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Technetium and the third dredge-up in bulge AGB stars

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Abstract. We searched for Technetium (Tc) in a sample of bright oxygen-rich asymptotic giant branch (AGB) stars located in the galactic bulge. Tc is an unstable element synthesised via the s-process in deep layers of AGB stars, thus it is a reliable indicator of both, recent s-process and third dredge-up. High resolution optical spectra obtained with the UVES spectrograph at ESO's VLT are used to search for resonance lines of neutral Tc. We present a method to improve the classification of stars with respect to their Tc content by using flux ratios. With the attained classification theoretical predictions on the luminosity limit for the onset of the third dredge-up are tested. Among the sample of 27 long period variables four were found to definitely contain Tc in their atmosphere, giving the first direct evidence for third dredge-up in the bulge. The results are shortly compared to what is found for field stars.

Key words. Stars: late type – Stars: AGB and post-AGB – Stars: evolution

1. Introduction

In the most luminous part of the Asymptotic Giant Branch (AGB) the behaviour of a star is characterised by Thermal Pulses (TP), recurrent thermal instabilities of the He shell accompanied by changes in luminosity, temperature, period and internal structure (see, e.g., Busso et al. 1999,for a review). Between these events of explosive He-burning, heavy elements can be produced via the "slow neutron capture process" (s-process, see e.g. Wallerstein et al. 1997) in the region between the hydrogen and the helium burning shells. The processed material is then brought to the stellar surface by the convective envelope that temporarily extends to these very deep layers. This event is called the third dredge-up (3DUP) and is the cause of the eventual metamorphosis of an oxygen-rich M-star to a carbon-rich C-star.

Technetium (Tc) is among the elements produced by the s-process and has no stable isotopes. The isotope of Tc with the longest half-life time produced via the s-process is ^{99}Tc with $\tau_{1/2}$ = 2.1×10^5 years. This makes Tc a reliable indicator of the 3DUP, because due to the short life time any Tc we see in a star has been produced during its previous evolution on the TP-AGB. Note, however, that the absence of Tc does not necessarily mean the absence of TPs but rather the absence of 3DUP for several TPs. This could be caused by a too low initial mass on the TP-AGB or by a too high mass loss rate at the end of the AGB evolution.

In an earlier paper (Lebzelter & Hron 2003, hereafter called paper I), we studied the Tc content of a sample of luminosity selected galactic field AGB stars (see also references in that work for earlier observations of Tc). The aim was to test theoretical predictions (Straniero et al. 1997; Busso et al. 1999; Lugaro et al. 2003,and references therein) on the minimum luminosity for 3DUP to occur. The results of that study suggest the theoretical minimum bolometric magnitude of M_{bol} = - $3\overset{m}{.}9$ to be in agreement with the observations. Also, a significant number of stars above the lower luminosity limit for 3DUP was found not to show Tc in their spectra. Being above the luminosity limit is thus not sufficient for a star to show Tc. Due to the uncertainties in distance (based on Hipparcos parallaxes) of field stars, the results are not built on very solid ground.

To improve the situation, a sample of targets with more accurate distances is required. Given the current accuracy of distance measurements of AGB stars and the low flux in the blue spectral region of these stars, the only reachable targets for such studies can be found in the galactic bulge. Using ESO's VLT, exposure times are short enough to execute observations of a statistically relevant sample in a reasonable time. Additionally, the population at least in the outer bulge is expected to be more homogeneous than the disk population. We therefore chose to observe bright AGB stars in the Palomar Groningen field no. 3 (PG3). For details about this bulge field and its long period stellar population we refer to Schultheis et al. (1998).

2. Sample selection

The selection of the sample was limited to oxygen-rich long period variables in PG3. This bulge field has been studied extensively in the past (Blommaert 1992; Ng 1994; Schultheis 1998) and periods for a considerable number of variable stars are known. In order to avoid foreground or background objects, we constructed a period K-magnitude diagram based on near-infrared photometry acquired at the ESO 1-m telescope at La Silla and additional data from DENIS (Epchtein et al. 1997) for some stars. The periods were taken from Wesselink (1987), also the stellar identifiers used here are from that work. A range of $\pm 1\overset{m}{.}0$ mag around the period K-magnitude relation for the SgrI field from Glass et al. (1995) was allowed for the potential targets to account for the depth of the bulge and the intrinsic scatter in brightness. Stars outside this range were considered to be in the fore- or background. The targets were chosen to be brighter than the RGB-tip (8.2 mag in K_0 at the bulge distance) to cover the AGB upwards. The distribution was chosen to be about equal between Semiregular and Mira variables.

