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First chemical analysis of extragalactic carbon stars

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Abstract. We have performed the chemical analysis of extragalactic carbon stars from VLT/UVES spectra. The derived individual abundances of metals and *s*-elements as well as the well known distance of the selected stars in the Small Magellanic Cloud and the Sagittarius dwarf galaxy permit us to test current models of stellar evolution and nucleosynthesis during the asymptotic giant branch phase in low metallicity environments.

Key words. AGB stars – carbon stars – nucleosynthesis – dwarf galaxies

1. Introduction

The satellite galaxies of the Milky Way are of special interest because they might be the unused basic building blocks of our own Galaxy according to the hierarchical galaxy formation scenarios (e.g. Bullock et al. 2001), or, alternatively, what should have been larger systems whose structure and evolution was modified by their proximity to our Galaxy (e.g. Grebel et al. 2003). Deep photometric studies over wide fields for the dwarf spheroidal (dSph) satellite galaxies reveal that they have very old stellar populations ($\sim$ 10 Gyr, e.g. Mateo 1998) although the detection of asymptotic giant branch (AGB) stars in some of them would indicate the existence of intermediate age populations and, therefore, that their star formation histories extended until some few Gyr ago. Indeed the inventory and chemical study of AGB stars in these external stellar systems provide clues for the comprehension of their star formation history and chemical evolution.

Carbon stars are a particular type of star which can be created either by the operation of third dredge-up (TDU) during the thermally pulsing (TP) AGB phase or by the accretion of carbon-rich material in a binary system when the present-day white dwarf was on the AGB. The former type are usually named *intrinsic* carbon stars and to this type belong the cool and luminous N-type stars, while the second type are named *extrinsic* carbon stars with the CH-type and the dwarf carbon stars being their prototype. There are other types of carbon stars, however, their origin is stil not well understood (Abia et al. 2003).

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Carbon stars are probably one of the main sources of *s*-elements in the galaxies as well as ^{7}Li, ^{12}C, ^{14}N and other rare isotopes such as ^{25,26}Mg, ^{26}Al (e.g. Wallerstein et al. 1997). One of the most important discoveries in the recent years concerning the *s*-process nucleosynthesis is its dependence on the initial metallicity of the star as well as on the neutron source which is actually operating (Busso et al. 1999). Depending whether ^{13}C or ^{22}Ne is the main neutron source the final *s*-element abundance pattern will be different. Because of their different chemical evolution histories dwarf spheroidal galaxies contain stars covering a wide range in metallicity ($-3.0 \leq$ [Fe/H] ≤ 0.0; Groenewegen 2004). This figure is also true for stars belonging to the same stellar system (e.g. Shetrone et al. 1998). This makes the AGB stars in satellite dSphs unique objects with which to test the current theories of stellar evolution and nucleosynthesis in the AGB phase. Moreover, the fact that the distance to these satellite galaxies is well known allows an accurate estimation of the stellar luminosity and mass, issues which are rather complicated and uncertain in galactic AGB stars.

Here we present a preliminary but detailed chemical analysis of the carbon star B30 of the Small Magellanic Cloud and of the stars named C1 and C3 of the Sagittarius dwarf spheroidal galaxy. These stars form part of a more extended study of the AGB star population in the satellite galaxies Draco, Ursa Minor, Carina and Sculptor. The abundance results are compared with theoretical nucleosynthesis predictions in low mass metal-poor AGB stars.

2. The extragalactic carbon stars

The stars B30, C1 and C3 were confirmed to be carbon-rich objects by Rebeirot et al. (1993) and Azzopardi et al. (1985), respectively, through low resolution spectra centered on strong CN and C_2 molecular bands. However, their particular carbon star spectral type is unknown. The analysis of extragalactic carbon stars is still more complicated than their galactic counterparts because for most of them there is little or no photometric information. In this situation, the estimation of their fundamental atmosphere parameters ($T_{\rm eff}$, log g and [Fe/H]) using calibrations from colour indexes is not possible. For the stars analyzed here nevertheless, there is available VJKH photometry (Aaronson & Mould 1985) from which it is possible to obtain an estimate of their luminosity and $T_{\rm eff}$ using the calibrations by Alksnis et al. (1998) and Ridgway et al. (1980). Note that these calibrations are obtained for near solar metallicity carbon stars belonging to our Galaxy, thus, it is not clear if they can be safely used for metal-poor stars such as those in the present sample.

