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The *s*-process in Post-AGB Stars

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Abstract. In this contribution an overview is given of recent accurate chemical abundance studies in post-AGB stars. The intrinsic nature of the enrichement and the spread in metallicity together with the absence of strong molecular veiling make post-AGB stars very useful to constrain AGB (chemical) evolutionary models. S-process enrichment is, however, not a general characteristic of post-AGB stars and a photospheric chemical study is not always a good tracer for the evolved status of an object.

1. Introduction

In 2002 we celebrate the 50th anniversary of the detection of technetium in spectra of R Andromedae and some other S-type stars by Paul Willard Merrill (1952). Since Tc has no stable isotope this detection proved that low-mass stars are capable of producing elements beyond the Fe stability peak. In stellar interiors, the neutron nucleosynthesis is expected to be "slow" (*s*-process) compared to the β-decay so the heavy element nucleosynthesis follows the valley of stability. There is now general agreement that the main neutron production comes from the $^{13}C(\alpha,n)^{16}O$ reaction with a minor activation during a thermal pulse of the $^{22}Ne(\alpha,n),^{25}Mg$ neutron source. Although progress has been enormous, the details on the neutron nucleosynthesis in the AGB stellar interior with the subsequent 3rd dredge-up are not all been solved (see Herwig and Lattanzio these proceedings). The main problem remains a detailed physical understanding of the boundary layers between convective and radiative regions affecting both the nucleosynthesis in the intershell as well as the dredge-up to the photosphere.

Quantitative surface abundance determinations of evolved stars offer a powerful tool to constrain (chemical) evolutionary calculations of AGB stars. The *s*-process stability peaks around close neutron shells with 50 respectively 82 neutrons make a natural distinction between light *s*-process elements (ls) around Sr and heavy *s*-process elements around Ba (hs). The [hs/ls] abundance ratio is often used as characterisation parameter for the integrated neutron irradiation but since more and more detailed models and observations become available, the wide range in overabundances and their distribution can be modelled in detail (e.g. Goriely & Mowlavi 2000). Using a range of ad-hoc ^{13}C abundances in the inter shell combined with the nucleosynthetic network and evolutionary code, Busso et al. (2001) explores the parameter space to explain the observed abundances in a wide range of objects.

Intrinsic objects are defined as stars for which the chemical enrichment took place in the star itself, while the extrinsic objects are binaries with a white dwarf companion. Their enrichment comes from material accreted during a previous evolutionary phase when the companion was a mass-losing enriched AGB star.

For AGB stars, these chemical studies are difficult due to the molecular veiling and the often unstable photospheres. Objects along the M-MS-S-SC-C spectral AGB sequence, determined by an gradual increase in the C/O numberratio, were shown to display also a general trend of increasing *s*-process overabundances (e.g. M stars: Smith & Lambert 1990; SC stars : Abia & Wallerstein 1998; C stars Utsumi 1985). Recently, however, a few observational studies were published which illustrates that this simple picture is an oversimplification: For C-stars it has been realised that the large overabundances found by Utsumi (1985) are overestimates due to blending problems in the intermediate resolution spectra. N-type carbon stars show only a moderate *s*-process enhancement and a surprisingly low $^{12}C/^{13}C$-ratio (Abia et al. 2001). In the same paper, also the overabundances found is SC stars published by the authors in 1998 are found to be too large. Finally, the J-type carbon stars do not only show a very low $^{12}C/^{13}C$ ratio and often a high Li abundances but also a lack of *s*-process overabundances (e.g. Abia & Isern 2000). The limited number of objects studied so far and the extremely strong veiling make both the detection of *s*-process lines and the model atmosphere structure modelling difficult. The errors on the abundances of carbon star and certainly on the isotopic ratios remain high (see Abia et al. 2001 and references therein).

PN central stars and their circumstellar matter, on the other hand, allow only the detection of a limited number of chemical elements. S-process nucleosynthetic products are trace elements but some *s*-process lines were recently identified in near-IR spectra of PNe (Dinerstein 2001).

For the extrinsic objects (Ba giants, sub-giants and dwarfs, metal deficient CH stars, yellow symbiotics etc.) the chemical analysis is easier but the characteristics of the original enriched AGB star is difficult to determine. Moreover, it is not clear to what extend we can use single-star modelling to binary objects. I refer to Busso et al. (1995) and and references therein for *s*-process characteristics of the Ba-stargroup. Finally, another important contribution to our understanding of stellar nucleosynthesis comes from the detailed analysis of pre-solar grains. These offer a unique and very detailed probe to determine isotopic ratios but of course the production site is more difficult to retrace (e.g. Herwig these proceedings; Zinner & Amari 1999).