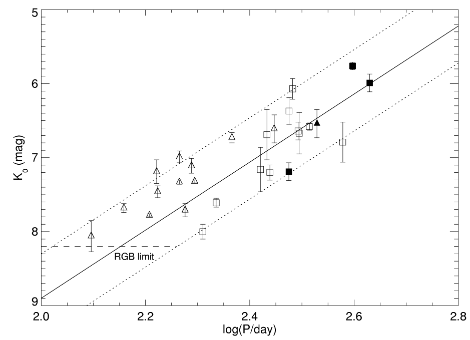

Fig. 1. Period - K magnitude diagram of our sample of long period variables in the galactic bulge. Squares and triangles represent Mira and Semiregular variables, respectively. The filled symbols are stars with positive Tc detection. The solid line is the period - K relation from Glass & Schultheis (2003).

To test for the membership in the bulge, we show a period K-magnitude diagram in Fig. 1. For the construction of this plot we additionally include 2MASS photometry of the stars where available. The drawn error-bars are the statistical standard deviations of the mean. For two stars (S942 and M315) alternative periods were found in the literature and adopted instead of the (uncertain) values from Wesselink (1987).

Within the error bars, all stars can be considered to be located in the bulge. We plot the relation from Glass & Schultheis (2003,sequence "C") as solid line instead of the relation from Glass et al. (1995) that was used for the sample selection. The former is an improved version of the latter. The dotted lines $0\overset{m}{.}6$ above and $0\overset{m}{.}5$ below sequence "C" mark the range in magnitude due to the finite depth of the bulge.

Apparently, the SRVs mainly fall above the period K-magnitude relation in Fig. 1. As the PG3 SRVs are in the same pulsation mode as the Mira variables (Schultheis et al. 1998), this fact can rather be explained by a selection bias towards brighter, i.e. closer, SRVs.

To get an estimate of the possible foreground contamination we used the Besançon model of population synthesis (Robin et al. 2003). We calculated the population of the central square degree of the PG3 field using the observed colour and apparent K magnitude range as criteria. No criteria for the pulsation could be included. The result is a level of 6% of foreground contamination, which gives 1 - 2 stars in a sample of 27. Taking into account the pulsation properties, the estimated percentage of foreground contamination would be much further reduced, since close-by M dwarfs could then be excluded. Thus, we are quite confident to have only bulge stars in our sample.

3. Observations

27 bulge AGB stars were observed with UVES at ESO's VLT in three nights in July 2000. For some basic characteristics of the objects, we refer to our forthcoming A&A paper on this subject. The observed wavelength ranges were 3770 - 4900 Å (blue arm) and 6670 - 9920 Å (red arm). With the blue arm, several resonance lines of neutral Tc were covered, among them the "classical" lines at 4238.19, 4262.27 and 4297.06 Å (wavelength in air). The resolution of the spectra is about 50 000. Typical exposure times were 1 h per target.

The spectra were reduced with the ESO provided pipeline written in MIDAS, version 2.1.0. The achieved SNR of the UVES spectra varies strongly with wavelength. For the regions around the Tc lines the SNR lies between 5 and 40. The four stars with Tc have a SNR of around 30 (M626, M1347, S942) and 5 (M1147), respectively.

4. Tc detection

For the decision whether a star shows Tc or not we first inspected the spectra visually by comparing them with synthetic spectra around the classical Tc lines. The synthetic spectra are based on MARCS atmospheric models (Gustafsson et al. 1975) with modifications introduced by Jørgensen et al. (1992), and with spherical radiative transfer routines from Nordlund (1984). The spectral synthesis has been recently improved by Gorfer (2005) and atomic line wavelengths are taken from the VALD data base[1] (Kupka et al. 1999). Line data of Tc from Bozman et al. (1968) was included in the spectral synthesis.

On visual inspection, three stars were identified to show the Tc lines. There are difficulties with the synthetic spectra in general, as the lines seem to be much more pronounced in the model spectra than what is observed. Albeit, all three Tc line are undoubtedly present in the stars with Tc.

At the position of the 4297 line there appears to be a somewhat smaller line also in stars that were classified as to have no Tc. This line is caused by chromium. For this reason we recommend to be cautious on classifying a star with respect to the occurrence of Tc when using only this line. In the three stars identified to show Tc by visual inspection, also at least the Tc lines at 3984.97, 4031.63, 4049.11 and 4095.67 Å were clearly identified.

For a more quantitative decision on the occurrence of Tc we define flux ratios between the Tc line centre and a pseudo continuum point close to the line position (averaging over six to ten wavelength points). In a plot of this ratio versus the respective ratio for another line, all stars that were identified to have Tc

[1] The wavelengths of VALD are vacuum wavelengths only below 2000 Å, otherwise they are quoted for air!

