug 22, 1995) was done as remote observing from Garching. Additional observations were obtained with the Coudé Spectrograph and the Coudé Feed telescope at Kitt Peak National Observatory on March 29, 1995.

The Calar Alto spectra were taken with a resolution of about 9 Å/mm (0.12 Å / pixel), which is comparable to the resolution used for the large survey by LLMB. The spectra of the two ESO-CAT runs were obtained with a resolution of 2.6 Å/mm (0.036 Å / pixel). For the observations at KPNO we used a resolution comparable to the Calar Alto data.

We observed 88 Semiregular variables in total, 7 of them were observed in more than one run to check for possible effects of different spectral resolutions. The Tc-rich MS-star o^1 Ori was observed in all four runs and was used as a reference point. Additionally, we observed 2 SRc, 2 Miras, 3 Lb-variables and 1 nonvariable S-star. 24 stars of our sample have results on their Tc abundance already published. These objects were used for identifying Tc in the spectra of our sample stars. As far as we know, the remaining 72 stars have never been searched for Tc. Adding the published results to our data we achieve a data base of 102 SRVs (type a and b) of spectral type M or MS.

The spectral regions covered by our observations were almost the same in all three runs and include the three lines of Tc at 4238, 4262 and 4297 Å, respectively. At the lower resolution all three lines could be observed at once, while at the higher resolution, two spectra with a shifted central wavelength had to be obtained. Unfortunately, due to weather conditions and other problems, some stars of the observing runs at ESO could therefore be observed only in one or two of the three lines.

The sample was selected to cover the different classes of SRVs described by KH92 and KH94 and to extend the existing data especially in those period ranges where only a few objects have been observed before. Furthermore the selection was limited by the sensitivity of the used instruments.

3. Classification

We based our classification on the presence or absence of the three Tc lines. Known detections and nondetections were used as a reference to identify the occurrence of the Tc line in the line blend. All three Tc lines are blended (see LLMB and Little-Marenin & Little 1979). Nevertheless, in our high resolution spectra it was possible to clearly see the presence or absence of Tc in the shape of the 4297 Å line blend (see Fig. 1). The 4262 Å line is also quite good to detect in high resolution spectra, while it seems to be not that reliable at lower resolution. The 4238 Å line is both useable in low and high resolution spectra. However, it is the weakest of the three resonance lines, hence it needs very high S/N.

We analysed the high resolution spectra first. Results from these data were then used to calibrate the classification criteria for the spectra with a somewhat lower resolution.

In most cases the classification obtained from the three lines in high resolution agrees quite well. Where it disagrees, the classification was based on the quality of the spectrum around the Tc-lines. If a clear classification could not be found in this way the star was classified as Possible.

As described above, the direct classification was only possible in our high resolution spectra. For our intermediate resolution data we followed the method described by LLMB (Fig. 2) and used the shift of the central wavelength of the 4297 Å blend. This blend contains the strongest of the Tc lines and it turned out to be the most useful for that kind of measurement. The position of the line blend was determined by a Gaussian fit and measured relative to a number of atomic lines (mainly iron) throughout the spectral range observed. Through this method we reached an

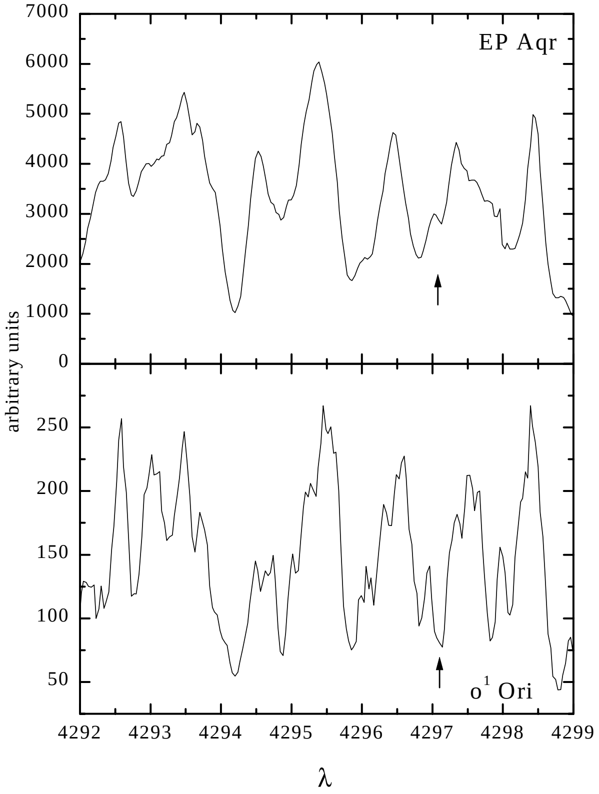

Fig. 1. Example of a high resolution spectrum of a SRV showing no Tc (upper panel) and showing Tc (lower panel), respectively. The laboratory wavelength of the Tc line is marked by an arrow. The absence or presence of the Tc-line at 4297 Å is clearly visible. Both spectra were obtained at ESO, La Silla. A wavelength shift for stellar velocity and heliocentric correction has been applied.

