Probing S-Process Yields of Field Carbon Stars by the Analysis of 21µm Post-AGB Stars

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Abstract: The observational data guiding the theoretical chemical evolutionary models of AGB stars come mainly from the analysis of intrinsic and extrinsic s-process enriched objects. The first are the stars of the M-MS-S-SC-C star sequence which is thought to reflect, at least partly, the evolution on the AGB of a single star towards an increasing C/O ratio. The second are all binaries with excess abundances acquired by mass-transfer from the companion which is now a white dwarf.

In this contribution we present a homogeneous abundance analysis of 21µm objects, which are carbon-rich probably single post-AGB stars. With their F to G spectral types a wide variety of chemical species can be studied quantitatively by using photospheric atomic lines. These objects are among the most s-process enriched objects known so far. We focus on the s-process distribution and the related neutron irradiation and compare the results with the enrichments observed in both intrinsic and extrinsic objects.

1 Introduction

A subgroup of field post-AGB stars shows in their mid-infrared spectra a 21µm emission feature. This feature is not found in AGB stars, nor in PNe, suggesting that the excitation and/or formation of its carrier is limited to the dust enveloppes of the transition objects. Although the nature of the 21µm feature is not known, a good correlation exists between the presence of circumstellar carbon molecules like \(\text{C}_2\) and \(\text{C}_3\) in the optical spectra and the presence of the IR feature.

Several studies were dedicated to reveal the chemical photospheric composition of the 21µm stars, confirming their post-3rd dredge-up character (large C/O ratios and s-process enhancements). Together with their carbon-rich dust enveloppes, spectral types and high luminosities, the 21µm stars are good candidate post-carbon stars. Since different authors use different line lists and atomic data, results are difficult to compare quantitatively. Therefore, a homogeneous (same method and line list) abundance analysis is presented in this contribution.

\(^{*}\)based on observations collected at the European Southern Observatory in Chile (61.E-0426), and at Roque de los Muchachos at La Palma, Spain

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Figure 1: Sample spectra of the programme stars and HR 1865 around the red carbon multiplet. The stars are velocity corrected. On top, the spectrum of the reference star HR 1865 is plotted. This massive supergiant (F10) has similar atmospheric parameters as the programme stars (Decin et al. 1998) but obviously no enrichment of helium burning products.

Figure 2: The region around \( \lambda 679 \) nm for the six programme stars and HR 1865. In this region, both lines of light (ls) and heavy (hs) s-process elements are present. Comparison with the normal supergiant HR 1865 proves that our stars are clearly s-process enhanced. The ratio of the line strength of the LaII-line at \( \lambda 667.427 \) nm and the YII-line at \( \lambda 679.541 \) nm for each star gives a very qualitative idea of the neutron exposure. From this spectral comparison we can expect a high neutron exposure for IRAS 05341+0852.
Table 1: Model parameters and metallicity of the six programme stars

|                | $T_{\text{eff}}$ (K) | $\log g$  | $\xi_t$ (km s$^{-1}$) | [Fe/H] |
|----------------|----------------------|-----------|------------------------|--------|
| IRAS 04296+3429 | 7000                 | 1.0       | 4.0                    | −0.6   |
| IRAS 05341+0852 | 6500                 | 1.0       | 3.5                    | −0.8   |
| IRAS 07134+1005 | 7250                 | 0.5       | 5.0                    | −1.0   |
| IRAS 19500−1709 | 8000                 | 1.0       | 6.0                    | −0.6   |
| IRAS 22223+4327 | 6500                 | 1.0       | 5.5                    | −0.3   |
| IRAS 23304+6147 | 6750                 | 0.5       | 3.0                    | −0.8   |

2 Observations and Analysis

Spectra were obtained using the Utrecht Echelle Spectrograph (UES) mounted on the 4.2m William Herschell Telescope (WHT) during several runs between 1992 and 1995. For one object (IRAS 07134), the NTT was used in combination of the EMMI spectrograph. For most spectra, we obtained a resolution of $\sim 50,000$ and a S/N $> 100$ (see Fig. 1 and 2 for sample spectra). Model atmospheric parameters (Table 1) were derived by the commonly used spectroscopic method: the effective temperature $T_{\text{eff}}$ from the excitation balance of the FeI-lines, the surface gravity $\log (g)$ from ionisation balance between FeI and FeII and the microturbulence $\xi_t$ by forcing the Fe abundance to be independent of the reduced equivalent width $W_\lambda/\lambda$ of the FeI lines. Abundances were obtained with the Kurucz model atmospheres. Special attention was paid to accurate $\log (g_f)$ values, using the most recent compilations. Only weak lines with equivalent widths smaller than 150 mÅ were used in the analysis.

