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Letter to the Editor

Cerium: The lithium substitute in post-AGB stars*

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Abstract. In this letter we present an alternative identification for the line detected in the spectra of s-process enriched low-mass post-AGB stars around 6708 Å and which was interpreted in the literature as due to Li. Newly released line lists of lanthanide species reveal, however, the likely identification of the line to be due to a Ce II transition. We argue that this identification is consistent with the Ce abundance of all the objects discussed in the literature and conclude that in none of the low-mass s-process enriched post-AGB stars there is indication for Li-production.

Key words. atomic data – line: identification – stars: AGB and post-AGB – stars: abundances – stars: chemically peculiar

1. Introduction

Few chemical species are so important to guide our theoretical understanding of both stellar and primordial nucleosynthesis as lithium (Li). The understanding of the solar Li abundance, the cosmic Li abundance and the evolution of Li in our Galaxy is, however, complicated and at least three different production sites must be explored: (1) big-bang nucleosynthesis; (2) spallation by cosmic ray particles on interstellar matter nuclei, and (3) stellar nucleosynthesis, mainly during the AGB evolution (e.g. Travaglio et al. 2001 and references therein).

The production of Li in AGB stars is an important ingredient in the deciphering of the Galactic chemical evolution. This production site is well documented observationally by the detection of several Li-rich AGB giants both in our Galaxy (e.g. García-Lario et al. 1999) and in the Magellanic Clouds (e.g. Smith & Lambert 1989; Plez et al. 1993). Also the in situ production of Li by the Cameron-Fowler transport mechanism is rather well understood theoretically, by the process dubbed "hot-bottom burning" in which the base of the convective stellar envelope penetrates hot enough layers for nucleosynthesis to take place and which guarantees quick transport of fresh ^{7}Li to cooler layers to prevent destruction by proton capture (e.g. Sackmann & Boothroyd 1992; Lattanzio & Forestini 1999). This hot-bottom process is, however, only expected to be active in intermediate mass stars of around 4–5 $M_{\odot}$ depending on the metallicity (e.g. Travaglio et al. 2001).

The high Li abundance of low-mass post-AGB stars described recently in the literature came, therefore, as a surprise. Indeed, several objects with a low metallicity in the post-AGB phase of stellar evolution were described to be enhanced in Li to such extent that production of Li has to be invoked to explain the derived abundances. The objects are IRAS 05341+0852 (Reddy et al. 1997), IRAS 22272+5435 (Začs et al. 1995; Reddy et al. 2002), IRAS Z02229+6208 and IRAS 07430+1115 (Reddy et al. 1999), IRAS 05113+1347 (Reddy et al. 2002) and they all combine a high Li abundance with a strong overabundance of neutron capture elements and a C/O number ratio larger than one. Their effective temperature and the presence of a significant amount of circumstellar dust indicate these objects to be in a post-AGB evolutionary stage. Their low metallicity and kinematics show these objects to be of low initial mass and for these stars, the 3rd dredge-up phenomenon, although not well understood by itself, is not expected to bring freshly produced Li to the stellar photosphere.

The presence of Li in these stars was inferred from the famous Li resonance doublet at 6707.76 Å and 6707.91 Å but in all stars, the doublet is shifted redwards by about 0.2 Å compared to the expected position based on the other photospheric lines. A differential velocity of the Li line-forming region is invoked to explain this shift. An additional indication for this identification was that similar shifts were found in components of the Na D and K I alkali line profiles (e.g. Reddy et al. 2002). Those profiles are, however, complex and often disturbed by emission components (see e.g. Figs. 5 and 6 of the same paper), making the presence of such a component at the correct

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* based on observations collected at the European Southern Observatory at Paranal in Chile (66.D-0171A) and at the Roque de los Muchachos Observatory at La Palma, Spain.
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velocity not clear. Contrary to the abovementionned older papers, the two newest quantitative Li abundances were derived by spectrum synthesis modelling in the wing of the "shifted Li line" at the photospheric position (Reddy et al. 2002).

Motivated by this unexplained velocity shift in the Li line, we investigated an alternative identification of this line which was also detected in our high signal-to-noise (S/N) UVES spectra in several objects. Given the facts that the stars are strongly enriched in s-process elements and that the line spectra of (ionised) s-process elements is not well documented, we scanned the newest s-process line lists for possible identifications. Here we report on our alternative identification of the line at 6708.1 Å as due to Ce II. The paper is organised as follows: In Sect. 2 we document our newest high S/N-spectra of some post-AGB stars; the next section is devoted to the line list update of the lanthanides while Sects. 4, 5 and 6 are devoted to our spectral analysis of the Li line region. We end this paper with a discussion in Sect. 7.