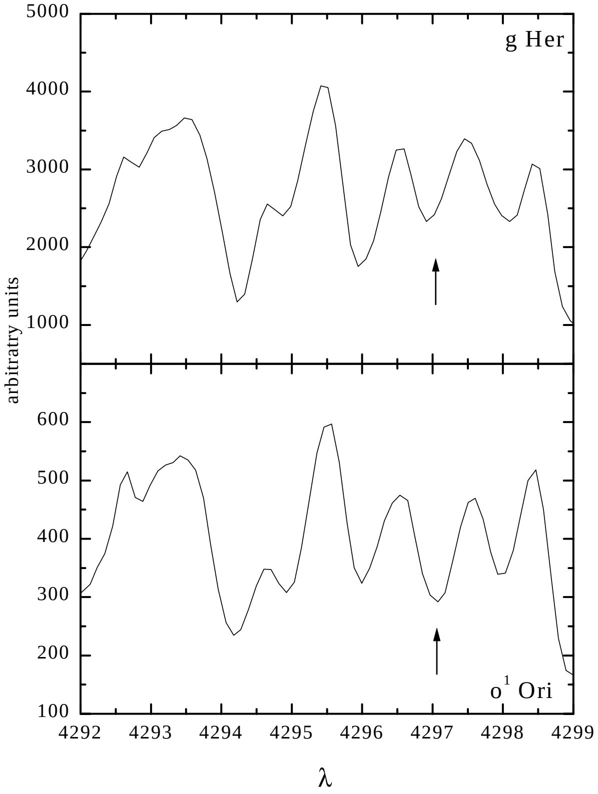

Fig. 2. Example of an intermediate resolution spectrum. Like in Fig. 1 the lower panel shows a star with Tc and the upper panel an object showing no Tc in its spectrum. The difference is visible in a shift of the line blend. Note the difference between high and intermediate resolution in the spectrum of o^1 Ori, observed in both resolutions. Both spectra were obtained at Kitt Peak National Observatory.

accuracy of the blend-position of typically 0.04 Å or 3 km s^{-1} for the Calar Alto and Kitt Peak spectra.

To calibrate the line blend position in terms of Tc content we used either our high resolution spectra or published classifications. We convolved our high resolution ESO spectra to the lower resolution of the Calar Alto and KPNO data with the help of single lines in the comparison spectra obtained at ESO and Calar Alto. In these convolved spectra we then measured the central position of the line blend in the same way as for our intermediate resolution spectra. For a few stars we could compare the blend positions from intermediate and convolved high resolution data. The differences are consistent with the above estimated accuracy. Stars observed only by LLMB were reclassified in the sense that doubtful LLMB objects were changed to No and the Probable stars to Yes. We also compared the line positions given by LLMB with our data wherever the same object has been observed. Our measurements are in good agreement with the LLMB values. A small systematic shift in the line position of -0.06 ± 0.01 Å between our data and their measurements, derived from the stars OP Her and o^1 Ori, has been applied to the positions taken from LLMB.

The result is shown in Fig. 3, where we plotted the position of the 4297 Å line blend against period. The figure includes SRa, SRb and Lb variables with spectral types M, MS and S. Calibration stars are shown as filled circles and crosses (Tc Yes and No, respectively). If the classification is based on intermediate resolution literature data, small symbols are used. The open boxes show the objects for which we have obtained intermediate resolution spectra and which have not been investigated previously. The stars plotted with a period of one day are Lb variables and one nonvariable S-star.

There is a small but obvious gap between the Yes and No cases around 4296.95 Å. Therefore we have defined this wavelength as the border between stars with and without Tc and used it to classify the remaining objects (open boxes). Since the size of the gap is close to the estimated error of the blend position we believe that also at intermediate spectral resolution the distinction between the Yes and No cases is quite reliable. This is supported by a comparison between the classification made in this way and the results of LLMB: only for 4 out of 23 stars there is disagreement between the classifications. In one case (TU CVn) there is an independent high-resolution spectrum of Vanture et al. (1991) which supports our classification. We note that LLMB had only few stars with high resolution spectra available to check their classification criteria.

