NITROGEN ISOTOPES IN ASYMPTOTIC GIANT BRANCH CARBON STARS AND PRESOLAR SiC GRAINS: A CHALLENGE FOR STELLAR NUCLEOSYNTHESIS

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ABSTRACT
Isotopic ratios of C, N, Si, and trace heavy elements in presolar SiC grains from meteorites provide crucial constraints to nucleosynthesis. A long-debated issue is the origin of the so-called A+B grains, as of yet no stellar progenitor thus far has been clearly identified on observational grounds. We report the first spectroscopic measurements of $^{14}$N/$^{15}$N ratios in Galactic carbon stars of different spectral types and show that J- and some SC-type stars might produce A+B grains, even for $^{15}$N enrichments previously attributed to novae. We also show that most mainstream grains are compatible with the composition of N-type stars, but in some cases might also descend from SC stars. From a theoretical point of view, no astrophysical scenario can explain the C and N isotopic ratios of SC-, J-, and N-type carbon stars together, as well as those of many grains produced by them. This poses urgent questions to stellar physics.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: carbon – stars: abundances

1. INTRODUCTION

After the exhaustion of He in the core, stars of mass $0.8 \lesssim M/M_\odot \lesssim 8$ become very luminous and cool and climb the so-called asymptotic giant branch (AGB). AGB stars are powered by two nuclear shells, alternatively burning H and He; He, in particular, burns recurrently in short explosive events called thermal pulses. After most thermal pulses, the convective envelope penetrates downward, bringing H- and He-burning products to the surface in a phenomenon called third dredge-up (TDU). Carbon is the main product of He burning; thus AGB products to the surface in a phenomenon called third dredge-up (TDU). Carbon is the main product of He burning; thus AGB stars, from their initially O-rich composition, become enriched in carbon (and in other He-burning products like s-elements).

For suitable values of the envelope mass (eroded by mass loss), AGB stars finally achieve an abundance ratio C/O $> 1$ (by number) in which case they become carbon stars of a class called C(N) (or N-type). This typically occurs between 1.5 and 3–4 $M_\odot$ for solar chemical composition (Abia et al. 2002; Cristallo et al. 2011). Above $M \gtrsim 4 M_\odot$, stars cannot become carbon-rich, because of both the large envelope mass to pollute and because the hot temperature at its base induces CN-cycling, burning the dredged-up carbon in a process called hot bottom burning (HBB; Renzini & Voli 1981).

It was inferred spectroscopically that compositional changes induce a spectral-type evolution along the sequence (Wallerstein & Knapp 1998): M → MS → S → SC → C(N) although there are some doubts on the nature of SC stars; see below. The composition determines the type of condensates forming in the circumstellar envelope. Oxides and silicates form in O-rich AGB stars (M, MS, S) while C-rich stars are parents to SiC and graphite dust. After its ejection into the interstellar medium by stellar winds, this cosmic dust can be trapped in meteorites that are now recovered in the solar system. Among these dust particles, SiC grains are probably the best studied (see, e.g., Davis 2011). They are classified on the basis of their nitrogen, carbon, and silicon isotopic ratios (see, e.g., Nittler 2003). The so-called mainstream (MS) grains, which constitute 93% of all SiC grains, show a huge range in the $^{14}$N/$^{15}$N ratio (from 10 to 10,000). Moreover, these grains show isotopic anomalies that can be only explained if they were formed from material exposed to s-process nucleosynthesis, which is thought to occur during the AGB phase of low-mass stars (see, e.g., Straniero et al. 2006). On the other hand, grains of type A+B (~4% of presolar SiC) also show a large spread in the N ratio, but low $^{12}$C/$^{13}$C ratios (~<10); their origin is still unclear (Amari et al. 2001).

