$^{12}C/^{13}C$ RATIOS AND Li ABUNDANCES IN LOW-MASS C STARS

CARLOS ABIA
Dpto. Física Teórica y del Cosmos
Universidad de Granada, 18071 Granada, Spain

AND

JORDI ISERN
Centre d'Estudis Avançats de Blanes (CSIC)
18032 Blanes, Spain

Abstract. High-resolution and high signal-to-noise-ratio spectroscopy is used to derive $^{12}C/^{13}C$ ratios from the Red System of the CN molecule at 8000 Å in several galactic low-mass C stars previously analyzed for lithium. It is found that Li-rich C stars usually have low isotopic ratios (< 15). This suggests that the Li and ^{13}C enrichments in C stars might be produced by a similar mechanism. However, due to the large uncertainties in the abundance derivations for both Li and carbon isotope ratios, this result must be confirmed with further studies.

1. Introduction

Currently the study of the origin of lithium is one of the most active fields of research in astrophysics. During the past few years new observational data and theoretical work have been added to the study of this elusive element. From the observational point of view, recent observations of a lithium abundance dispersion in the stars of M92 (Deliyannis et al. 1995) constitute the most compelling evidence for some (perhaps a severe) depletion in the *Spite plateau* stars. Although this result should be confirmed with further observations, it casts doubt on the widely accepted primordial lithium abundance (Li/H $\approx 10^{-10}$). In any case, whatever the primordial abundance of lithium might be, there is a wide consensus that in order to produce the current abundance of this element (Li/H $\approx 10^{-9}$), an extra source is needed, perhaps of stellar origin. Concerning this, the detection of an intense gamma-ray emission in the Orion region (Bloemen et al. 1994)

R.F. Wing (ed.), The Carbon Star Phenomenon, 89-95.

has been linked with the existence (until now hypothetical) of a low-energy component in the galactic cosmic-ray spectrum. This low-energy component might have important consequences on the production of the light elements (Li, Be, B) by spallation reactions in the insterstellar medium. In addition, two new sites of primary lithium production have been proposed recently: nucleosynthesis induced by neutrinos in supernova explosions (Woosley et al. 1990), and the thermonuclear runaway during a nova event (Hernanz et al. 1996). However, apart from the large uncertainties involved in these calculations, these two mechanisms still lack observational confirmation (if they are possible at all). Hence, at present the only compelling evidence for the stellar production of lithium are the AGB stars (S and C stars).

The production of Li in AGB stars was initially proposed by Cameron (1955) and expanded by Cameron & Fowler (1971). Basically, it requires a hot convective envelope where the series of reactions ^{3}He$(\alpha,\gamma)^7$Be(e$^-$, $\nu)^7$Li might take place. ^{7}Be produced in the first reaction is carried out by convection to the outer and cooler layers of the star where it decays to ^{7}Li. At the same time (p,α) reactions destroy some of the lithium produced, but a kind of *equilibrium* abundance is established in the outer envelope and, eventually, this lithium may be detectable spectroscopically. Indeed, for a long time it has been known that some AGB stars in the Galaxy (and now also in the Magellanic Clouds) show huge features at the λ 6708 Å Li I resonance line (Sanford 1955; Torres-Peimbert & Wallerstein 1966). These *super-Li-rich* stars probably have abundances of lithium one or two orders of magnitude higher than the current galactic abundance (Li/H $\approx 10^{-8} - 10^{-7}$) (Abia et al. 1991).

A couple of years ago, we started a theoretical and observational project to gain a better understanding of the lithium production in AGB stars. The main goals of this project were threefold: (*a*) to derive accurate lithium abundances in as large a number of C stars as possible in order to obtain good statistics on the super-Li-rich phenomenon; (*b*) as a second step, to calculate observationally the Li yield from C stars; and (*c*) to study what exactly are the physical conditions which should occur in an AGB star to produce lithium. Here we summarize the most important results achieved concerning points (*a*) and (*b*) and, due to the great utility of the ^{12}C/^{13}C ratio for tracing stellar interiors, we present some new results about this isotopic ratio in C stars, trying to give some light on point (*c*).