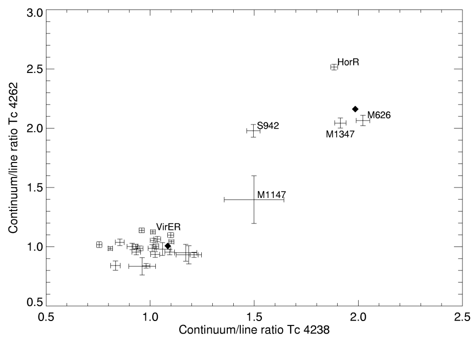

Fig. 2. Continuum to line flux ratios for the Tc lines at 4238 Å and 4262 Å. We include the field stars R Hor and ER Vir (analysed in Lebzelter & Hron 2003) for this plot. The filled diamond symbols represent the flux ratios derived from synthetic spectra with and without Tc, respectively, both based on a MARCS atmospheric model with $T_{\rm eff}$ = 3400 K, [Fe/H] = -0.5, log g = 0.0, one solar mass and solar C/O ratio.

by visual inspection clearly separate from the other stars. In Fig. 2 we show this ratio for the lines at 4238 and 4262 Å, as these appear to be the strongest and least blended ones. One more star (M1147) separates from the compact group of "Tc no" stars as well, although not that clearly. About the same picture is achieved using flux ratios of the other Tc lines. We also include flux ratios of synthetic spectra with and without Tc in Fig. 2.

The error bars on the flux ratios were estimated by adding random noise with the magnitude of the inverse of the SNR that was provided by the pipeline to the observed spectrum. The standard deviation in the flux ratio derived from one hundred such realisations of the spectrum gives the the error bar. The SNR of the spectrum of M1147 is around 5 in the blue region, resulting in a quite large uncertainty. Still, it is small enough to classify this star as "Tc yes" with probably a lower content of Tc then the three other stars. For the rest of the stars the occurrence of Tc can safely be excluded.

5. Discussion

In Fig. 3 we show a $(J-K)_0$ colour magnitude diagram of the sample stars. We first discuss the upper panel, which shows the bolometric magnitude as directly calculated from the near IR photometry. The bolometric correction BC_K from Kerschbaum et al. (in preparation) based on $(J-K)_0$ is used and a distance modulus of $14\overset{\mathrm{m}}{.}5$ to the bulge is assumed.

Obviously, all four stars with Tc fall above the theoretical luminosity limit for 3DUP, thus confirming this limit. The findings of Lebzelter & Hron (2003) are supported by our results.

In Fig. 3 also two isochrones from Girardi et al. (2000) with two age-metallicity combinations are included (see legend). The chosen range in age and metallicity for the isochrones is suggested by the results of Schultheis et al. (1998). We did not use the $(J-K)_0$ from Girardi et al. (2000) but take their effective temperature and use a $(J-K)_0/T_{\rm eff}$ calibration determined from interferometric and near infrared photometry of field Mira variables. With this calibration the isochrones reach to redder $(J-K)_0$ colours. Still, the isochrones do not cover the reddest objects, and both of them have their AGB tip at a luminosity fainter by one magnitude than what is observed. This fact can be explained if one assumes a younger age of the selected objects: The observed colours and bolometric magnitudes can be reached by assuming an age of only 3 Gyrs or younger.

This is supported by the fact that stars containing Tc are found at all in the present sample: According to current mixing models, a minimum initial mass of 1.5 $M_\odot$ is required for a star in order to experience 3DUP. A star of this mass takes approximately 3 Gyrs to evolve from the ZAMS to the AGB phase. It seems likely that the most massive stars in our sample have about this mass, yet not being massive enough to dredge up enough carbon in order to become a C-star. This age estimate must not be adopted for the whole bulge, as our sample might be biased towards a young, massive population that is only a small "contamination" to the bulk of the bulge.

The uncertainty in luminosity of the sample stars is dominated by the distance uncer-

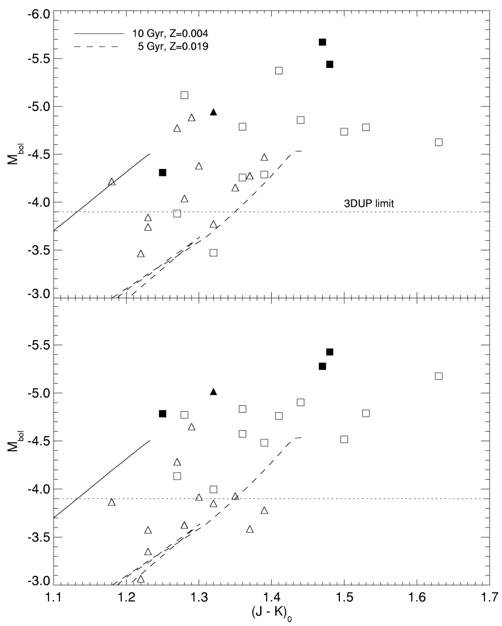

Fig. 3. Colour luminosity diagram of the sample stars. Symbols are the same as in Fig. 1. The dotted horizontal line marks the minimum luminosity at the stage where 3DUP sets in. Isochrones from Girardi et al. (2000) represented in solid and dashed lines are also included in the plot (see legend). The upper panel shows M_{bol} as directly determined from the NIR photometry, the lower panel is constructed by correcting for the depth-induced scatter using Fig. 1.