3 Results

The results of our analysis are presented in Fig. 3. The metallicity relative to the solar value ranges from $-0.3$ to $-1.0$ (Table 1), indicating that our sample indeed consists of an old and hence low-mass population. From Fig. 3 it is clear that all stars display a huge photospheric carbon enhancement. This is illustrated in Fig. 4. Oxygen is also enhanced, but, especially for the cooler stars, an accurate oxygen abundance is hampered by the small number of lines. Accurate C/O ratios are therefore hard to obtain, but are found in between 1.0 and 2.9. The slight overabundances of the $\alpha$-elements are considered to be normal for this metallicity range. The most convincing argument for the post-3rd dredge-up character of the studied stars is the huge enhancement in s-process elements. This is illustrated in Fig. 4. The 21 $\mu$m stars turn out to be among the most s-process enriched objects known so far.

4 Discussion

4.1 Neutron Exposure

We defined for each star the [hs/ls] index as the ratio of heavy (Ba, La, Nd, Sm) to light (Y, Zr) s-process elements. The abundances of unobserved species were estimated using the tables of Malaney (1987). The [hs/ls] index is a good indicator for the mean neutron exposure $\tau_0$, whereas [s/Fe] is a measure for the total s-process enrichment.
Figure 3: The abundances of our six programme stars relative to iron [\text{[el/Fe]}].
In Fig. 4 (left panel) a strong correlation is found between the $[\text{hs}/\text{ls}]$ index and the total enrichment of the s-process elements as parameterised by the $[\text{s}/\text{Fe}]$-index, in the sense that more enriched objects also display a higher integrated neutron irradiation. Since in carbon stars the asymptotic values of the s-process distribution is probably reached (Busso et al. 1995), this means that the dredge-up efficiency is strongly linked with the neutron production in the intershell!

On the right panel of Fig. 4 the $[\text{hs}/\text{ls}]$ index is shown as a function of metallicity. The expected trend (increasing $[\text{hs}/\text{ls}]$ with decreasing metallicity because of the larger amount of neutrons per seed nucleus) shows a large intrinsic scatter and suggests that other fundamental parameters strongly determine the internal nucleosynthesis and dredge-up phenomena. The 21$\mu$m stars are the only intrinsically enriched objects showing a large spread in metallicity.

### 4.2 Comparison with Other Enriched Stars

To compare the results on the 21$\mu$m objects with other stars, we recalculated all published $[\text{hs}/\text{ls}]$ indices so that all indices are calculated using the same species (Y, Zr, Ba, La, Nd, Sm). The s-process enhancement of the 21$\mu$m stars is compared with other intrinsic objects in Fig. 5. This enhancement turns out to be larger than in MS, intrinsic S and SC AGB stars and comparable with the enhancement in C stars. This result confirms the interpretation of the 21$\mu$m stars as post-carbon stars and strengthens the correlation between the C/O ratio (M-MS-S-SC-C sequence) and s-process enhancement.

A comparison with extrinsic (+intrinsic SC) objects (Fig. 6) shows that the neutron exposure of the 21$\mu$m stars fall roughly in the same range as the CH subgiants and is on average lower than in Ba-giants with the same metallicity. The theoretically expected trend of increasing $[\text{hs}/\text{ls}]$ index with decreasing metallicity shows a very large intrinsic spread. Note that the weakly enriched metal deficient Ba-stars show very small $[\text{hs}/\text{ls}]$ indices.

### 5 Conclusions

A complete abundance analysis has been carried out on the spectra of six 21$\mu$m sources. We confirmed their post-carbon character as they show high C/O ratios and huge carbon and
s-process enhancements. We further focussed on the s-process abundance distribution and found a very strong correlation between the [hs/ls] index (which is a measure for the neutron nucleosynthesis efficiency) and the total enrichment of the s-process elements (which is mainly determined by the dredge-up efficiency). The anti-correlation of the [hs/ls] index with the metallicity of the 21μm objects is less well determined and contains a large scatter. This scatter is certainly intrinsic and confirms that also other fundamental parameters strongly determine the internal nucleosynthesis and dredge-up phenomena during the AGB evolution.

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