2. Results

2.1. LITHIUM

The stars studied here constitute a flux-limited and homogeneous sample of galactic C stars taken from the *Two-Micron Sky Survey* (Neugebauer

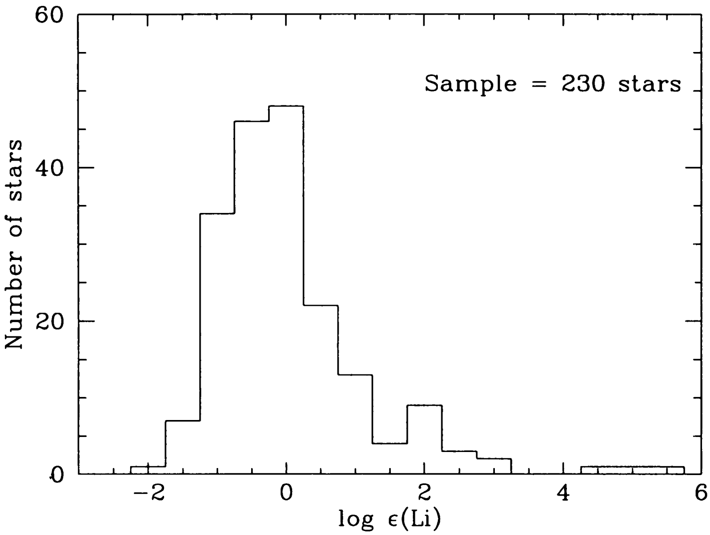

Figure 1. Li abundance histogram for the C stars studied.

& Leighton 1969). This survey covers almost 75% of the sky. The main characteristics of this sample are reviewed in Claussen et al. (1987); we only summarize the most important points. It is assumed that these stars have absolute 2.2 μm magnitudes similar to those of C stars in the Magellanic Clouds; thus, the sample should penetrate a volume of radius ~ 1.5 kpc about the Sun covering a range in bolometric magnitudes of $-3.5 \leq M_{\rm bol} \leq -6$. From the scale height from the galactic plane ($z \sim 200$ pc), the sample should have stars with progenitor masses between 1.2 and 1.6 $M_\odot$. This is an important point (problem?) because current models for AGB stars do not produce lithium in stars with initial masses $M < 4M_\odot$ (see Lattanzio et al. 2000).

Between 1990 and 1993, we observed about 230 galactic C stars around the λ6708 Å Li I feature using high-resolution spectroscopy (for details about observations, reduction procedures and analysis, see Boffin et al. 1993; Abia et al. 1993a). The final statistics concerning Li abundances can be seen in Figure 1. It is apparent from this figure that most of the stars are distributed around abundances of log ϵ(Li) ≈ 0.0 (on the scale of log N(H) $\equiv 12$), but it is also evident that there is a nice long tail toward higher lithium abundances ($\sim$ 15% of the stars). Some of the stars in this tail (2–3%) have Li abundances log ϵ(Li) > 4.0. It is straightforward to estimate the Li yield from C stars with the statistics shown in Figure 1 and the mass-loss rates derived by Claussen et al. (1987) (see their figure 10). This yield is found to be $\dot{M}_{\rm Li} \approx 4.5 \times 10^{-14}$ $M_\odot$/yr/C-star. However, note that this yield is extremely dependent on the mass-loss rate during the

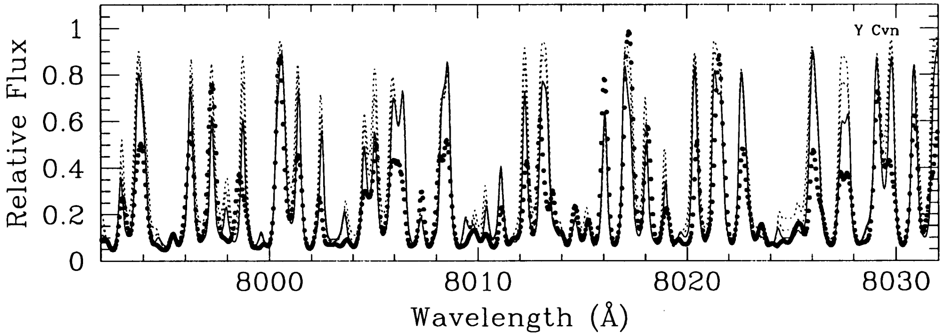

Figure 2. Observed (black dots) and theoretical (continuous and dotted lines) spectrum of Y CVn for three values of the $^{12}C/^{13}C$ ratio: 15, 6 and 2. The features where the synthetic spectra coincide are ^{12}CN lines.

super-Li-rich stage, on the actual stellar lithium abundances, and on the assumed star-formation rate during the life of the Galaxy (for details, see Abia et al. 1993b). All these parameters are rather uncertain to the extent that, for example, more than 80% of the yield given above might be due to a single star, IY Hya, which has log $\epsilon(\mathrm{Li}) \approx 5.0$ and $\dot{M} \geq 10^{-5}\ M_{\odot}/\mathrm{yr}$. In any case, when this yield is introduced in a simple model of galactic chemical evolution for the solar neighborhood, it is possible to reproduce the observed evolution of the Li/H vs. [Fe/H] relationship (see Abia et al. 1995). This shows that AGB stars might well be the most important source of Li in the Galaxy. Further studies should be done to confirm or refute this statement. Effort should be made to improve the accuracy of the Li abundances in AGB stars. Current uncertainties in the analysis and in the model atmospheres tell us that Li abundances (and those of any other chemical element) cannot be determined with a precision higher than 0.4–0.5 dex in C stars.