Table 1 shows the main characteristics derived for the stars in this study. We assume a distance of 63 and 24 kpc to the SMC and Sagittarius dSph, respectively, with a reddening of $E(B - V) = 0.08$ and 0.14 (Cioni et al. 2000; Ibata et al. 1995). The C/O and ^{12}C/^{13}C ratios have been derived from spectral synthesis fits to the 7990-8050 Å spectral region. We give a range in the C/O ratio because our estimate is different depending on the spectral region studied. This probably means that our model atmospheres cannot reproduce well the atmosphere of these stars and/or that our molecular and atomic line list in the spectral regions studied are still not complete. Models atmospheres for metal-poor cool carbon-rich stars from the Uppsala's Group and Y. Pavlenko (private communication) are used. The mean metallicity of the stars were derived also from synthetic fits to several metallic lines (Ti, V and Fe, mainly) placed in different regions of the spectra as well as the *s*-elements abundances (see Abia et al. 2002 for details). The metallicity derived in our stars agree with the average metallicity estimated in these satellite galaxies. Note, that recent spectroscopic derivations of the metallicity in several RGB stars show that an unique metallicity for these stellar systems can no longer be assigned. These studies reveal a large metallicity dispersion among the stars in these stellar systems. For instance, in Sagittarius dSph, stars in the range $-1.5 \leq$[Fe/H]≤ 0.0 are found (Smecker-Hane et al. 1998; Bonifacio et al. 2000). This clearly shows that dwarf satellite galaxies have had a star formation history much more complicated than previously

Table 1. Main characteristics (preliminary) of the carbon stars studied

Satellite galaxy	Star	M_{bol}	T_{eff} (K)	[Fe/H]	C/O	$^{12}C/^{13}C$
SMC	B30	−5.5	3100	−1.1	1.10-1.20	> 200
Sag. dSph	C1	−3.1	3750	−0.8	1.05-1.10	45
	C3	−4.9	3500	−0.3	1.02-1.05	30

thought and in consequence, a corresponding chemical evolution. The formal error in the abundances due to uncertainties in the model atmosphere parameters and the location of the spectral continuum, when added quadratically, range between ±0.3 − 0.4 dex.

3. Results

Our chemical analysis reveals that all the three stars have *s*-elements enhancement at similar levels: B30 has [ls/Fe]= +0.80 and [hs/Fe]= +1.30, C1 has [ls/Fe]= +0.80 and [hs/Fe]= +1.65 and C3 has [ls/Fe]= +1.25 and [hs/Fe]= +1.15, respectively. We follow the same criteria as in Abia et al. (2002) defining ls as the average abundance between the low-mass *s*-elements (Y, Zr, Sr) and hs for the high-mass elements (Ba, La, Nd, Sm). Note that in these stars we have also been able to derive abundances of other interesting species such as Li, Zn, Rb, Nb, Ru, Hf or W. A detailed discussion of the chemical composition of these stars will be published elsewhere.

On the basis of their luminosity (see Table 1) B30 and C3 are probably intrinsic carbon stars, while C1 (less luminous) would be extrinsic. However, one should have in mind that a low metallicity AGB star can become a carbon star with a few number of TPs and TDU episodes (even only one, e.g. Straniero et al. 2003), in consequence, the star may become carbon-rich in a less advanced stage on the AGB phase, at lower luminosity. Of course, the detection of Tc in these stars would give the answer to their intrinsic or extrinsic nature. On the other hand, these stars have not been yet monitored for radial velocity variations.

Another interesting point is the value of the C/O ratio estimated for these stars. Similarly to the galactic carbon stars (e.g. Lambert et al. 1986), they have C/O ratios slightly larger than one. On the basis of theoretical models of AGB stars of low metallicity, one would expect a larger C/O ratio because with just a few TP and TDU episodes, models predict a C/O ratio larger than 10 or more (see Domínguez et al. 2004). Also, the predicted $^{12}C/^{13}C$ ratio would be larger than 100. Although, the lower limit estimated for the $^{12}C/^{13}C$ ratio in B30 might be in agreement with this latter figure, the ratios derived in the other stars are difficult to understand. Certainly, a value $^{12}C/^{13}C= 30$ in C3 cannot be explained except if one admits the operation of a deep non-standard mixing process (Nollet et al. 2003; se also Busso et al. in this volume) which would bring protons into hot regions where they are burn to ^{13}C.

