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s-process nucleosynthesis in very metal-deficient post-AGB stars*

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Abstract. In this contribution, we present a detailed abundance study of a star that challenges our current understanding of the *s*-process: V453 Oph. This RV Tauri star of low intrinsic metallicity displays simultaneously mild *s*-process overabundances and a low C content. The remarkable pattern is confirmed and strengthened in an analysis relative to another, very similar RV Tauri star without *s*-process enrichment: DS Aqr. Two nucleosynthetic models have been explored to explain the abundances of V453 Oph. In a *radiative* model, *s*-process elements are generated in the radiative zone in the He-rich intershell during the interpulse phase, while in the *convective* model, the *s*-process elements are produced in convective conditions during the thermal pulse only. Both models succeed in explaining the mild *s*-process overabundances, but only the convective model is able to produce *s*-process elements without enhancing the carbon content significantly.

1. Introduction

RV Tauri is the prototype of a class of pulsating stars showing alternating deep and shallow minima in their lightcurves, with periods between 30 and 150 days. RV Tauri stars occupy the high-luminosity end of the pop II Cepheids (see e.g. Wallerstein 2002, for a review on pop II Cepheids). It is a heterogeneous class of variables, with lightcurves showing often cycle-to-cycle variability and amplitude variations.

The precise evolutionary status of RV Tauri stars was unknown for a long time, but now there is general agreement that RV Tauri stars are post-AGB stars, since many of them show a strong far-IR excess, originating from a circumstellar dust shell, which is a relic from the strong AGB mass loss (Jura 1986). Moreover, their genuine high luminosity was confirmed by members in globular clusters and in the LMC. However, clear *chemical* post-AGB characteristics, like high C or *s*-process abundances, were not found (Giridhar et al. 2000; Maas 2003). Instead, many RV Tauri stars show a remarkable depletion pattern, in which the refractory elements are depleted relative to the non-refractories (see e.g. Figure 3 in Maas et al. 2002, for a typical depletion pattern). In such a pattern, a clear anti-correlation is seen between the photospheric abundance of an element and its condensation temperature.

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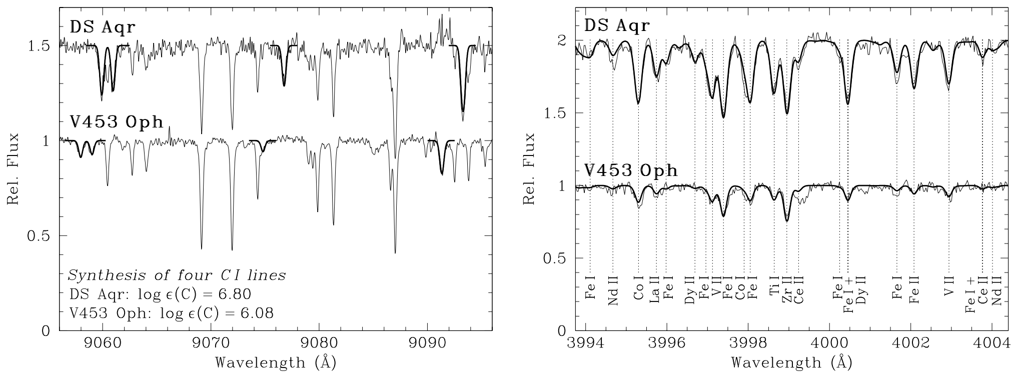

Fig. 1. *left panel* Spectrum synthesis of four C I lines around 9080 Å shown by a thicker line. The spectra on this figure were not velocity corrected, so that telluric lines are easily identified. *right panel* Spectrum synthesis (thicker line) of the region around 4000 Å.

This pattern is not the consequence of a nucleosynthetic process, but of a chemical one, which is still poorly understood. Probably the depletion is caused by a gas-dust separation mechanism that occurs after the severe mass loss at the end of the AGB. Such mechanism may only be effective in a stable circumstellar environment, like a circumstellar or circumbinary disk (Waters et al. 1992). Observationally, the [Zn/Fe] ratio is a very good indicator for depletion; these two elements have the same nucleosynthetic history, but they have very differing condensation temperatures.

In this contribution, we study the photospheric composition of DS Aqr and V453 Oph, two RV Tau stars with a low intrinsic metallicity. Following Kholopov et al. (1998), the two stars have a pulsation period of around 80 days. This period corresponds to a luminosity of about 8000 $L_{\odot}$, if the P-L relation for RV Tauri stars in the LMC is applied. Additionally, DS Aqr has a large galactic latitude ($b = -61^{\circ}.56$), and V453 Oph a large radial velocity ($-124\,\mathrm{km\,s^{-1}}$). The low Fe content and the kinematics point to a low mass nature of both objects. Consequently, these two objects are most likely in their post-AGB phase of evolution. However, no IR-excess was detected by the IRAS satellite. In a first, observational part of this contribution (Sect. 2 and 3), the observations and analysis of these two stars are discussed. We will present the remarkable result that V453 Oph displays slight, but real *s*-process overabundances without any carbon enhancement. In a second, theoretical part (Sect. 4), we study the models that were calculated in an attempt to explain the remarkable abundance pattern in V453 Oph.