Spectroscopically, C(N) stars show strong CN and C$_2$ bands. They also display absorption lines of F and s-elements, whose enrichment is in good agreement with stellar and nucleosynthesis models (Abia et al. 2002, 2010; Cristallo et al. 2011), so that the AGB evolutionary stages are thought to be well understood. Their $^{12}$C/$^{13}$C ratios are typically ~>30, averaging ~60. Other types of carbon-rich giants exist, but their origins are more unclear. Among them, SC-type stars show molecular bands indicating C/O ratios close to unity; s-element enrichments are not always present and the $^{12}$C/$^{13}$C ratios range from CN-cycle equilibrium (3–4) up to ~100. A few SC stars are super Li-rich (Abia & Isern 1997), with Li abundances larger by four to five orders of magnitude than for C(N) giants. They also show the largest F enrichments,~5 [F/Fe] ~ 1 (Abia et al. 2010), in solar-metallicity ([Fe/H] ~ 0) carbon stars. Furthermore, they seem to be on average more luminous than C(N) giants (Guandalini 2008), suggesting stellar masses ~>4 $M_\odot$, thus casting doubts on their position in the spectral sequence going from M to C(N) types. Another subgroup of carbon stars, J-type, shows strong features of $^{13}$C-bearing molecules, indicating $^{12}$C/$^{13}$C ~< 15. They have no s-element enhancement and are, in most cases (~<80%), moderately Li-rich (Abia & Isern 1997). Their relation to the quoted spectral sequence is unclear. Several J stars (~30%) show infrared emission lines associated with silicate dust, which is a peculiar property, given their C-rich
composition, although chemical kinetics allows for the formation of O-based compounds in C-rich environments (Cherchneff 2011). The emission seems to come from O-rich disks in binary systems (Chen et al. 2007), indicating binarity as a common property of these stars.

Here we derive for the first time the $^{14}$N/$^{15}$N ratios in a sample of near solar metallicity Galactic carbon stars of different spectral types. Our analysis reveals that the N isotopic ratios in N-type stars nicely cover the range found in the MS SiC grains, while those derived in J and SC types support an origin for A+B grains in these peculiar stars. We briefly discuss the results in the framework of the standard AGB phase stellar evolution and conclude that no known evolutionary scenario can explain the full range of $^{14}$N/$^{15}$N ratios found in these stars.

### 2. OBSERVATIONS AND ANALYSIS

We obtained very high resolution echelle spectra ($R \approx 170000$) of 19 N-, 8 J-, and 8 SC-type Galactic carbon stars of near solar metallicity with the SARG spectrograph at the 3.5 m TNG telescope. The signal-to-noise ratio in the spectral region of interest ($\sim8000\ \text{Å}$) was typically $\geq300$. In this wavelength interval, there are various $^{12}$C$^{15}$N absorption features sensitive to the $^{15}$N abundance. The CN line list by Hill et al. (2002) was improved to allow the identification of $^{12}$C$^{14}$N, $^{13}$C$^{14}$N, and $^{12}$C$^{13}$N lines. First, wavelengths were improved using the energy levels of Ram et al. (2010a) for $^{12}$C$^{15}$N, and of Ram et al. (2010b) for $^{13}$C$^{14}$N. They were supplemented by wavelengths from Kotlar et al. (1980) or calculated by extrapolation of the molecular constants when needed. Isotopic shifts were computed for all isotopic combinations, using the usual isotope relationship for constants when needed. Isotopic shifts were computed for all lines of the $^{12}$C$^{15}$N and $^{13}$C$^{14}$N isotopologues for a given band.

### Table 1

#### Selected $^{13}$C$^{15}$N Lines

| Wavelength (Å) | $\chi$ (eV) | log $gf$ |
|----------------|-------------|----------|
| 7980.300       | 0.035       | −2.629   |
| 7980.357       | 0.035       | −2.400   |
| 7985.440       | 0.041       | −2.627   |
| 7985.501       | 0.041       | −2.353   |
| 7985.536       | 0.197       | −1.867   |
| 8029.694       | 0.184       | −1.626   |
| 8029.921       | 0.095       | −2.655   |
| 8030.014       | 0.095       | −2.113   |
| 8037.581       | 0.105       | −2.087   |
| 8037.733       | 0.197       | −1.609   |
| 8063.541       | 0.239       | −1.562   |