The rare post-AGB stars form ideal complementary tracers for the AGB nucleosynthetic and dredge-up processes since their F-G spectral type allow accurate abundance determinations of a very wide range of elements based on atomic lines. Figure 1 displays a UVES spectrum of a strongly enriched object to illustrate the quality of atomic line spectra that are available now. Moreover, post-AGB stars show a large spread in intrinsic metallicity which makes the study of the suspected metallicity effect on the AGB nucleosynthesis possible. Contrary to AGB stars, their chemical compositions reflect the end-products of the AGB evolution. The *s*-process abundance distribution are probably the asymptotic values.

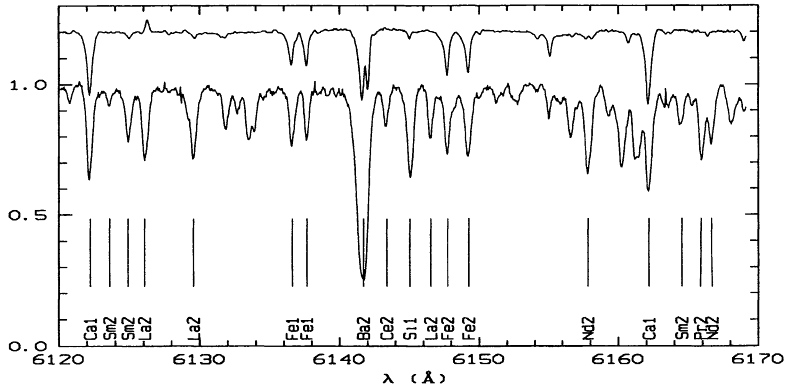

Figure 1. A comparison between a small part of a UVES high resolution spectrum of a strongly enriched post-AGB object IRAS05341+0852 (lower spectrum, m(v) = 13.) and a non-enriched objects of similar temperature and metallicity (HD 112374). The spectrum of IRAS05341+0852 is dominated by atomic line transitions of *s*-process elements. The lack of strong molecular veiling in most post-AGB objects, make that accurate abundances can be obtained on the basis of high signal-to-noise and high-resolution spectra for a wide range of chemical elements.

In this contribution I review the remarkably diverse detailed chemical patterns observed in intrinsic post-AGB stars and focus on the abundances of *s*-process elements. For a general review on the *s*-process in stars I refer to Busso, Gallino & Wasserburg (1999) and references therein. It turned out that among the post-AGB stars, a subsample belongs to the most enriched objects known. On the other hand, very similar objects exist with no trace of chemical enrichment at all. In what follows I limit the discussion to objects where no direct or indirect evidence for a binary companion has been reported. For binary post-AGB stars with a large range in orbital separation, there is growing evidence that the (chemical) evolution can only be explained by binary interaction but this will not be addressed here (e.g. Van Winckel & Reyniers 2001).

2. 21 μm stars

The first detections of *s*-process enriched post-AGB stars (Klochkova 1995, Začs Van Winckel et al., 1995) were soon followed by more detailed studies (e.g. Decin et al. 1998; Reddy et al. 1997, 1999, 2002; Van Winckel & Reyniers 2000). It was realised that enriched objects also showed special spectral features in their circumstellar spectra: a strong solid state feature at 21 μm was associated with carbon rich material since in most objects also PAH's were detected (see Volk these proceedings and references therein). The photospheric chemical studies of these objects confirmed the carbon enrichement. 21 μm stars are therefore post carbon stars.

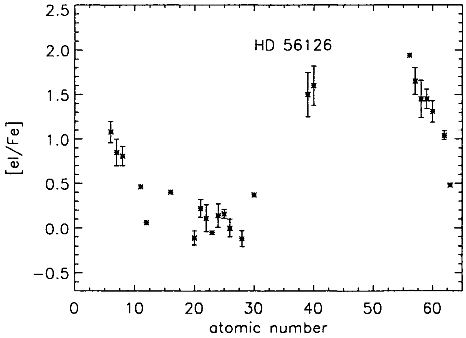

Figure 2. The chemical composition of HD 56126 obtained from atomic lines by Van Winckel & Reyniers (2000). The metallicity of the object is [Fe/H] = −1.0. Note the wide range of elements and the large overabundances of CNO and both the light and heavy s-process elements.

A good prototypical example of a carbon-rich post-AGB star is HD 56126 (Van Winckel & Reyniers 2000). In Figure 2 we see that the metal deficient star ([Fe/H]=−1.0) with a large radial velocity (+85 km s^{-1}) is indeed strongly enriched in s-process elements. C, N and O were found to be overabundant with [C/Fe] = +1.1; [N/Fe] = +0.9 and [O/Fe] = +0.8 respectively indicating a C/O ratio of close to 1. The C/O ratio is, however, not very well constrained using absolute chemical abundances based on atomic lines. With an average [s/Fe] = 1.5, HD 56126 belongs to the most s-process enriched objects known but the s-process efficiency is rather low ([hs/ls]=−0.1). The distribution was modelled by Busso et al. (2001) using a parameterised ^{13}C pocket which is rather small.