2. High S/N post-AGB spectra with VLT+UVES

In the framework of our ongoing program to study the photospheric chemical composition of stars in their last stages of evolution, high resolution, high S/N spectra of a selected sample of 11 post-AGB objects were obtained with the UVES spectrograph mounted on the 8.2 m VLT-KUEYEN telescope. The observations were carried out in service mode during two periods (04–07/2000 and 01–02/2001). The resolving power of these spectra varies between ~55 000 and ~60 000. Sample spectra can be found in Fig. 1 (the two spectra on top).

The chemical diversity present in the whole post-AGB class of stellar objects (e.g. Van Winckel & Reyniers 2001) is also reflected in this new sample: only three out of the eleven objects are clearly s-process enhanced, two of which are observed for the first time at high resolution. We already completed a detailed abundance analysis for each of these objects, but these will be published elsewhere.

3. The Ce II D.R.E.A.M. line data

One of the problems in dealing with strongly s-process enriched objects is the lack of accurate atomic data of many s-process elements. Besides the more general lack of accurate oscillator strengths, even the wavelengths of the transitions of neutral and ionised s-process species are badly known. Given the fact that the optical spectrum of the strongly enriched objects like IRAS 05341+0852 is completely dominated by such transitions (Fig. 1), this limits severely the astrophysical interpretation of such data.

The main purpose of the "Database on Rare-Earths At Mons University" (D.R.E.A.M.), created recently and accessible at the address `http://www.umh.ac.be/~astro/dream.shtml`, is to provide such an update concerning the radiative properties of rare-earth atoms and ions. These properties are obtained by systematic and detailed calculations performed within the framework of a pseudo-relativistic Hartree-Fock (HFR) method (Cowan 1981) including core-polarization effects (see e.g. Quinet et al. 1999).

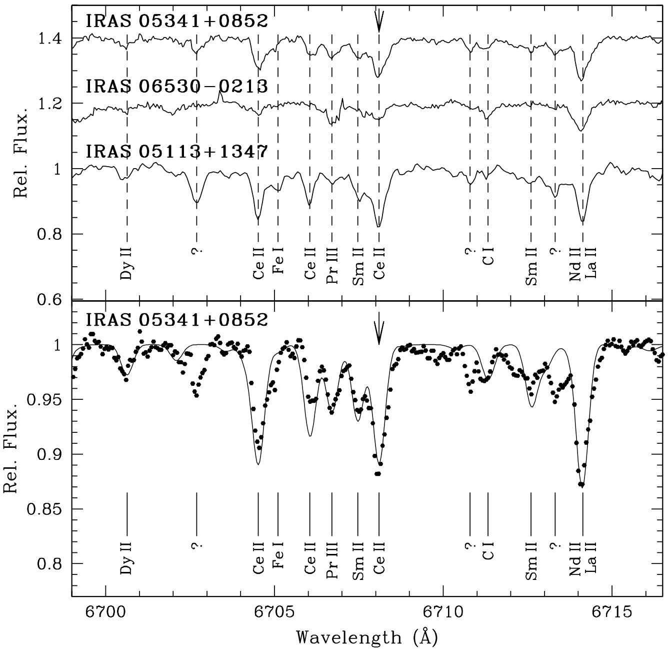

Fig. 1. *Upper panel*: Line identification of the 6708 Å region for three heavily s-process enriched objects. The Ce II 6708.099 Å line matches exactly the "shifted Li line". Note also that for some lines in these objects a definitive identification is still missing. *Lower panel*: Spectrum synthesis (full line) of the 6708 Å region for IRAS 05341+0852 (dots). For this synthesis we used the abundances found in our abundance analysis without any modification, in order to get an idea of the quality of the line list in this region. The lithium doublet was *not* included in our list.

In the particular case of doubly ionized cerium, about 15 000 lines with wavelengths based on *experimental* energy levels are listed in the database for which atomic data were obtained using the computational procedures described by Palmeri et al. (2000) and Zhang et al. (2001). This linelist extends considerably the one reported in Kurucz' database which only contains the Ce II lines observed by Meggers et al. (1975).