2.2. THE $^{12}C/^{13}C$ RATIOS

The carbon isotopic ratio $^{12}C/^{13}C$ is a very useful tracer of H–burning in stellar interiors. In order to understand the conditions in which Li might be produced in AGB stars we have derived this isotopic ratio in some of the stars previously analyzed for lithium. However, the determination of this ratio in C stars is not an easy task as shown by previous studies on this topic (see e.g. Fujita & Tsuji 1977; Lambert et al. 1986). This is mainly due to saturation effects, the difficulty of locating the continuum, and the uncertainties mainly in the upper layers of the current model atmospheres, where most of the useful molecular lines for this kind of analysis are formed.

The $A^2\Pi - X^2\Sigma^+$ electronic transition of the CN molecule around 8000 Å offers an opportunity in the near infrared for this analysis in C stars. This spectral range is not free from the problems metioned above, but using synthetic spectrum analysis with high-resolution and high signal-to-noise spectra permits an analysis as accurate as other methods (see Ohnaka & Tsuji 2000). We derived the ^{12}C/^{13}C ratio in 40 C stars focusing our attention mainly on the stars in the tail of the distribution of Figure 1. Details about observations and analysis can be found in Abia & Isern (1996), where previous results are presented. Figure 2 shows an example of fitting to the star Y CVn, a well known J-type star. We derive for this star a mean value of ^{12}C/^{13}C = 3.5. Note however that there are still important discrepances between the synthetic and observed spectra. Most of the stars studied are distributed around ^{12}C/^{13}C = 20–35, which is in excellent agreement with the results by Ohnaka & Tsuji (2000) for a larger example of AGB stars. We estimate a total uncertainty in the isotopic ratio of $\pm\ 8 - 12$, the larger the isotopic ratio the larger the uncertainty. However, this result contrasts with that of Lambert et al. (1986) who found ^{12}C/^{13}C ratios mostly around 50–60 (see the Discussion section following the Ohnaka & Tsuji paper in this volume for a possible explanation for that). Most of the stars with low carbon isotopic ratio are Li-rich stars (log ϵ(Li) $>$ 1.0). This is shown in Figure 3. From this figure it is clear that there is a correlation between lithium abundance and ^{12}C/^{13}C ratio (note however the error bars). We might conclude that as lithium is produced by the Cameron & Fowler mechanism, some ^{12}C burning occurs. In fact, despite the important uncertainties in the analysis we found that our Li-rich and ^{13}C-rich stars have ^{12}C/^{16}O ratios slightly lower than 1 (however C/O $>$ 1 as C = ^{12}C+^{13}C), showing that indeed ^{12}C is burned in the envelope. The difficulty is that current stellar models for AGB stars cannot obtain both high Li and high ^{13}C abundances for initial masses lower than 4 $M_\odot$. At masses as low as 1–2 $M_\odot$ the bottom of the convective envelope in these models is too cool to develop any kind of burning. However, there is a possibility that was pointed out by Wasserburg et al. (1995): the existence of deep circulation currents below the bottom of the standard convective envelope could transport matter from the non-burning bottom of the convective envelope down to regions where some CNO processing takes place in low-mass RGB and AGB stars. This cool-bottom processing, with the simultaneous operation of the third dredge-up, may produce a C star with a low ^{12}C/^{13}C ratio. No calculation has been done yet concerning lithium in this situation, but the temperatures achieved in this cool-bottom burning allow us to guess that it is quite possible that the Cameron & Fowler mechanism works in such conditions. In fact Wasserburg et al. (1995) show that this mechanism works during the RGB phase.