2. Observations and analysis

In our ongoing programme to study the photospheric chemical abundances of post-AGB (e.g. Van Winckel 2003; Reyniers et al. 2004) and RV Tauri stars (e.g. Maas et al. 2002), high resolution spectra of DS Aqr and V453 Oph were taken with the FEROS spectrograph in 2001, which was – at that time – mounted on the ESO 1.52m telescope at La Silla. The resolving power of these spectra is around 48000, and the wavelength coverage is from 3600 Å to 9200 Å in one shot. The signal-to-noise (S/N) ratio depends on the wavelength range, being the highest at around 6000 Å (~110 for DS Aqr and ~180 for V453 Oph). At shorter wavelengths, the ratio is decreasing to ~50 at 4000 Å for both stars.

Atmospheric model parameters were determined by the spectroscopic method, in which the parameters rely on a fine analysis of the iron lines. The high number of Fe lines (316 for DS Aqr and 136 for V453 Oph) ensures a very accurate determination of the parameters. A summary of the parameters is found in Table 1.

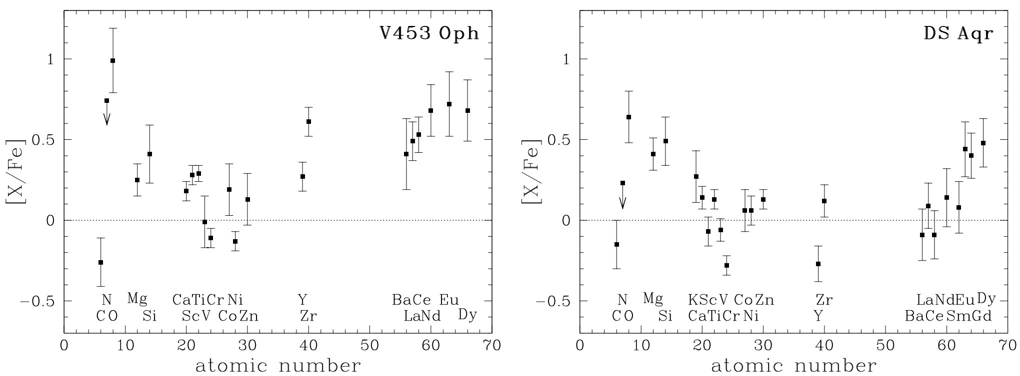

Fig. 2. Abundance results for our two programme stars. The errorbars on the abundances represent an estimate of the total error.

Table 1. The model parameters of V453 Oph and DS Aqr as determined using the Fe lines. The derived metallicity is also given.

object	T_{eff}	$\log(g)$	ξ_t	[Fe/H]
V453 Oph	6250	1.5	3.0	−2.23
DS Aqr	5750	0.5	3.5	−1.62

The model parameters were confirmed by the results of other elements with a large number of lines and elements with lines of two ionisation stages. Abundances were calculated using the latest Kurucz models (Castelli & Kurucz 2003) in combination with the abundance calculation program MOOG by Sneden (version April 2002).

The linelist that was used is the same as the list described in Van Winckel & Reyniers (2000) and Reyniers et al. (2004). In compiling this list, we devoted special effort to include the most accurate oscillator strengths available. In addition, only weak lines are used, in order to avoid non-LTE effects as much as possible. Abundances were calculated by their equivalent widths; some abundances were calculated by spectrum synthesis (C, N and Eu). The synthesis of C is shown in Figure 1. As a final abundance check, we performed a spectrum synthesis of the region around 4000 Å (Figure 1). The observed and synthetic spectrum closely match, so we can conclude that atmospheric parameters and abundances are accurately determined.