**Notes.** Several of these lines may contribute to the selected features in the analysis (see the text).

### Table 2

#### Nitrogen and Carbon Isotopic Ratios

| Star          | S/N | $^{14}$N/$^{15}$N$_{12C15N}$ | $N_{\text{max}}$ | $^{14}$N/$^{13}$N$_{12C15N}$ | $^{12}$C/$^{13}$C | Reference |
|---------------|-----|------------------------------|------------------|-----------------------------|-----------------|-----------|
| AQ And        | 640 | 0.03 ± 0.08                  | 3                | 1230 ± 260                  | 30              | 2         |
| AW Cyg        | 410 | −0.43                        | 2                | >750                        | 21              | 4         |
| BL Oro*       | 620 | 0.40 ± 0.20                  | 3                | 3700 ± 3000                 | 57              | 1         |
| EL Aur        | 500 | 0.20 ± 0.13                  | 4                | 2300 ± 1500                 | 50              | 4         |
| LQ Cyg        | 290 | 0.0                          | 5                | 1170 ± 470                  | 40              | 4         |
| NQ Gem        | 570 | 0.18 ± 0.60                  | 2                | 3700 ± 3900                 | 23              | 5         |
| ST Cam*       | 560 | 0.01 ± 0.25                  | 4                | 1300 ± 1000                 | 61              | 1         |
| SY Per        | 390 | −0.37                        | 2                | >800                        | 43              | 4         |
| TX Psc*       | 650 | 0.05 ± 0.15                  | 3                | 1040 ± 150                  | 43              | 1         |
| U Cam*        | 290 | −0.28                        | 2                | >2000                       | 97             | 1         |
| UU Aur*       | 590 | −0.02                        | 2                | >1000                       | 52             | 1         |
| V460 Cyg*     | 560 | 0.40 ± 0.29                  | 2                | 4600 ± 2500                 | 61             | 1         |
| V759 Mon      | 370 | 0.05 ± 0.38                  | 4                | 1600 ± 1400                 | 65             | 5         |
| V Alg*        | 580 | > −0.02                      | 2                | >1800                       | 82             | 1         |
| W Cam         | 630 | 0.07 ± 0.10                  | 3                | 1300 ± 200                  | 40             | 6         |
| W Ori*        | 480 | 0.51 ± 0.45                  | 3                | 4300 ± 2500                 | 79             | 1         |
| X Cne*        | 220 | 0.40 ± 0.44                  | 3                | 3300 ± 1800                 | 52             | 1         |
| Y Tau*        | 590 | −0.12 ± 0.25                 | 3                | 880 ± 190                   | 58             | 1         |
| Z Psc*        | 570 | 0.00 ± 0.45                  | 3                | 1300 ± 1100                 | 55             | 1         |
| J-type        |     |                              |                  |                             |                 |           |
| BM Gem        | 340 | 0.03 ± 0.55                  | 2                | 1330 ± 800                  | 9              | 3         |
| RX Peg        | 490 | 0.15 ± 0.55                  | 2                | 1800 ± 1100                 | 8              | 3         |
| UV Cam        | 440 | −0.22                        | 2                | >700                        | 4              | 3         |
| V353 Cas      | 360 | 0.18                         | 1                | 2400                       | 7              | 3         |
| V614 Mon      | 620 | ···                          | ···              | ···                         | 8              | 3         |
| VX And*       | 650 | −0.25                        | 1                | 900                         | 13             | 1         |
| WX Cyg        | 230 | > −2.20                      | 2                | >-6                         | 4.5            | 3         |
| Y Cyn         | 500 | 0.30                         | 1                | 3200                       | 3              | 3         |
| SC-type       |     |                              |                  |                             |                 |           |
| GP Ori*       | 240 | −0.27 ± 0.20                 | 5                | 660 ± 360                   | 40             | 6         |
| RS Cyg        | 540 | −1.02 ± 0.15                 | 3                | 105 ± 600                   | 40             | 5         |
| RR Her        | 460 | −0.84 ± 0.29                 | 2                | 220 ± 240                   | 43             | 5         |
| KZ Peg*       | 260 | ···                          | ···              | ···                         | 12             | 6         |
| UV Aur        | 260 | −0.95 ± 0.14                 | 3                | 125 ± 100                   | 20             | 6         |
| VX Gem        | 220 | −0.45 ± 0.64                 | 2                | 900 ± 990                   | 6              | 6         |
| WZ Cas*       | 380 | −0.18 ± 0.25                 | 3                | 640 ± 240                   | 5              | 3         |
| BD +10 3764   | 630 | −0.20 ± 0.39                 | 2                | 1100 ± 1400                 | 49             | 5         |

**Notes.** S/N is the signal-to-noise ratio achieved at $\sim8000\ \text{Å}$. $N_{\text{max}}$ is the number of $^{13}$C$^{15}$N lines used. The errors are the dispersion in N ratios when more than one $^{12}$C$^{15}$N line was used. For the stars marked with an asterisk, C and O abundances were derived from the analysis of 2.2 $\mu$m spectra.