Isotopic ratios are more difficult to determine in these hotter central stars but circumstellar molecules of C_2 and CN were detected in many of them (Bakker et al. 1997). In a subsequent paper (Bakker & Lambert 1998) an analysis of ^{13}C baring molecules was presented and an isotopic ratio of $^{12}C/^{13}C = 72 \pm 26$ was found for HD 56126. For other objects only lower limits on the $^{12}C/^{13}C$ were proposed and they cluster around ≥ 25 (see Reddy et al. 2002 and references therein).

Since it is often difficult to compare quantitatively chemical composition results of different authors using different instrumentation and certainly oscillator strengths, Van Winckel & Reyniers (2000) made a homogeneous study of six 21 μm stars. From this study it is clear that the theoretically often expected increase in neutron irradiation by decreasing metallicity is present but the spread is large and certainly intrinsic. For the same metallicity there is a lower [hs/ls] index in the post-AGB stars than there is for Ba stars. The overabundance [s/Fe] is, however, very well correlated with the [hs/ls] index (see Figure 7 in that paper).

The comparison with intrinsic AGB carbon stars is not straightforward since the objects studied recently in detail (Abia et al 2001) are mainly solar metal-

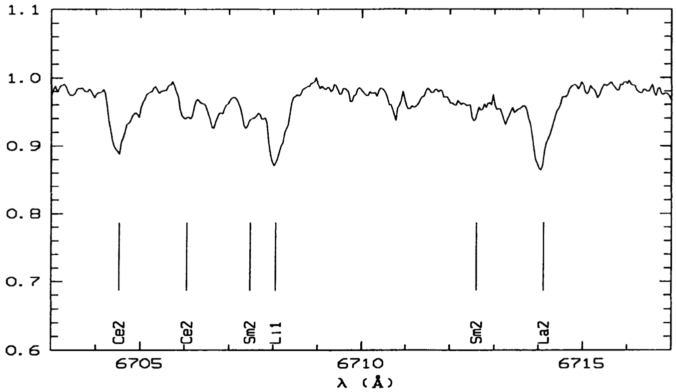

Figure 3. A Uves spectrum of high S/N confirming the detection of Li in iIRAS 05341+0852 by Reddy et al. (1997).

licity objects. These show, however, a significantly lower *s*-process enrichment. The difficulty in obtaining accurate abundances from cool C-stars is illustrated by the fact that for the same low metallicity object (V CrB) Kipper (1998) found a [ls/Fe] of $\sim$ 1.5 but Abia et al. (2001) propose [ls/Fe] of only 0.3.

For the lowest metallicities (or highest neutron irradiation) a leakage from the hs peak to the lead peak is expected (e.g. Goriely & Mowlavi, 2000; Busso et al., 2001) and recently also observed (Van Eck et al., 2001) in low metallicity extrinsic objects. The metallicity spread of the intrinsic post-AGB stars does not extend to low enough metallicities to expect high Pb abundances.

2.1. Li enrichment

In five 21 μm stars evidence is found for the presence of weak Li-lines (e.g. Reddy et al., 2002 and references therein). In some objects there is a not well understood small velocity shift in the Li line but no other identification is probable. Some detections are clearly confirmed by better spectra (Figure 3). With the observed line strengths Li abundances were found in the 2.1–2.6 dex range, indicating a nucleosynthetic production in the object itself. Li enrichment is found in massive AGB stars (Plez et al., 1993) and is well explained by the process called hot-bottom-burning in which the base of the convective envelope penetrates hot enough regions for the CNO hydrogen burning to take place (e.g. Lattanzio these proceedings). For low-mass objects like the metal poor post-AGB stars, the Li production cite is less clear.

In these post-AGB stars Li enrichment is accompanied by an on average high ^{12}C/^{13}C ratio (Reddy et al., 2002) contrary to the Li rich J-type C-stars which show a strong ^{13}C enhancement and ^{12}C/^{13}C ratios in the order of 3-5 (Abia et al., 2001). Moreover, J-type carbon stars are *not* enhanced in *s*-process elements where the 21 μm stars belong to the most *s*-process enriched objects known. It is fair to say that the Li enrichment is not very well understood and not expected in the standard AGB model calculations.