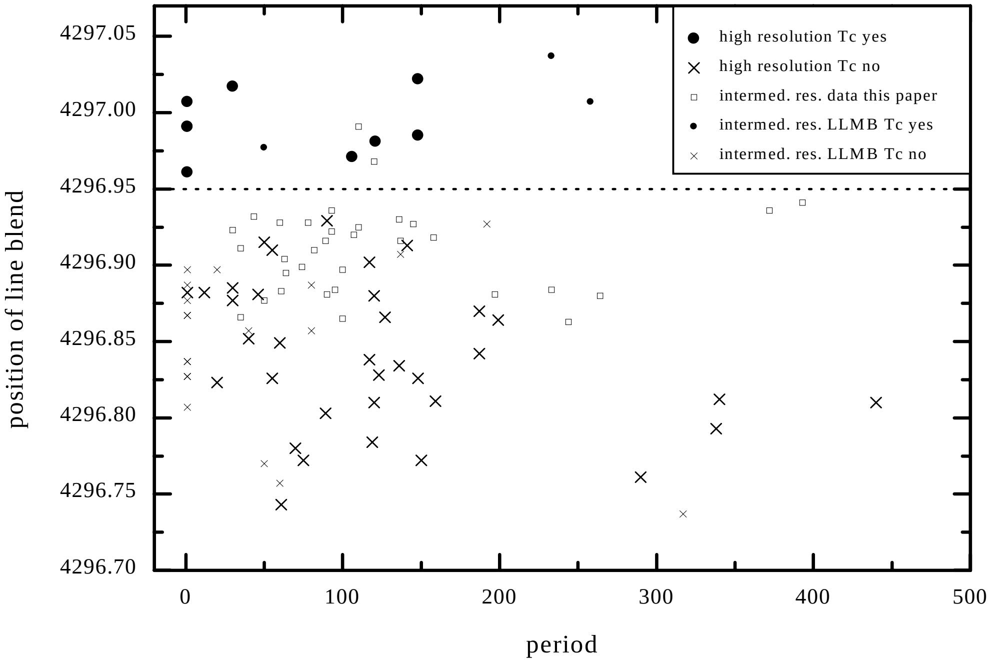

Fig. 3. Measured position of the line blend around 4297 Å including the Tc-line versus period. Irregular variables and non-variable stars are plotted with a period of 1 day. The filled circles indicate stars showing Tc according to our high resolution data or the literature. The crosses are those stars showing no Tc. Small symbols are used for stars for which only intermediate resolution data are available. Open boxes indicate objects that have not been analysed previously and are classified using this diagram. The dashed line marks the adopted limit between stars with and without Tc.

According to the wavelength limit, all the Possible cases based on high resolution data are classified as No from the position of the line blend. Therefore they will be included in that group for the remaining discussion.

4. Results

Table 1, 2 and 3 list all objects observed showing no Tc lines, clearly showing Tc lines and possibly showing Tc lines, respectively. The classification into blue, red and Mira-type SRVs from KH94 is given when available, as well as infrared colours from IRAS[1]. Those stars measured in only one of the three lines are marked. The period of W Boo has been corrected to 30 days due to a measurement published by Eggen (1973). The General Catalogue of Variable Stars (Kholopov et al. 1985–88, hereafter GCVS) lists a period of 450 days.

4.1. Carbon and S/MS stars

The few C-stars among the SRVs, for which LLMB give a line position, were not included in Fig. 3. Our observations did not include any carbon stars. We could therefore not check from high resolution spectra if the applied method is usable for M and C stars, too. A check of C-stars with the help of high resolution spectra would be interesting, but due to the typically small flux in this wavelength region obtaining high resolution spectra needs quite long exposure times. An investigation on Tc in C-type stars is in preparation (Barnbaum C., private communication 1998).

Our total sample contains several stars classified as MS. These are thought to be only marginally different from normal M stars (e.g. Smith & Lambert 1990) and will thus be included in the following discussion. The only exception is o^1 Ori which has a white dwarf companion (Vanture et al. 1991) and differs significantly in the [25]$-$[60] flux from SRVs of comparable period. Chen et al. (1995) find that this star is extended at 60 μm. According to Jorissen & Mayor (1992) o^1 Ori might be an extrinsic S star that just entered the TP-phase on the AGB. The five S stars in Fig. 3 will also be excluded from the discussion.

4.2. Correlation with stellar parameters

For further analysis our total sample of objects is restricted to all SRa and SRb variables with spectral types M and MS, a known period and an available Tc classification. We only exclude o^1 Ori due to the reasons given in the previous section. We compared the Tc abundance of the stars in this sample with different observational data. With regard to spectral type we found that in general Tc is clearly detected only in stars with spectral type later than M5. Nevertheless, beyond M5 the fraction of stars showing Tc does not seem to increase towards later spectral types. Jorissen et al. (1993) note that M stars without dust shells (from IRAS-data) generally do not show Tc. Our data support this result. With the exception of OP Her, all stars found to be Tc-rich have an IRAS-colour [12]$-$[25] > -1.1. Comments on OP Her are found in Jorissen et al. No relation between the presence/absence of Tc and the V$-$[12] or H$-$K colours was found.