**References.** Sources for $^{13}$C/$^{12}$C: (1) Lambert et al. 1986; (2) Ohnaka & Tsuji 1996; (3) Abia & Isern 2000; (4) Abia et al. 2002; (5) Zamora 2009; (6) derived in this work.
high signal to noise and resolution ($R \sim 65,000$) spectra (kindly provided by K. Hinkle 2010, private communication) obtained at the 4 m Kitt Peak Observatory telescope using a Fourier transform spectograph. Then, the N abundance as well as the final C/O ratio were derived from CN lines in the 8000 Å region in an iterative way until agreement with the values obtained in the infrared spectral range was reached. We note, however, that uncertainties in the absolute abundance of N within ±0.3 dex does not affect the nitrogen ratio derived.

A C-rich spherical MARCS (Gustafsson et al. 2008) model atmosphere was chosen for each star according to its stellar parameters, and synthetic LTE spectra were calculated in the 8000 Å region, using the Turbospectrum v10.1 code (Plez 2012). Theoretical spectra were convolved with a Gaussian function with the corresponding FWHM to mimic the spectral resolution in each range plus the macroturbulence parameter (9–13 km s$^{-1}$). We used $\chi^2$ minimization techniques to determine the $^{14}\text{N}/^{15}\text{N}$ ratios providing the best fit to each $^{12}\text{C}^{15}\text{N}$ feature. The goal was to fit not only the selected lines but also the overall shape of the spectra. The N isotopic ratios thus derived were then combined to obtain an average. The N ratios obtained from the $^{12}\text{C}^{15}\text{N}$ features at 7980 and 8064 Å were considered twice in deriving this average. These features are the most sensitive to $^{14}\text{N}/^{15}\text{N}$ variations. In this way we measured reliable N isotopic ratios for 22 stars of our sample; in a few cases we did not detect $^{15}\text{N}$ and for the rest we established lower limits on $^{14}\text{N}/^{15}\text{N}$ (see Table 2). In most cases, the overall uncertainty in the N ratios is estimated to be less than a factor of four. This mainly reflects the sensitivity to changes in the atmospheric parameters adopted plus the dispersion in the $^{14}\text{N}/^{15}\text{N}$ ratio derived among the different features. This also includes the uncertainty in the placement of the spectral continuum ($\lesssim 3\%$) and in the calculated wavelength of the $^{12}\text{C}^{15}\text{N}$ features ($\lesssim 15$ mÅ). Thus, to minimize the errors we performed a relative line-by-line analysis with respect to the C(N) star LQ Cyg ($^{12}\text{C}^{15}\text{N}$LQ Cyg) for which we measured $^{14}\text{N}/^{15}\text{N} \approx 1170$. For this star we obtained a very good global fit to its spectrum. The relative analysis reduced the dispersion in $^{14}\text{N}/^{15}\text{N}$LQ Cyg derived for a given star (see Table 2). We estimate a total uncertainty of ±0.4 dex for $[^{14}\text{N}/^{15}\text{N}]_{\text{LQ Cyg}}$.

