THE ASTROPHYSICAL JOURNAL, 460:443–448, 1996 March 20


# CLUES FOR LITHIUM PRODUCTION IN GALACTIC C STARS: THE $^{12}C/^{13}C$ RATIO

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*Received 1995 January 24; accepted 1995 September 26*

## ABSTRACT

High-resolution spectroscopy is presented for 11 Population I Galactic carbon stars (C stars). Carbon isotopic ratios ($^{12}C/^{13}C$) and lithium abundances are derived from LTE synthetic spectra. It is found that the $^{13}C$-rich stars are also Li-rich. We argue that the Li and $^{13}C$ enrichment in Galactic C stars might be produced by a similar mechanism. Evidence of the operation of hot bottom burning (HBB) is found in the $^{13}C$-rich stars. However, theoretical models for asymptotic giant branch stars do not predict the simultaneous existence of HBB and Li production in stars with initial masses $M \sim 2\ M_{\odot}$, which is the typical initial mass of the stars analyzed here. We briefly discuss the observations in terms of the current models for C stars.

*Subject headings:* stars: abundances — stars: AGB and post-AGB — stars: carbon

## 1. INTRODUCTION

Asymptotic giant branch (AGB) stars are excellent laboratories for testing current theories of stellar evolution and nucleosynthesis. Helium shell flashes (thermal pulses) during the AGB phase can result in the production of carbon that is subsequently mixed upward to the surface via the third dredge-up. In this way an S star can become a carbon star (C star), defined as a star that has C/O > 1 at its surface. Lithium might also be produced during thermal pulses through the so-called Cameron & Fowler mechanism (Cameron & Fowler 1971), via the series of nuclear reactions $^3He(\alpha, \gamma)^7Be(e^-, \nu)^7Li$. Because of the convective nature of the envelope, Li can be transported from the hot, deep envelope toward the outer and cooler layers quickly enough to avoid its destruction by ($p$, $\alpha$) reactions. On this basis, two scenarios compete to describe the Li production: the plume-mixing model (Scalo & Ulrich 1973) and hot bottom burning (HBB; see, e.g., Iben & Renzini 1983). In both models the Li produced can survive in the atmosphere for some time and can eventually be detected by stellar spectroscopy. There is observational evidence that AGB stars do produce Li. Some AGB stars in the Galaxy, as well as some in the Magellanic Clouds, exhibit strong Li I 6708 Å lines, as found by Smith & Lambert (1990) and Abia et al. (1993, hereafter ABIR). Despite the difficulty involved in the derivation of the Li abundance in AGB stars, these studies indicate that some are Li-rich, log $\epsilon$(Li) ≥ 2;[1] some even have log $\epsilon$(Li) ≥ 5, 2 orders of magnitude greater than the currently assumed cosmic abundance of Li.

It is obvious that one source of clues to understanding Li production in AGB stars is the study of the correlations between Li and other elements that are useful as tracers of stellar interiors (CNO ratios, $s$-process elements). The $^{12}C/^{13}C$ ratio is one of these chemical probes. However, the determination of the $^{12}C/^{13}C$ ratio in cool C stars is not a trivial task. The transformation of an oxygen-rich (C/O < 1) into a carbon-rich (C/O > 1) star results in an enormous increase in the strength of the absorption that arises from the CN and/or $C_2$ molecular bands normally used to derive this abundance ratio. As a consequence, these molecular features are extremely blended, continuum levels are difficult to determine, and equivalent widths are impossible to measure. Moreover, the great strength of the molecular features used in the analysis introduces saturation effects, and in consequence, the standard curve-of-growth techniques fail. Nevertheless, a pseudo–curve-of-growth technique based on the measurement of the central depths of molecular lines with similar intensity can yield accurate results, which, in some favorable cases, are almost free from any uncertainty in the atmospheric structure or the line-formation mechanism (e.g., the saturation effect; Fujita & Tsuji 1977). It is not surprising, therefore, to find important discrepancies in previous $^{12}C/^{13}C$ determinations (Querci & Querci 1970; Climenhaga et al. 1977; Dominy et al. 1978; Johnson, O'Brien, & Climenhaga 1982). Comparison of synthetic spectra with high-dispersion, high signal-to-noise ratio observations of selected molecular features and the use of realistic atmosphere models should actually be the best approach to the determination of $^{12}C/^{13}C$ ratios in C stars.

In this paper, we present carbon isotopic-ratio determinations from synthetic spectra in a sample of Galactic C stars for which Li abundances have previously been determined. Since knowledge of an accurate value of the $^{12}C/^{13}C$ ratio is fundamental to deriving Li abundances from the 6708 Å Li I feature, we have reanalyzed old spectra taken in the Li region (ABIR) and derived new Li abundances by using the carbon isotopic ratios derived here. The results are discussed in terms of current models for AGB stars.

## 2. OBSERVATIONS AND ANALYSIS

We observed the red system of the CN molecule around 8000 Å. The isotopic splitting between the $^{12}$CN and $^{13}$CN lines in this spectral range is enough for determinations of the $^{12}C/^{13}C$ ratio in cool stars if high-resolution spectros-

[1] We follow the standard abundance notation: log $\epsilon$(X) = log (X/H) + 12, where X/H is the abundance by number of the element X.

copy is used. The observations were performed with the 2.5 m Nordic Optical Telescope (NOT) at the El Roque de los Muchachos Observatory. We used the IACUB spectrograph in a configuration that gave 0.18 Å of spectral resolution in the ~50 Å covered in our spectra. The typical signal-to-noise ratio achieved in the spectra was greater than 100. Exposures of bright, hot, rapidly rotating stars were made at the start and end of each night to aid in the removal of the telluric lines. The spectra were reduced using the IRAF software package. The residuals of the wavelength calibration never exceeded 0.05 Å.[2]