3. Abundance results

The abundance results for the two stars can be found in full detail in our upcoming A&A paper (Deroo et al. 2004). Here we only give a graphical presentation of our results (Figure 2). The abundances relative to iron [X/Fe] are plotted against atomic number Z. The standard notation is used, i.e. $[X/Fe] = \log(X/X_\odot) - \log(Fe/Fe_\odot)$. The interpretation of an abundance pattern for an evolved star is always a difficult exercise, especially in this metallicity range, since one has to disentangle the initial composition from possible (internal or external) enrichments. The initial composition for a star of metallicity around −2 is, however, quite well known through studies of unevolved dwarfs and (sub)giants, and it roughly follows the iron deficiency, except for oxygen, α- and r-process elements. Such a “initial pattern” is seen in DS Aqr (with the exception of the CNO elements, see below): α-elements are somewhat enhanced at a level of +0.4 dex, together with the r-process elements Eu, Gd and Dy. The other elements, including the *s*-process elements, roughly follow the iron deficiency. The only elements that have been altered during the evolution of DS Aqr seem to be the CNO elements, with an underabundant C and overabundant N and O content. Such a

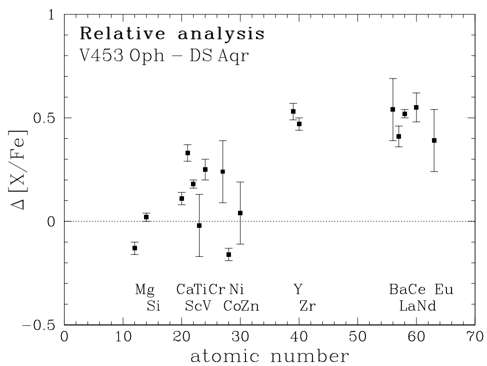

Fig. 3. Abundance results for the *relative* analysis, in which strictly the same lines were used for both stars.

CNO pattern is characteristic for a 1st dredge-up event, in which the CNO cycle has transformed carbon into nitrogen, while the total CNO abundance has not changed.

Comparing the abundance pattern of DS Aqr with the one of V453 Oph, the pattern is very similar, with the remarkable exception of the *s*-process elements Y and Zr (the light *s*-process elements or the Sr-peak) and Ba, La, Ce, and Nd (the heavy *s*-process elements or the Ba-peak). These elements are all enhanced by ~0.5 dex, and they are definitely *not* compatible with [X/Fe] = 0, even if we take the total estimated errors into account. Therefore we can conclude that V453 Oph clearly displays evidence for a slight but real *s*-process enrichment. Also note that in both stars no signs of depletion are seen; the [Zn/Fe] ratio is +0.13 for both stars.

In order to further decrease possible sources of errors, a strict *relative* analysis was made between the two stars, using exactly the same lines for both stars. The results of this analysis are presented in Figure 3. From this figure it is clear that this kind of analysis significantly improves the consistency for the results on the *s*-process elements.

The *s*-process enrichment makes V453 Oph the first RV Tauri star displaying *chemical* evidence for the post-AGB nature of this class of luminous pulsating stars. Another RV Tau star with *s*-process elements was found in ω Cen by Gonzalez & Wallerstein (1994), but the enrichment in this particular star is probably caused by the self-enrichment of this cluster and hence reflecting the initial composition. But also the *s*-process enrichment in V453 Oph is very intriguing, since it is *not* accompanied by an expected carbon enhancement. Indeed, instead of a carbon enhancement, a carbon *deficiency* of [C/Fe] = −0.26 is measured, while every nucleosynthetic AGB model predicts that *s*-process production in a low mass star is accompanied by carbon production. In the next paragraph, we will explore the possibility of producing *s*-process elements without significantly producing carbon. Note that extra partial CN burning cannot be invoked to lower the C abundance, since then a much higher N abundance would be observed.

4. AGB nucleosynthesis

The origin of the *s*-process enrichment of V453 Oph can have either an intrinsic or an extrinsic origin. In the intrinsic scenario, the *s*-process elements are produced by the star itself, and subsequently dredged-up to the surface in a 3rd dredge-up event. In an extrinsic scenario, the *s*-process enhancement is caused by mass-transfer from an enriched AGB companion that is now seen as a white dwarf. Since radial velocity measurements are lacking, we do not have strong arguments in favour of or against one of these two scenarios. However, the non-detection of a near-IR excess excludes the presence of a dusty disk, which is often seen in binary RV Tauri stars. Moreover, the intrinsic luminosity is large, pointing to a genuine post-AGB nature.

In general, two different scenarios are invoked to explain intrinsic *s*-process enrichment: in the less massive objects, the $^{13}C(\alpha,n)^{16}O$ reaction, which takes place under radiative conditions, is nowadays believed to be the major neutron source (e.g. Busso et al. 1999). For hot AGB stars, however, another *s*-process scenario is also invoked. It concerns the production of *s*-elements under convective conditions by the $^{22}Ne(\alpha,n)^{25}Mg$ neutron source. Both scenarios were explored in order to explain the *s*-enrichment of V453 Oph without a C enhancement. In the following, these scenarios are referred to as radiative and convective *s*-process models.