Figure 1 shows examples of synthetic fits to $^{12}\text{C}^{15}\text{N}$ features in four of the studied stars with different $^{14}\text{N}/^{15}\text{N}$ ratios. Figure 2 shows the $^{14}\text{N}/^{15}\text{N}$ ratios derived for our sample stars (normalized to LQ Cyg) versus their $^{12}\text{C}/^{13}\text{C}$ ratios. Overplotted (gray symbols) are the isotopic ratios measured in MS and A+B SiC grains (Hoppe et al. 1994; Amari et al. 2001; Hynes & Gyngard 2009). The black point indicates model N and C isotopic ratios for a 2 M$_\odot$ AGB star of solar metallicity at the time that it becomes C-rich ($^{12}\text{C}^{15}\text{N}$LQ Cyg $\approx +0.2$, $^{12}\text{C}/^{13}\text{C} \approx 70$). These values derive from the combined action of the first dredge-up (RGB phase), where the $^{14}\text{N}/^{15}\text{N}$ ratio grows from the initial (solar) value, 470 (Marty et al. 2011) to $\sim 1000$, and the subsequent evolution before the C-rich AGB phase. This includes some (small) contribution from non-convective (extra) mixing during the RGB phase, as required by observations (Palmerini et al. 2011). This point, plotted for C/O = 1, represents a lower limit of N isotopic ratios for solar metallicity C(N) stars. This limit slightly increases for increasing stellar mass and decreasing metallicity. Further extramixing during the AGB phase would move the point along the diagonal arrow, while more TDU episodes would increase the $^{12}\text{C}/^{13}\text{C}$ ratio along the right-hand arrow (see Figure 2).

3. RESULTS AND DISCUSSION

Among the carbon stars studied, J-type giants are defined mainly by their low $^{12}\text{C}/^{15}\text{C}$ and by the absence of s-elements. Their spectra are difficult to analyze, showing broad lines and unidentified features that cannot be well reproduced. In spite of this, their C and N isotope ratios closely match those of the A+B grains (see Figure 2). The observational uncertainties are large, but not enough to hamper this conclusion. This is therefore the first experimental, unambiguous evidence ascribing at least part of A+B grains to J stars, confirming previous qualitative hints (Amari et al. 2001). Interestingly enough, the fraction of
A+B grains within all SiC grains (~5%; Davis 2011) is very similar to that of J-type stars among all Galactic AGB carbon stars (~4%–10%; Boffin et al. 1993; Barnbaum et al. 1996). We also identified, for the first time, a few (although two are lower limits) $^{15}$N-rich ($^{14}$N/$^{15}$N $\lesssim$ 1000 or $^{14}$N/$^{15}$N$_{\text{LQ Cyg}}$ $\lesssim$ −0.07) J stars (Figure 2), an amazing result, with no explanation in red giant models, which invariably predict $^{14}$N-rich envelopes. Note also that the very low $^{12}$C/$^{13}$C ratios (≤4), shared by many A+B grains and by some J stars, cannot be achieved by nucleosynthesis scenarios for red giants except in the case of HBB or extreme extramixing processes (see below). These, however, imply large $^{14}$N production and O-rich environments. Low C and N isotopic ratios were so far obtained only in simulations of nova explosions (José et al. 2004), but apart from the fact that novae do not account for the entire range of C and N ratios of A+B grains, there is no known connection between novae and J stars. Actually, until now, very few carbon-rich grains could really be ascribed to novae (Gehrz et al. 1998).

On the other hand, we note that almost all the data for C(N) stars lie above $^{14}$N/$^{15}$N $\gtrsim$ 1000 (or $^{14}$N/$^{15}$N$_{\text{LQ Cyg}}$ $\gtrsim$ −0.07, Figure 2), occupying the same region as many MS grains. As our detection limit is $^{14}$N/$^{15}$N$_{\text{LQ Cyg}}$ $\lesssim$ +0.7 (or $^{14}$N/$^{15}$N $\lesssim$ 5000), we cannot even exclude the existence of C(N) stars with higher $^{14}$N-enrichments, as shown by several MS grains. Since MS grains also show $s$-process signatures (Zinner et al. 1987; Gallino et al. 1990), they are believed to form in N-type stars. Data of C(N) stars confirm the large spread of N and C isotopic ratios measured in SiC grains, stressing our incapability to explain isotopic abundances for several grains and a few C(N) giants with any theoretical scenario proposed to date. For instance, the occurrence of any non-convective (extra) mixing episode, linking the envelope to regions where proton captures occur, would further increase $^{14}$N/$^{15}$N up to values around 10⁴, and also lower the $^{12}$C/$^{13}$C ratio (Nollet et al. 2003; diagonal arrow in Figure 2). Any such process would imply an anti-correlation between N and C isotopic ratios, but there is no evidence of this in N-type stars or MS grains. Furthermore, the existence of grains with N isotopic ratios similar and/or lower than solar is not explained by stellar nucleosynthesis or galactic chemical evolution. This has been ascribed to isotopic fractionation or terrestrial contamination (Jadhav et al. 2012; Adande & Ziyurs 2012), but now we have shown that some C(N) stars also lie on that region (although, being lower limits, their uncertainty prevents us from conclusive statements). The above situation, however, challenges our current understanding of stellar evolution.