A dependency on period was found so far as Tc appears among M-type SRVs exclusively at periods of more than 100 days. This is illustrated in Fig. 4 which gives the total number of analysed M/MS-type SRVs and the percentage of SRVs showing Tc as a function of period. Considering that the Possible detections actually may have no Tc, about 21 % of the SRVs in the period range between 100 and 150 days show Tc lines. Only about 7 % of the 28 objects with periods above 150 days show

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[1] Throughout this paper we define IRAS colours as [A]$-$[B]$=-2.5\log(F_A/F_B)$

Tc lines. Although the number of stars per period bin is small in this period range, there seems to be an indication that the actual fraction is even lower, especially at periods above 250 days. We note that the small number of objects with longer periods is not a characteristic of our sample but a general property of the SRV period distribution (KH92). Due to the small number of stars, the influence of uncertain or multiple periods (Lebzelter et al. 1995, Mattei et al. 1997) has to be considered. We will come back to this point in the discussion. For the bulk of the SRVs the periods should be correct because otherwise no relations between period and other stellar properties would have been found in previous investigations of these objects.

Using the SRV classification system of KH94, Tc is only detected in the spectra of 'red' or 'Mira-type' SRVs. As our data set contains 35 'blue' M-type SRVs the absence of Tc in this group seems to be a quite reliable result. Nevertheless only 13 % of the 67 'red' or 'Mira-type' SRVs show Tc, another 5 % (4 stars) possibly show Tc. These percentages are quite consistent with the above results and the fact that the KH94 classification combines several of the properties used above.

We note that it seems not very likely that the absence of Tc in the hotter objects (early spectral types, 'blue' SRVs) could be due excitation or ionisation effects. Ionisation effects are excluded due to the temperature of the absorbing layer (around 3000 K) and the ionisation potential of Tc. Although the Tc lines will get stronger at lower temperatures, this applies also to the other components of the blends (various metallic lines) and therefore we don't expect a significantly higher detection probability at lower temperatures.

5. Discussion and conclusions

Including the stars previously observed and excluding the S and C stars, we can summarize our results as follows:

- Tc is not found in SRVs with periods below 100 days, spectral types earlier than M5 and photospheric IRAS colours. These objects are 'blue' SRVs in the KH94 classification system.
- Among the 'red' or 'Mira-type' SRVs (periods longer than 100 days) the fraction of Tc-rich stars is about 15 % with a probably lower fraction among the stars with periods above 150 days.
- The fraction of Tc-rich stars among the SRVs is comparable to the fraction among the short period Miras (periods around 250 days) but significantly lower than the fraction among the typical Miras (periods longer than 300 days) where it is around 75 %.

When discussing our results in terms of the evolutionary connection between Miras, 'red' and 'blue' SRVs and with regard to the conditions and parameters of the third dredge-up one has to keep in mind the substantial uncertainties in the modelling of the third dredge-up (e.g. Frost & Lattanzio 1996). But there seems to be a certain agreement about the general characteristics of the dredge-up and the production of s-process elements. So we believe that some qualitative conclusions can be drawn and that our results can put further quantitative constraints on the theoretical models.

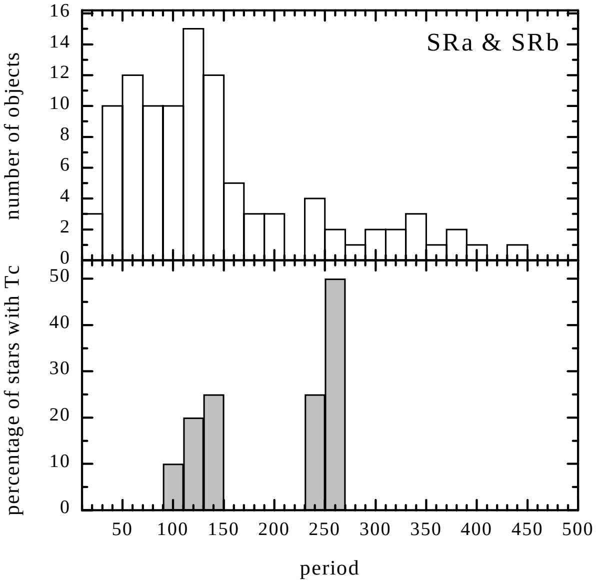

Fig. 4. Number of M-type SRVs observed (upper panel) and percentage of SRVs showing Tc (lower panel) as a function of period binned in 20 day intervals. Data published by LLMB have been included. SRcs and the strange object o^1 Ori are not included.