4. The identification of the 6708.1 Å line

As soon as the Ce II line list was released, we realized that the Ce II line at 6708.099 Å ($\chi = 0.701$ eV, log $gf = -2.12$) was an obvious candidate to identify the "shifted Li line" in the s-process enriched post-AGB stars. We decided to make a complete identification of the 6708 Å region for the s-process enriched post-AGB stars by extracting all spectral lines from the VALD database (Kupka et al. 1999) from 6695 to 6725 Å. From this list, we removed the lithium doublet. Then, we added the Pr III lines and the Ce II 6708.099 Å line from the D.R.E.A.M. database. Although the accuracy of an oscillator strength is always hard to assess, it is reasonable to consider that the f value of the 6708.099 Å transition is probably accurate within a few percent (typically 10 to 15%) in view of the moderate complexity of the electronic configurations involved in Ce II. We chose not to replace all other Ce II VALD log (gf) values by D.R.E.A.M. data in order not to compromise a comparison with previous results (see later). For two carbon lines in our list, we modified the log gf values to more recent values (Hibbert et al. 1991).

We estimated the equivalent widths for all the lines in this region using abundances determined from our new spectra. These calculations were made using R.L. Kurucz model atmospheres in combination with C. Sneden's latest version (April 2002) of his LTE line analysis program MOOG. We could identify in this way most lines in the Li-region (see Fig. 1), including the line previously identified as the "shifted Li line", indicated with an arrow.

Moreover, we synthesised the 6708 Å region for IRAS 05341+0852 (Fig. 1). The aim of this synthesis was not to derive abundances, but to test the quality of our constructed line list. It turned out that most of the lines were adequately fitted, but some lines are clearly still missing. It is striking that even relatively strong lines, such as the line at ~6702.7 Å, are not yet identified, but are very probably also of s-process origin. The region close to the 6708.1 Å line is very well fitted with the new Ce II covering the "shifted Li line".

As a final test of our lithium substitute, we calculated the Ce abundance from the 6708.099 Å line for all post-AGB stars showing the "shifted Li line", and compared it to the calculated or published Ce abundance. The equivalent widths for the different stars are obtained as follows:

- IRAS 05341+0852 and IRAS 06530−0213: measured from KUEYEN+UVES spectra. The abundance analyses of these objects will be published elsewhere.
- IRAS 05113+1347 and IRAS 22272+5435: measured from Fig. 7 in Reddy et al. (2002).
- IRAS Z02229+6208 and IRAS 07430+1115: taken from Table 10 in Reddy et al. (1999).

For IRAS 05113+1347 we have also an own WHT+UES spectrum (see Fig. 1) from which we obtained W_λ(6708.1Å) = 81 mÅ. However, we chose to use the Reddy et al. W_λ to be consistent with their abundance analysis and model for this star. For IRAS 22272+5435, Začs et al. (1995) mention W_λ(6708.1Å) = 106 mÅ.

From the comparison summarized in Table 1, we can conclude that there is a good to excellent agreement between the Ce abundance calculated from the 6708.099 Å line and the calculated or published Ce abundance. Only for the stars IRAS Z02229+6208 and IRAS 07430+1115 the difference in abundance is larger (but still <0.7 dex). However, the Ce abundance for these stars is based on only four lines and therefore it should be reanalysed. It is clear, though, that also for these stars the identification of the 6708.1 Å line as a "shifted Li line" is much less probable than as a Ce II line. Moreover, it is unlikely that the same velocity shift should prevail for circumstellar Li or Li in photospheric downdrafts (e.g. Reddy et al. 2002) in all post-AGB objects.

5. Lithium upper limits

As seen in Fig. 1, the new Ce line matches the "shifted Li line" very well. Reddy et al. (2002) computed a spectrum synthesis of this region and derived the Li abundance from an indication of extra absorption at the photospheric wavelength, without modelling the "shifted Li line" itself (see Fig. 7 of their paper). Other Li abundances covered in the discussion and Table 8 of the same paper were derived from the shifted line equivalent width.