tainty due to the depth of the bulge. Taking the difference of a star to sequence "C" in the period K-magnitude diagram (Fig. 1) and subtracting (or adding) it from (or to) the bolometric magnitude, we arrive at an "alternative" version of the colour magnitude diagram as shown in the lower panel of Fig. 3. The AGB tip luminosity remains unchanged, not altering the conclusion on the age of the bulge drawn above. Two things emerge from this alternative diagram: Firstly, the SRVs now mainly fall below the theoretical luminosity limit for 3DUP. This is not surprising regarding the probable selection bias towards closer SRVs discussed above. More surprising is the fact that in this diagram the stars showing Tc in their spectra seem to form the upper envelope: At a given $(J-K)_0$ colour only the brightest objects have Tc. As colour can be converted to temperature, we can also say that at a given temperature only the brightest stars have Tc.

There has been reasoning that Tc could decay below the detection limit if 3DUP does not occur for several TPs (see Busso et al. 1992,and paper I). This can be the case when the convective envelope, besides the core mass the second important parameter for 3DUP, is eroded due to mass loss below a critical limit. Indeed, the star M1147 seems to have a reduced Tc abundance, although it is one of the brightest (and most evolved) objects in the sample. One may speculate that this star has lost so much mass that the envelope is not massive enough anymore to drive dredge-up, and Tc has already decayed to a lower abundance level. However, a very high mass loss rate is not indicated by the IRAS colours of the sources: From the $K_0-[12]$ colour that is available for eight of the objects (including M1147), a mass loss rate of $10^{-6} M_{\odot} yr^{-1}$ or less can be estimated.

By determining relative abundances of Tc and other s-process elements, a distinction between stars which did not (yet) have 3DUP and stars where dredge-up has stopped some time ago due to the eroded envelope allowing Tc to decay (even below the detection limit) is possible. This will be one of the major goals for the future work on these highly evolved objects.

5.1. Comparison with field stars

The "Tc yes" star with the shortest period in this bulge sample is M626 with a period slightly below 300 d. The two stars with the longest period in our sample (M1347 and M1147) both show Tc. This compares well with the findings of paper I where the fraction of "Tc yes" among field Mira variables increases above a period of 300 d. The only Semiregular variable in the sample according to Wesselink (1987) (S942) was classified as Mira in Plaut (1971). Following the latter, only Miras are found to show Tc in our sample (we still keep the SRV symbol for S942 in the figures).

Comparison between Fig. 1 here and Fig. 4 in paper I shows that the range in period is much smaller for the bulge stars than for the field stars. The same holds for the range in bolometric magnitude. This is a consequence of the higher homogeneity of the bulge sample.

Regarding the fraction of stars above the 3DUP luminosity limit which show Tc we find similarity between the two samples: in the field sample, the fraction is 20%, while in the bulge the fraction is 19% (21% for the alternative color luminosity diagram).

6. Conclusions

We present high resolution UVES/VLT spectra and NIR photometry of bulge AGB variables, aiming at a detection of Technetium. Their membership in the bulge is shown using a period K-magnitude diagram. In a sample of 27 stars, four were found to have Tc, giving the first direct evidence for recent or ongoing third dredge-up in these stars. For the distinction between "Tc no" and "Tc yes" stars, we compare the observed spectra to synthetic ones by including line data of Tc in the spectral synthesis calculations. A more precise distinction is possible using flux ratios between the Tc line flux and a pseudo-continuum flux. Using this method, even for very low SNR (down to 5) a reliable distinction with this respect can be made.

In a colour luminosity diagram of the sample all stars with Tc clearly fall above the theoretical third dredge-up limit of $M_{bol} = -3\overset{m}{.}9$, being in agreement with this prediction. Including synthetic isochrones in this diagram shows that the observed AGB tip luminosity is in contradiction with what is expected for a population of 5 Gyrs age (and solar metallicity) or older; the observed AGB tip is clearly brighter and redder. Also, the occurrence of "Tc yes" stars is a hint towards the existence of a younger and more massive population in the bulge.

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