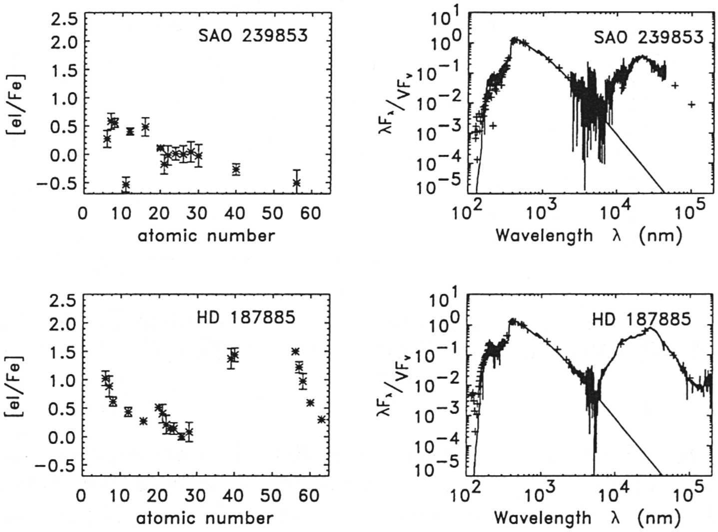

Figure 4. The SED and chemical composition of two objects metal poor ([Fe/H] = −0.7) objects HD 187885 and SAO 239853. Although the SED is very similar, the chemical composition is very different: while HD 187885 is strongly enriched in C and *s*-process elements, SAO 239853 is not at all enriched, nor in C neither in *s*-process elements.

3. 3rd dredge-up

All the 21μm stars analysed till now show a strong signature of *s*-process enrichment accompanied by a high C/O ratio. These objects form, however, only a small part of the sample of field post-AGB stars. Other objects with a double peaked energy distribution (see Figure 4) were analysed but no trace of a chemical enrichment was found.

In Figure 4, I show the spectral energy distribution (SED) of two objects with similar temperature, kinematics, surface gravity and metallicity ([Fe/H] = − 0.8). The SED of both objects show a similar dust excess both in strength and in dust-temperature. Their chemical composition is, however, drastically different. While HD 187885 displays one of the strongest *s*-process excesses known, there is no trace at all of *s*-process enhancement in SAO 239853.

This is further illustrated in Figure 5. There is no overlap between the strongly enhance 21 μm stars and the non-enhanced objects, while both groups cover the same spread in metallicity. Since in the canonical picture the envelope of a star is gradually enriched during the AGB evolution by a series of thermal pulses and dredge-ups, this plot is surprising. Clearly a larger sample of post-

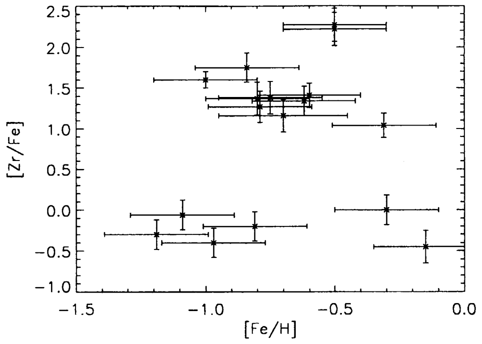

Figure 5. The Zr overabundance in function of metallicity of a series of post-AGB objects. There is a clear distinction between the heavily enriched 21 μm stars and the non-enriched objects. The same spread in metallicity is observed in both classes.

AGB stars should be analysed to confirm the picture but intermediately enriched objects are yet to be discovered: either a post-AGB star shows very strong enrichment, or it is not at all enriched.

4. Discussion

Some post-AGB stars are indeed among the most s-process enriched objects known. Their spectral type offer a very useful possibility to probe the characteristics of the s-process and dredge-up phenomena of intrinsic AGB stars. Moreover, the enriched s-process stars are all post-carbon stars ($C/O > 1$) and thanks to accurate abundances of a wide range of chemical elements, are ideal objects to constrain AGB nucleosynthetic models. The isotopic ratios are difficult to constrain in post-AGB objects but thanks to circumstellar optical absorption bands of electronic transitions of C_2 and CN, the $^{12}C/^{13}C$ ratio can be estimated. HD 56126 is the best studied example and the ratio is estimated to be 72 ± 26. For other objects only lower limits could be deduced of about > 25. A remarkable high Li abundance was found in a few objects which is not expected for low-mass stars. All s-process enriched objects are confirmed or suspected 21 μm stars.

Other post-AGB stars exist with very similar characteristics in SED and metallicity range that are not at all enriched. Intermediately enriched post-AGB stars are yet to be discovered. To know whether this reflects a true distribution or is due to a bias in the selection criteria remains to be studied. Since the very fast post-AGB evolutionary phase make post-AGB stars rather rare, it is tempting but difficult to place results on individual objects in the big picture of stellar (chemical) evolution.

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