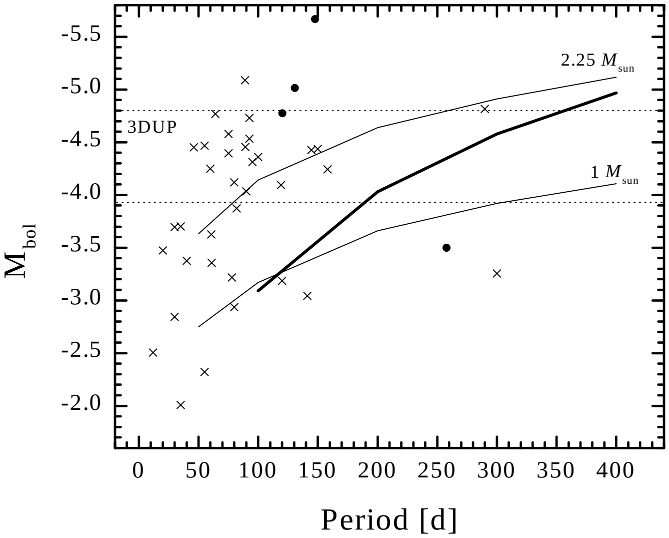

Fig. 5. Period-luminosity diagram for SRVs and Miras. Crosses and filled circles show SRVs without and with Tc, respectively. The thick full line is the relation for Miras from Alvarez & Mennessier (1997), the thin full lines are theoretical relations for solar metallicity stars with 1 $M_\odot$ and 2.5 $M_\odot$. The dashed lines mark the luminosity range expected for a core mass of 0.58 $M_\odot$ which is a probable minimum mass for the occurence of the third dredge-up (3DUP). See Sect. 5 for further details.

5.1. Evolutionary status of SRVs

The lack of Tc in the ‘blue’ SRVs strongly supports the suggestion by KH92 that due to the temperatures, luminosities and number density of these objects, the ‘blue’ SRVs are on the early AGB and not on the RGB or TP-AGB.

Since generally the time interval between two successive thermal pulses is shorter than the half-life of ^{99}Tc of $2{\cdot}10^5$ yr (see e.g. Vassiliadis & Wood 1994), the Tc abundance is reduced only slightly between pulses. The Tc abundance therefore quickly increases during the first pulses and then stays almost constant, provided dredge-up occurs at each pulse (Busso et al. 1992). The large difference in the fraction of Tc-rich stars between the ‘red’ SRVs and the typical Miras makes it therefore quite unlikely that TP-AGB variables in general oscillate between the SRV and Mira stage. A similar conclusion was also reached by KH92 on the basis of the similar number densities of Miras and ‘red’ SRVs in the solar neighbourhood. Ivezić & Knapp (1999) have argued in favour of such an oscillation on the basis of the different dust temperatures needed to fit the energy distributions of SRVs and Miras. However, in view of the complexity of the stellar atmospheres and the dust formation process, several other reasons can cause or mimic such a difference in the dust temperature (e.g. Aringer et al. 1999).

Neither can the similarity between the ‘red’ SRVs (typical periods around 100 days) and the short period miras with respect to Tc be due to such an oscillation. First, the short period Miras contain a significant fraction of low metallicity objects (e.g. Hron 1991) which is not the case for the SRVs and probably also influences the detection of Tc (e.g. weaker blending lines). Second, if stars would oscillate between SRV and Mira-like variability (without changing the pulsation mode), the longer period of the Miras would require this phase to be at the end of a thermal pulse cycle where the temperature is lowest and the luminosity is highest (Vassiliadis & Wood 1994). However, the ‘red’ SRVs are not less luminous and probably cooler than the short period Miras. This is indicated by the results of the HIPPARCOS mission (Kerschbaum & Olofsson 1998, Alvarez et al. 1997) and the observed spectral types and colours (KH92, Schultheis et al. 1998) of the SRVs. If the period difference between the SRVs and Miras is due to a different pulsation mode (Lebzelter et al. 1999), the necessary mode-switch from SRV to Mira-like variability will likely occur in the high-luminosity part of the pulse cycle (Fox & Wood 1982, Xiong et al. 1998), which would lead to the same argument.

In view of the above mentioned expected evolution of the Tc-abundance, the very small number of long period SRVs with Tc rules out a temporary evolution from short period to long period SRVs. A possible reason for the apparent lack of Tc might be undetected multiperiodicity which seems to be frequent among SRVs, especially for periods above 120 days (Mattei et al. 1997). The detection of multiple periods requires however a dense and long-term sampling of the light curves which is available only for a few visually observed stars. Thus the long period SRVs could at least partly have two periods with the shorter period being around 150 days. To clarify if the long period SRVs are actually a distinct group of stars, much better light curve data are needed.

There seems to be no similarity between the ‘Mira-type’ SRVs and the Miras with regard to the fraction of Tc-rich objects. This is in agreement with the different pulsational properties of these two groups of stars. Hinkle et al. (1997) measured the radial velocity variations of IR CO lines for two ‘Mira-type’ SRVs (RU Cyg and SV Cas) and found a considerably smaller velocity amplitude than for Miras. Further investigations on these objects are needed to clarify their relation to the other groups of variables.