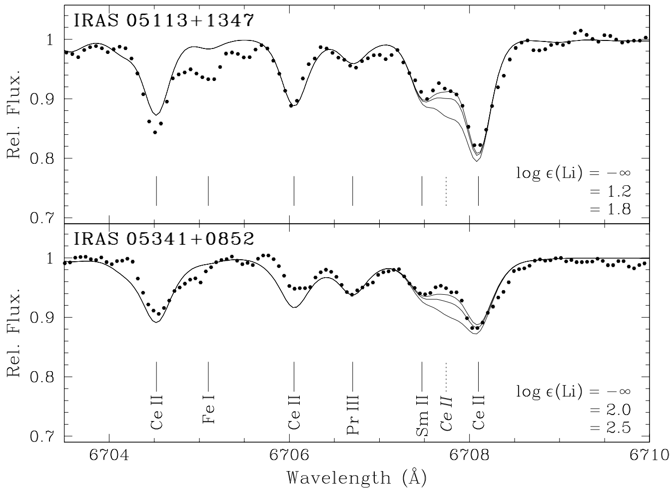

Fig. 2. Fine synthesis of the 6708 Å region. Observed spectra (dots) are compared with spectrum syntheses (solid lines) with three different Li abundances: (1) no lithium, (2) our upper limit and (3) the Li abundance reported in literature. The hypothetical Ce II line at 6707.74 Å from Lambert et al. (1993) was also included in the line list and marked in the figure in italic.

To test this result, we derived upper limits for the lithium abundance in the three stars from Table 1 of which we have spectra, one of which was discussed and shown in Fig. 7 of Reddy et al. (2002). For this purpose, we used the same atomic and molecular line list as Reddy et al. (2002) including the s-process line at 6707.74 Å introduced by Lambert et al. (1993) who assumed it to be a Ce II transition. Sample syntheses and upper limits are given in Fig. 2. If the suspected s-process lines at 6707.74 Å is excluded, the upper limits shift up by ~0.5 dex for the cooler IRAS 05113+1347 and ~0.2 dex for IRAS 05341+0852. The upper limit for IRAS 06530-0213 (not shown) was log ϵ(Li) < 2.9. It is clear that no detection of a contribution due to Li could be made when taken all lines of this complex region into account.

6. Conclusion

The line at 6708.1 Å which is seen in some heavily s-process enriched post-AGB objects was identified in the literature as due to Li, despite the redward shift of about 0.2 Å compared to other photospheric lines. The line was assumed to be formed in infalling circumstellar gas or photospheric downdrafts to explain the shift. Using the recent atomic data on lanthanides released in the D.R.E.A.M. project, we can safely identify this line as not being due to Li but coming from a Ce II line transition at 6708.099 Å. Indeed, the Ce abundance derived from this single line is comparable to the Ce abundance derived from other Ce II lines in the spectra. Moreover no inclusion of a significant amount of lithium at photospheric wavelength

Table 1. Comparison between the Ce abundance calculated from the 6708.099 Å line and the calculated or published Ce abundance for the post-AGB stars showing the "lithium-shift". Most stars show a good to excellent agreement between the two abundances, implying a safe identification of the 6708.1 Å line as being due to Ce II.

Object	Ce II 6708 equivalent width (mÅ)	Ce abund. from 6708 line (log ϵ)	calculated or published Ce abundance log ϵ (n, σ)	adopted model $T_{\rm eff}$, log g, ξ_t, [M/H] (K, cm s^{-2}, km s^{-1})	ref.
IRAS 05341+0852	53.5	3.40	3.35 (23, 0.15)	6500, 1.0, 3.5, −1.0	1
IRAS 06530−0213	21.5	3.54	3.34 (18, 0.14)	7250, 1.0, 5.0, −0.5	1
IRAS 05113+1347	106.	2.83	2.84 (12, 0.20)	5250, 0.25,4.5, −0.5	2
IRAS 22272+5435	85.	2.99	2.76 (6, 0.14)	5750, 0.5, 4.5, −1.0	2
IRAS Z02229+6208	65.	2.75	2.09 (4, 0.04)	5500, 0.5, 4.25,−0.5	3
IRAS 07430+1115	40.	2.90	2.45 (4, 0.12)	6000, 1.0, 3.5, −0.5	3

References for columns 2, 4 and 5: (1) this letter, (2) Reddy et al. (2002), (3) Reddy et al. (1999).

was needed in a synthesis of three objects, among which the most s-process enriched object known. We claim that in none of the post-AGB objects there is evidence for in situ Li production and conclude that there is no need to invoke special non-standard mixing during the AGB evolution to explain the claimed high abundances of this fragile element in these stars. Note that this new line identification is no alternative for (super) Li rich lower luminosity objects.

This result dramatically illustrates the importance of reliable and complete line lists when doing analyses of these strongly s-process enriched objects, the spectra of which are dominated by lines coming from s-process elements.

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