4.1. The radiative *s*-process model

The most favoured *s*-process model is associated with the partial mixing of protons (PMP) into the radiative C-rich layers at the time of the third dredge-up (3DUP). *S*-process calculations were performed using this PMP model for an 1.5$M_\odot$ Z=0.0001 AGB model star. The model has been evolved self-consistently up to the 49th interpulse-pulse sequence. However, no 3DUP is found to take place, so that only a mild *s*-process develops in the convective pulse through the ^{22}Ne(α,n)^{25}Mg neutron source. At the end of the 49th pulse, protons are artificially injected into the C-rich layers to simulate the PMP scenario (as described in Goriely & Mowlavi 2000). An efficient *s*-process develops in the radiative zone and after the 50th pulse, a 3DUP is assumed. The left panel of Figure 4 compares the observed abundances with the radiative *s*-process model predictions. Clearly, the abundance distribution agrees well with the observations. However, the overabundance obtained for C ([C/Fe] = +1.5) is incompatible with the observed value ([C/Fe] = −0.26).

4.2. The convective *s*-process

In the convective model, the *s*-process originates exclusively from the neutron irradiation due to the ^{22}Ne(α,n)^{25}Mg source, requiring temperatures of about 3.5 10^8K. In the 1.5$M_\odot$ Z=0.0001 model star, the maximum temperature at the bottom of the thermal pulse amounts to about 3.3 10^8K. To allow an *s*-process to develop in the pulse, the ^{22}Ne(α,n)^{25}Mg reaction rate has been increased by a factor of 10 with respect to the NACRE recommended rate. This value is well within the uncertainties still affecting this rate (Koehler 2002). With this increased rate, the full sequence of the 50 pulse-interpulse in the 1.5$M_\odot$ Z=0.0001 model star have been calculated ending with a parameterised dredge-up. The resulting elemental abundance distribution is shown in the right panel of Figure 4 and reproduces the observations satisfactorily. However, the C prediction ([C/Fe] = +1.2) is again not compatible with the observations.

The only model that does provide a compatible C abundance with observations is a 3$M_\odot$ Z=0.0001 model star. In this case, temperatures as high as 3.7 10^8K are encountered and a significant *s*-process takes place. The resulting surface enrichment obtained assuming a dredge-up at the end of the 18th computed pulse is given in Figure 4 and is again in good agreement with the observations. Even the predicted C abundance ([C/Fe] = +0.1) is in agreement with the observations. Therefore this seems the only model to be able to reproduce simultaneously the *s*-process enrichment and the low C abundance. However, a 3$M_\odot$ star model with a very low metallicity is unlikely a good match for V453 Oph from evolutionary viewpoint (see introduction).

5. Conclusion

RV Tauri stars are believed to be post-AGB stars for almost two decades now, but clear *chemical* evidences (like carbon and *s*-process enrichment) for this evolutionary status were never found. In this contribution, an abundance analysis is presented of the first RV Tauri star that does provide this evidence: V453 Oph. Since an extrinsic enrichment seems unlikely, the mild but real *s*-process overabundances prove that this object suffered a 3rd dredge-up. An even bigger surprise comes with the fact that this enrichment is *not* accompanied by an expected carbon enrichment. The N abundance shows that C is not destroyed by partial CN burning. In an attempt to explain this unique abundance pattern, it turned out that only a model of 3$M_\odot$ in which the neutrons are supplied by the ^{22}Ne source can reproduce *s*-process enrichment without significantly increasing the carbon abundance. Such a high mass is, however, not compatible with the low metallicity of V453 Oph. Therefore, our current AGB models fail to explain the abundance pattern in V453 Oph.

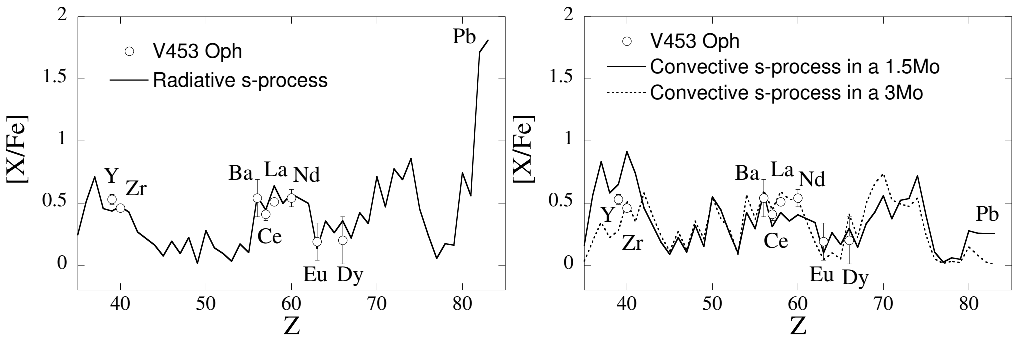

Fig. 4. Comparison of the observed relative surface abundances of V453 Oph with the radiative (*left panel*) and convective (*right panel*) *s*-process models.

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