5.2. The third dredge-up

Stellar evolution calculations predict that the third dredge-up requires a certain minimum core mass (e.g. Vassiliadis & Wood 1994, Mowlavi 1999) and is probably also less efficient for lower masses (Straniero et al. 1997, Mowlavi 1999). Thus one can conclude that for lower inital masses, more thermal pulses and hence a larger fraction of the TP-AGB lifetime is needed before the minimum core mass for the detection of Tc is reached. From theoretical pulsation models (e.g. Fox & Wood 1982) one can deduce that at a given luminosity (or approximately a given core mass) lower mass stars have longer periods and are more likely to pulsate in a lower mode (which again means longer period). The low fraction of SRVs with Tc could thus be a consequence of a small contribution from high mass stars which are above the critical luminosity and have a short period or pulsate in a higher pulsation mode than Miras. If this is correct, then the Tc-rich SRVs should be the most luminous objects at a given period. To check this we have computed absolute bolometric magnitudes from JHKL and IRAS photometry (mainly KH94) and the HIPPARCOS parallaxes. The results are shown as an $M_{\rm bol}$/period diagram in Fig. 5. Note that we have restricted our sample to stars where the parallax error is not more than 0.3 times the parallax and that we have applied a correction for the Lutz-Kelker bias as in Kerschbaum & Olofsson (1998). Unfortunately, this leaves only four Tc-rich stars. Three of these are indeed at or above the luminosity limit for SRVs without Tc of $-4\overset{\rm m}{.}7$ to $-5^{\rm m}$ (Fig. 5). Since $M_{\rm bol}$, period and the Tc-content are observationally totally independent quantities it would be hard to produce such a result by observational errors. The reason for the very low luminosity of the fourth star, V Boo, is however unclear. The star might be a peculiar object because of its long period, its sometimes very large amplitude and its suspected period variations (Szatmary et al. 1996, Kiss et al. 1999). Furthermore, V Boo has been classified only as Probable by LLMB and no high resolution data exist. In the figure we also show the luminosity range expected for a core mass of 0.58 $M_\odot$ during a thermal pulse cycle. This core mass is the minimum value required for the third dredge-up as found e.g. by Mowlavi (1999) from theoretical calculations for solar metallicity stars and by Marigo et al. (1996) from synthetic stellar evolution models for the carbon star luminosity function in the LMC. The upper luminosity limit, which applies to more than half of the pulse cycle time, is close to the border for the

Table 1. Stars showing no Tc in their spectra. Variability type, period and spectral type were taken from the GCVS. Column 4 lists the uncorrected IRAS [12]−[25] colour ($-2.5\log(F_{12}/F_{25})$; IRAS Science Team 1988). Column 2 gives the observing run(s) during which the used spectrum was obtained: Aug94 = Calar Alto (intermed. res.), Feb95 = ESO (high res.), Mar95 = KPNO (intermed. res.), Aug95 = ESO (remote observing, high res.). If no observing date is given data are taken from the literature as indicated in column 8. Column 7 lists the classification based on KH94. A remark is given in column 8, if only one line was used for the classification, and if results of the Tc contents have been published before: LLMB = Little et al. (1987), SL88 = Smith & Lambert (1988), Vanture = Vanture et al. (1991).

Object	**ObsDate**	**Type**	**[12]−[25]**	**Period**	**Spectr.Type**	**class.KH94**	**Remark**
And RS	Aug94	SRa	−0.858	136	M7-M10	red	
Aps θ	Feb95	SRb	−0.836	119	M7	red	LLMB no
Aqr V	Aug94,Aug95	SRa	−1.128	244	M6e	red	
Aqr Z	Aug95	SRa	−0.692	135	M1e-M7e	red	4262 only
Aqr EP	Aug94,Aug95	SRb	−0.746	55	M8	red	
Aql V450	Aug94	SRb	−1.473	64	M5-M8	blue	
Aql V499	Aug95	SRa	−0.722	159	M6	red	
Ari RZ	Aug94	SRb	−1.485	30	M6	blue	Vanture no, LLMB no
Ari T		SRa	−1.007	317	M6e-M8e	Mira-type	LLMB no
Boo W	Mar95	SRb	−1.477	30	M2-M4	blue	4297 only
Boo RV		SRb	−0.627	137	M5e-M7e	red	LLMB no
Boo BY		Lb	−1.425		M4		LLMB no
Boo CF	Mar95	Lb	−1.427		M2		
Cam BD		Lb	−1.445		S5,3		SL88 no, LLMB no
CMa GH	Feb95	SRb	−1.449	20	M6	blue	
CMi BC	Feb95,Mar95	SRb	−1.380	35	M5	blue	
CVn V		SRa	−0.787	192	M4e-M6e	red	LLMB no
CVn TU	Mar95	SRb	−1.448	50	M5	blue	LLMB yes, Vanture no
Cap RS	Aug95	SRb	−0.764	340	M4	red	
Cas SV	Aug94	SRa	−0.500	264	M6.5	Mira-type	
Cas V393	Aug94	SRa	−1.458	393	M0	blue?	
Cas V465	Aug94	SRb	−0.894	60	M5	red	
Cen V744	Feb95	SRb	−0.717	90	M8	red	
Cen V806	Feb95	SRb	−1.599	12	M5	blue	LLMB no
Cet UY	Aug95	SRb	−0.735	440	M7	red	
Cet UZ	Aug95	SRa	−0.759	122	M2	red	
Cet α		Lb	−1.561		M2		LLMB no
CrB RR	Mar95	SRb	−1.403	61	M5	blue	
CrB RY	Mar95	SRb	−0.599	90	M10	red	
Crv SV	Feb95	SRb	−1.495	70	M5	blue	4297 only
Crt RX	Feb95	SRb	−1.368	300	M3	blue	
Cyg AF	Aug94	SRb	−0.883	92	M5e-M7	red	LLMB no
Cyg AI	Aug94	SRb	−0.589	197	M6-M7	red	
Cyg V973		SRb	−1.442	40	M3	blue	LLMB no
Cyg V1059	Aug94	SRa		372	M	red?	
Cyg V1070	Aug94	SRb		73	M7	red?	
Cyg V1339	Aug94	SRb	−1.403	35	M3-M6	blue	
Cyg V1351		Lb	−1.397		M5		LLMB no
Del CZ	Aug95	SRb	−1.290	123	M5	blue	
Del EU		SRb	−1.387	60	M6	blue	LLMB no
Dor R	Feb95,Aug95	SRb	−1.275	338	M8e	red	
Dor WZ	Feb95	SRb	−1.544	40	M3	blue	
Dra TT	Mar95	SRb	−0.981	107	M6	red	4297 only
Dra TX	Mar95	SRb	−0.922	78	M4e-M5	red	
Dra AH	Aug94	SRb	−1.057	158	M7	red	
Dra CU		Lb	−1.436		M3		LLMB no
Eri Z		SRb	−0.918	80	M4	red	LLMB no
Eri RR		SRb	−0.839	97	M5	red	LLMB no
Eri SU	Aug95	SRb	−0.814	112	M4	red	
Eri VY	Aug95	SRb	−0.558	102	M6	red	
Eri BR	Aug95	SRb	−1.057	175	M5	red	