Finally, SC-type carbon stars are rare (~1% of AGB carbon stars), indicating very short evolutionary times or uncommon evolutionary paths. With a C/O ratio very close to unity, O-rich and C-rich grain formation still relies on poorly known chemical kinetic processes (Cherchneff 2011). In fact, SC stars show little evidence of dust and the solids that form include relatively uncommon species, such as trolite (FeS; Hony et al. 2002). They may represent a short transition from C/O ≤ 1 to C/O ≥ 1 compositions; but then N and C isotopic ratios should be close to those of N-type stars and s-elements should always be enhanced. Instead, these stars are all $^{15}$N-rich (with $^{14}$N/$^{15}$N $\lesssim$ 1000), independently of their C isotope ratio, and s-element enhancements exist in some but not all of them. While the composition of these stars is consistent with both the MS and A+B $^{15}$N-rich grain groups, their origin is a mystery. It was suggested that they are massive (≥4 $M_\odot$) O-rich AGB stars, forming C-rich envelopes only for a short time due to an efficient dredge-up (Frost et al. 1998). The suspected larger masses would explain the extreme Li enhancements observed in some of them through HBB and the Cameron & Fowler (1971) mechanism. However, if HBB were sufficiently active to produce a significant amount of Li, very low F, C/O, and $^{12}$C/$^{13}$C ratios, and very large (≥10⁴) $^{14}$N/$^{15}$N ratios would result, all clearly at odds with observations (Figure 2). In general, therefore, the chemical pattern of SC stars, including N isotopes, although in line with that of various presolar grains, cannot be explained by standard stellar evolution. Note that nuclear rate uncertainties in CNO cycling are not large enough to account for the peculiar isotopic abundances we measured. Perhaps some of these stars formed with initial $^{14}$N/$^{15}$N ratios dispersed over a huge range, but physical paths leading to such a scenario are not known. Moreover, determinations of $^{14}$N/$^{15}$N in the local interstellar medium (ISM) yield values for this ratio (290 ± 40) close to the terrestrial and solar ones, with a small gradient in distance moving away from the Galactic center (21.1 ± 5.2 kpc$^{-1}$ + 123.8 ± 37.1: Adande & Ziyurs 2012). Although such measurements in the ISM are difficult, there seems to be no space for a wide dispersion of values. So far, tentative explanations of the huge range of N ratios in SiC grains assumed contamination either from terrestrial N or from cosmic-ray spallation (that should correlate with grain size and meteoritic age, respectively; Jadhav et al. 2012). Alternatively, non-equilibrium chemistry in the ISM might trigger isotopic fractionation (Adande & Ziyurs 2012; Bonal et al. 2012).

However, all these suggestions are now in conflict with evidence...
that anomalous nitrogen isotopic admixtures already existed in the parent C-rich red giants.

Summing up, our new data observationally establish for the first time that while C(N) stars are parents of MS grains with high $^{14}\text{N}/^{15}\text{N}$ ratios, J-type carbon stars might generate A+B grains, and SC stars might be a source for the grains with low $^{14}\text{N}/^{15}\text{N}$ ratios. However, no known evolutionary scenario can explain the whole resulting evidence. One might guess that some mixing/nucleosynthesis mechanism occurs during a stellar merging, producing peculiar stars as a result (Zhang & Jeffery 2013). However, this is a qualitative speculation and the underlying physics is still largely unexplored.

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**Facility:** TNG (INAF-IAC), CAO:2.2m (FOCES/CAHA-IAA)

**Note added in proof.** Part of the analysis of the stars NQ Gem, V758 Mon, RS Cyg, RR Her and BD +10 3764 was made using spectra obtained with 2.2m telescope at CAHA observatory using the FOCES spectrograph (R ~ 35,000) kindly provided by O. Zamora (2012, private communication).

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