Figure 1 shows the [hs/ls] vs. [M/H] ratios derived in the sample stars compared with the theoretical predictions for a 1.5 $M_\odot$ AGB star assuming that the main neutron source is the $^{13}C(\alpha, n)^{16}O$ reaction. For comparison the [hs/ls] ratios derived in galactic N-type carbon stars (Abia et al. 2002) are also shown. The [hs/ls] ratio is a measure of the neutron exposure in the *s*-process. It is clearly seen that the [hs/ls] ratios derived in B30, C1 and C3 nicely fit into the region allowed by the theoretical models. However, because of the large error bars this kind of plot cannot discriminate between the actual neutron source which is operating: i.e. a similar plot comparing observational data with theoretical predictions assuming that the $^{22}Ne(\alpha,n)^{25}Mg$ is the main neutron source would give a similar agreement. To do that, it would be necessary to make use

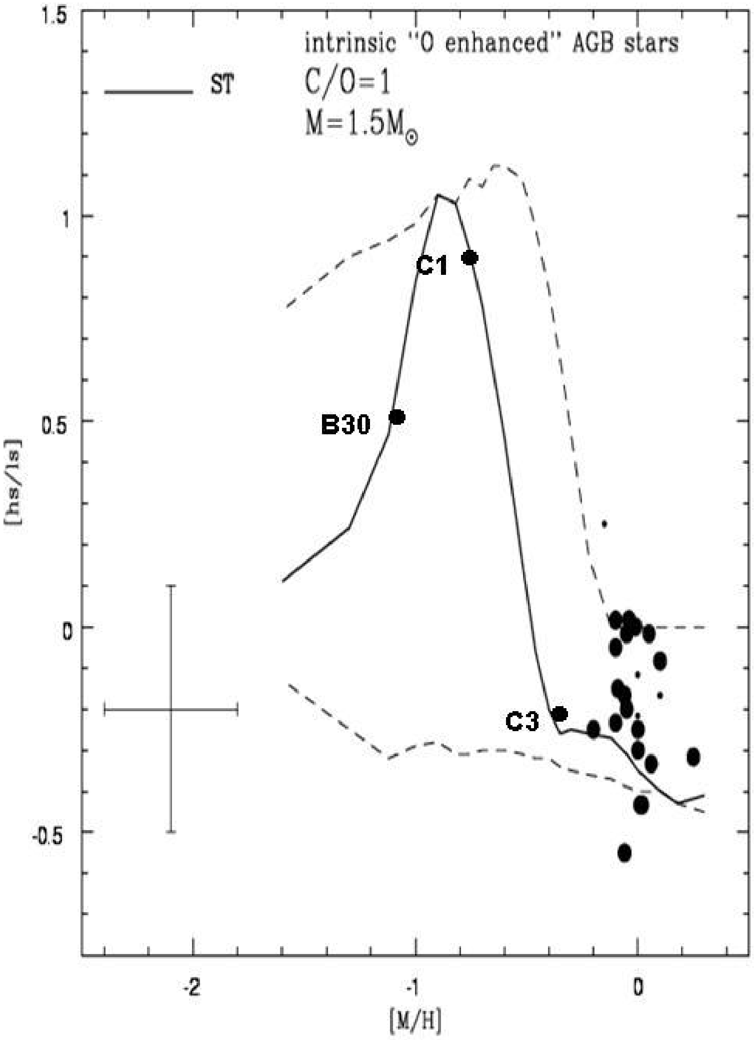

Fig. 1. Comparison of the [hs/ls] vs. [M/H] ratios (M is the average metallicity) derived in the stars B30, C1 and C3 with theoretical *s*-process nucleosynthesis predictions for a 1.5 $M_\odot$ AGB star at C/O∼ 1. Theoretical models were computed adopting an initial oxygen enhancement according to the relationship [O/Fe]= −0.5 [Fe/H]. Dashed lines limit the region allowed by the models according to the different ^{13}C-pocket choices (see Busso et al. 2001). The solid line corresponds to the prediction with the standard (ST) ^{13}C-pocket choice (4×10^{-6} $M_\odot$). Data points at [M/H] ∼ 0.0 are the galactic carbon stars studied in Abia et al (2002). Interesting enough, the figures derived in the extragalactic carbon stars seem to fit the ST curve. Note the large error bar, however. Obviously, a larger sample of stars is needed.

of the properties of the branching at different places in the *s*-process path, (e.g. at the ^{85}Kr branching, Abia et al. 2001). On the other hand, detailed reproduction of the derived *s*-element abundances can neither discriminate between the intrinsic or extrinsic nature of the stars analyzed because it is impossible on nuclear grounds only, to distinguish between the effect of an abundance dilution with the envelope of the unperturbed companion (in the extrinsic case) with the *s*-process nucleosynthesis prediction obtained considering a limited number of TDU episodes (in the intrinsic case). In this sense, a promising tool would be the measurement of the Nb abundance. This is because the abundance of the only stable isotope ^{93}Nb is determined by the decay of ^{93}Zr with life-time $\tau_{1/2} \sim 1.5 \times 10^6$ yr. This lifetime is considerably longer than the duration of the AGB phase, thus, the direct comparison of Nb abundance with its neighbors (e.g. Zr, Y) would give a hint about the nature of the star observed: in the intrinsic case one expects the Nb abundance to be one oder of magnitude lower than those of Y and/or Zr.

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