Table 1. (continued)

Object	ObsDate	Type	[12]−[25]	Period	Spectr.Type	class.KH94	Remark
Eri DM	Feb95,Aug95	SRb	−1.504	30	M4	red	
Eri DV		Lb	−1.471		M3		LLMB no
For ST	Aug95	SRa	−0.934	277	M6	red?	
Gem BQ	Mar95	SRb	−1.461	50	M4	blue	
Gem η	Mar95	SRa	−1.516	233	M3	blue	LLMB no
Gem μ		Lb	−1.546		M3		LLMB no
Gru δ^2		Lb	−1.492		M4		LLMB no
Her g	Mar95	SRb	−1.171	89	M6	red	LLMB no
Her X	Mar95	SRb	−0.756	95	M6e	red	4297 only, LLMB no
Her IQ	Aug94	SRb	−1.227	75	M4	blue?	
Her LQ		Lb	−1.483		M4		LLMB no
Her V566	Aug94	SRb	−1.525	137	M4	blue	
Hya W	Feb95	SRa	−1.370	361	M7.5e-M9e	Mira-type	LLMB yes
Hya RT	Feb95	SRb	−1.027	290	M6e-M8e	Mira-type	LLMB yes
Hya UX	Aug95	M		262	M		
Hya AK	Feb95	SRb	−0.787	75	M4	red	
Hya II	Feb95	SRb	−1.494	61	M4	blue	
Lac HT	Aug94	SRb	−1.419	82	M4	blue	
Leo R	Mar95	M	−1.298	310	M6e-M8e		
Lep S	Feb95	SRb	−0.656	89	M6	red	
Lep RX	Feb95	SRb	−0.886	60	M6.2	red?	LLMB no
Lib σ		SRb	−1.671	20	M3	blue	LLMB no
Lyn UW	Mar95	Lb	−1.541		M3		
Lyr R	Aug94	SRb	−1.444	46	M5	blue	LLMB no, Vanture no, WD88 no
Oph V988	Aug94	SRb	−0.758	63	M7e	red	
Ori α	Mar95	SRc	−1.076	2335	M1-M2		
Pav S	Aug95	SRa	−0.979	381	M7e-M8e	Mira-type	
Pav X	Aug95	SRb	−0.774	119	M	Mira-type	
Pav Z	Aug95	SRb	−1.027	135	M7e	Mira-type	
Peg SV	Aug94	SRb	−0.645	145	M7	red	
Peg GZ	Aug94	SRa	−1.512	93	M4	blue	
Per ρ		SRb	−1.481	50	M4	blue	LLMB no
Phe S	Aug95	SRb	−0.763	141	M3e-M6e	red	
PsA V	Aug95	SRb	−0.874	148	M	red	
Sgr RW	Aug95	SRa	−0.735	187	M4-M6	red	
Sco V380	Aug95	SRa		187	M1	blue	
Sct RW	Aug95	SRb	−1.139	117	M5	red	
Ser τ^4	Mar95	SRb	−0.788	100	M5	red	4297 only, LLMB no
Tel RW	Aug95	SRb	−0.874	127	M4-6	red	
UMa Z		SRb	−0.987	196	M5e	red	LLMB no
UMa RY		SRb	−0.764	310	M2-M3	Mira-type	LLMB no
UMa ST	Mar95	SRb	−0.923	110	M4-M5	red	
UMi RR	Mar95	SRb	−1.440	43	M5	blue	LLMB no
Vel EP	Feb95	SRa	−0.552	240	M6	red	4262 only
Vel GI	Feb95	SRb	−1.621	120	M3	blue	
Vel GK	Feb95	SRb	−1.644	120	M3-M5	blue	
Vel GL	Feb95	SRb	−1.470	117	M4	blue	
Vir BK	Feb95	SRb	−0.971	150	M7	red	4297 only
Vir ER	Feb95	SRb	−1.410	55	M4	blue	
Vir ET		SRb	−1.482	80	M2	blue	LLMB no
Vir EV	Feb95	SRb	−1.347	120	M4	blue	