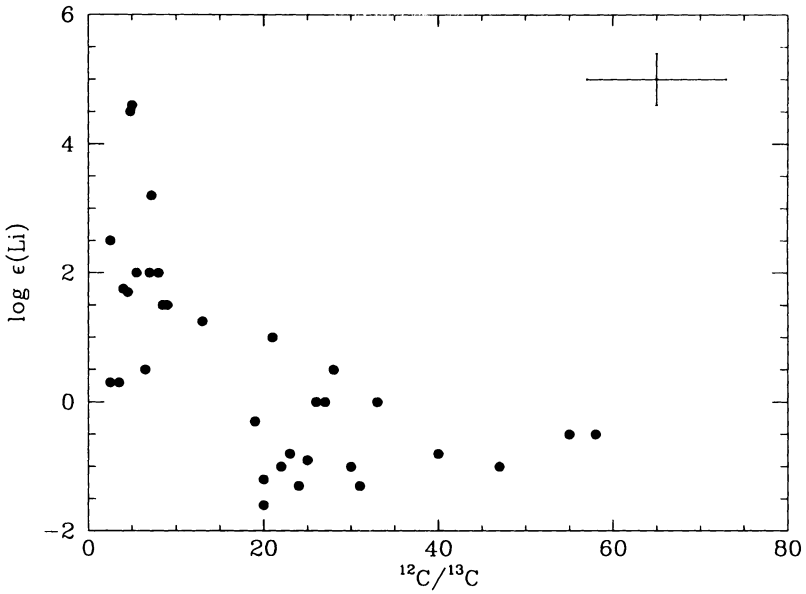

Figure 3. Li abundances vs. $^{12}C/^{13}C$ ratios. A correlation is clearly present.

Finally, we would like to emphasize that the derivation of abundances in AGB stars still involves large uncertainties. Note for example that varying the C/O ratio used in the analysis by a few hundredths changes the abundance derived for Li and/or ^{13}C by a factor 2 or even 3. At present, we cannot determine the C/O ratio in AGB stars as accurately as a few hundredths!

References

Abia, C., Boffin, H. M. J., Isern, J. & Rebolo, R. 1991, *A&A*, 245, L1
Abia, C., Boffin, H. M. J., Isern, J. & Rebolo, R. 1993a, *A&A*, 272, 455
Abia, C. & Isern, J. 1996, *ApJ*, 460, 443
Abia, C., Isern, J. & Canal, R. 1993b, *A&A*, 275, 96
Abia, C., Isern, J. & Canal, R. 1995, *A&A*, 298, 465
Bloemen, H. et al. 1994, *A&A*, 281, L5
Boffin, H. M. J., Abia, C., Isern, J. & Rebolo, R. 1993, *A&A Supp.*, 102, 361
Cameron, A. G. W. 1955, *ApJ*, 121, 144
Cameron, A. G. W. & Fowler, W. A. 1971, *ApJ*, 164, 111
Claussen, M. J., Kleinmann, S. G., Joyce, R. R. & Jura, M. 1987, *ApJ Supp.*, 65, 385
Deliyannis, C. P., Boesgaard, A. M. & King, J. R. 1995, *ApJ*, 452, L13
Fujita, Y. & Tsuji, T. 1977, *PASJ*, 29, 711
Hernanz, M., José, J., Coc, A. & Isern, J. 1996, *ApJ*, 465, L27
Lambert, D. L., Gustafsson, B., Eriksson, K. & Hinkle, K. H. 1986, *ApJ Supp.*, 62, 373
Lattanzio, J. C., Frost, C. A., Cannon, R. C. & Wood, P. R. 2000, in IAU Symp. 177: *The Carbon Star Phenomenon*, ed. R. F. Wing (Kluwer), p. 449

Neugebauer, G. & Leighton, R. B. 1969, *Two-Micron Sky Survey: A Preliminary Catalog* (NASA SP–3047)
Ohnaka, K. & Tsuji, T. 2000, in IAU Symp. 177: *The Carbon Star Phenomenon*, ed. R. F. Wing (Kluwer), p. 81
Sanford, R. F. 1950, *ApJ*, 111, 262
Torres-Peimbert, S. & Wallerstein, G. 1966, *ApJ*, 146, 724
Wasserburg, G. J., Boothroyd, A. I. & Sackmann, I.-J. 1995, *ApJ*, 447, L37
Woosley, S. E., Hartmann, D. H., Hoffman, R. D. & Haxton, W. C. 1990, *ApJ*, 356, 272

Discussion

Plez: A word of caution: The disappearance of most opacity-contributing molecules in stellar atmospheres with C/O ratios very close to 1 leads to a strong cooling of the outer layers of these atmospheres with a resulting strengthening of resonance lines like the Li I 6707 Å line. It is therefore critical to know the C/O ratio accurately. There is also the possibility of circumstellar contamination of the Li I line (observed by us for some S type stars). This can be checked at higher resolution and by looking at the K I line at 7699 Å.

Abia: Yes, certainly the derivation of Li abundances in AGB stars is a difficult task full of uncertainties. However, we have determined the C/O and ^{12}C/^{13}C ratios from other spectral ranges before determining the Li abundance. Anyway, we are currently studying the Li I lines at 6103 Å and 8126 Å, less sensitive to uncertainties in the upper atmosphere, to check the validity of the Li abundances that we have derived from the Li I resonance line at 6707 Å. Concerning the possibility of circumstellar contamination, it is not clear at all whether the 7699 Å K I line would be a useful test or not. There is an *AJ* paper by C. Barnbaum showing that this line forms in C stars at a very different optical depth than the 6707 Å Li I line.