occurence of Tc in SRVs. Thus our results for the SRVs give some support to the current models for the third dredge-up.

From the Mira period/luminosity relation also given in Fig. 5 one can see that the period range where Tc is found in Miras (periods longer than 250 days, see LLMB) is again consistent with the theoretical minimum luminosity estimates for the third dredge-up. The increasing fraction of Tc-rich Miras with increasing period probably can be fully explained by (i) the gen-

Table 2. Observed stars showing Tc in their spectra. Columns have the same meaning as Table 1

Object	ObsDate	Type	[12]−[25]	Period	Spectr.Type	class.KH94	Remark
Aql V915		Lb	−1.283		S5-S7		SL88 yes, LLMB yes
Boo V		SRa	−1.153	258	M6e	Mira-type	LLMB yes
Cam AA		Lb	−0.949		M5		SL88 yes, LLMB yes
Cnc RS	Mar95	SRc	−0.904	120	M6		LLMB yes, Vanture yes SL88 yes, WD88 yes
Cyg W	Aug94	SRb	−0.974	131	M4e-M6e	red	LLMB yes, Vanture yes
Cyg RU		SRa	−0.643	233	M6e-M8e	Mira-type	LLMB yes
Del U	Aug94	SRb	−0.650	110	M5	red	
Her OP	Aug94,Mar95	SRb	−1.250	120	M5	red?	LLMB yes, SL88 yes
Her ST	Mar95	SRb	−0.781	148	M6-7	red	LLMB yes, SL88 yes
Oph SY	Aug95	SRb	−0.717	132	M5	red	
Ori o^1	Aug94,Feb95, Mar95,Aug95	SRb	−1.500	30	MS	blue	LLMB yes, SL88 yes, WD88 yes
Peg TX	Aug94	SRb		120	M5e	red?	
Peg UW	Aug95	SRb	−0.878	106	M5-M7	red	
Peg HR		SRb	−1.467	50	S5,1		LLMB yes, SL88 yes
Pup NQ	Feb95	Lb	−1.455		S6,3		4297 only, SL88 yes
HR 8062	Aug94	NV?			S4,1		LLMB yes, Vanture yes

Table 3. Observed stars possibly showing Tc in their spectra. Columns have the same meaning as Table 1

Object	ObsDate	Type	[12]−[25]	Period	Spectr.Type	class.KH94	Remark
Mic T	Aug95	SRb	−1.026	347	M6e	red	LLMB poss
Mon X	Feb95	SRa	−0.983	156	M1e-M6e	red	4297 only, LLMB no
Pup L^2	Feb95	SRb	−1.140	141	M5e-M6e	red	LLMB yes
Vir SW	Feb95	SRb	−0.754	150	M7	red	

eral increase of luminosity (core mass) and period for stars of a given mass during the evolution along the AGB, (ii) a certain range of initial masses (higher mass stars will be a few $0\overset{\rm m}{.}1$ brighter at a given period than the average relation) and (iii) a higher dredge-up efficiency for higher core masses. The first two points are illustrated by the theoretical relations for 1 $M_\odot$ and 2.5 $M_\odot$ derived from the Bessell et al. (1989) evolutionary tracks and the period-mass-radius relation of Vassiliadis & Wood (1994). A mass range for the Miras from 0.8 $M_\odot$ to 2.6 $M_\odot$, as estimated by Alvarez & Mennessier (1997), seems to be compatible with the available data on the occurence of Tc and the probable minimum luminosity for the third dredge-up. The large but still somewhat uncertain fraction of Tc-rich Miras with periods above $350^{\rm d}$ and the slope of the observed Mira period/luminosity relation could indicate that the *average* initial mass increases towards longer periods.

In combination with previous investigations our results on the presence of Tc in SRVs thus support an evolutionary scenario on the AGB from ‘blue’ SRVs to ‘red’ SRVs and on to long period Miras. Except for the most massive stars, the third dredge-up occurs only during the Mira stage. Since theoretical predictions for the the third dredge-up still contain many uncertainties (see e.g. Frost & Lattanzio 1996), our results also provide some further constraints for such models.

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