An important task in the analysis of cool stars is locating the continuum in the spectrum. The spectral region at 8000 Å in a typical C star is completely blended (because of CN absorptions) in such a way that the continuum level is difficult to find. This problem can be diminished if high-resolution spectroscopy is used since, in this case, some continuum windows may be accessible in the observed spectrum. The spectral range observed here contains some of these *theoretically* expected continuum windows (e.g., at $\lambda \sim 7990$, 8014, and 8036 Å; Wyller 1965). Indeed, our spectra have maximum flux points at these wavelengths. We therefore connected these points in each spectrum to initially establish a *pseudo*continuum. The final continuum was placed by comparing the observed spectrum with the theoretical one. Because the line list used for the synthetic-spectra calculation has more than 4000 features, it is reasonable to think that the theoretical continuum points are not too far from the true continuum. In fact, the synthetic spectra show maximum flux points at the wavelengths noted above. In no case was it necessary to modify the initial placement of the continuum by more than 2%. Errors introduced by the uncertainty in the continuum's position are noted below.

The atomic line list in the spectral range studied (7990–8035 Å) was kindly provided by J. Brown & G. Wallerstein. The molecular list ($^{12}$CN and $^{13}$CN) was taken from the SCAN tape (Jørgensen & Larsson 1990), which represents the most recent calculation of the *gf*-values and lower excitation energies of the red ($A\,^2\Pi$–$X\,^2\Sigma^+$) CN system. Nevertheless, the wavelength identification of the CN lines in this work is not very accurate, so, for some wavelengths, they were adjusted (see the paper by these authors for details). Errors in the *gf*-values should cancel for an isotopic analysis. The dissociation energy ($D_0$) of the CN molecule used was 7.65 eV, assumed to be the same for $^{12}$CN and $^{13}$CN. Inspection of the solar atlas of Moore, Minnaert, & Houtgast (1966) reveals that no molecular species other than CN are present in our spectral range. However, Lambert et al. (1986, hereafter LGEH) claim the existence of $C_2$ lines at $\sim 0.8\ \mu$m. We found, nevertheless, that at any optical depth the number density of the CN molecule is 1 or 2 orders of magnitude higher than that of $C_2$. Therefore, we do not expect $C_2$ lines to have contributed significantly to our spectra. The complete line list (atomic plus molecular) has more than 4300 lines in the spectral range studied. Effective temperatures were either derived by use of the Johnson color index ($J-K$) and the calibration by Heng, Chen, & Zhang (1985) or taken from the literature when a more accurate determination was found (e.g., angular-diameter measurements, infrared-flux method; see LGEH; Olofsson et al. 1993). We adopted $\log g = 0.0$ for all the stars (we do not have atmospheric models other than for this gravity). This is a typical value for a C star. A microturbulent broadening in the range $\xi = 4$–6 km s$^{-1}$ was introduced on the Doppler width of the absorption features. Synthetic spectra were smoothed by convolution with Gaussian profiles representing instrumental (0.18 Å FWHM) and macroturbulent (~5 km s$^{-1}$) broadening.

The atmospheric models used are a grid of unpublished carbon-star models by K. Eriksson & B. Gustafsson, the same models as used by ABIR. A model atmosphere for each star was interpolated from the existing grid based on $T_{\rm eff}$ and CNO abundances. The interpolated models were used to synthesize the spectra in LTE with, as a starting point, ABIR's CNO abundances and a solar $^{12}$C/$^{13}$C ratio (89). Logically, the determination of the C/O ratio must precede that of the isotopic ratio. However, no important differences were found between the CNO abundances used here to fit the $^{12}$CN lines (the strongest features in the spectra; see Fig. 1) and those in ABIR. Subsequently, the $^{12}$C/$^{13}$C ratio was reduced until it matched the $^{13}$CN features. These are at $\lambda \sim 7991.1$–7991.7, 7993.1, 7996.7–7996.8, 7998.2, 8004.6, 8006, 8014, 8019.5, 8023, and 8034 Å. The features at $\lambda \sim 8014$, 8023, and 8034 Å were considered to be the main indicators of the $^{13}$C abundance because of their weaker and less blended nature. These were fourfold weighted in the final $^{12}$C/$^{13}$C ratio; the features at $\lambda \sim 7991$, 7796, and 8006 Å were threefold weighted, those at $\lambda \sim 7993$, 7998 and 8019 Å doubly, and, finally, the $^{13}$CN feature at 8004 Å only once weighted, following a criterion that is a function of the fit's quality to the $^{13}$CN features. Other combinations give essentially the same result. For a given star, the dispersion around the mean $^{12}$C/$^{13}$C ratio derived from individual $^{13}$CN lines ranges from $\pm 2$ in the $^{13}$C-rich stars to $\pm 5$ in the stars with weak $^{13}$CN absorption. This dispersion is consistent with the uncertainty inherent in the fit itself (by eye): $\Delta(^{12}\mathrm{C}/^{13}\mathrm{C}) = \pm 2$–6.

Figure 1 shows a synthetic fit to the star VX And. The global fit is rather good, although there are some observed features that are not well matched (e.g., at $\lambda \sim 8001$, 8007–8009, 8028 Å; certainly some features are still missing in our line list). We derived for this star $^{12}$C/$^{13}$C = 8, which is in good agreement within the uncertainties (see below) with the value obtained by LGEH ($^{12}$C/$^{13}$C = 13) from the analysis of CO and CN features in the infrared. The agreement with these authors is also excellent for WZ Cas: $^{12}$C/$^{13}$C = 5, against 4.5 from LGEH.

### 2.1. *Errors*

There are several sources of error in the determination of the carbon isotopic ratio. It is the C/O ratio assumed in the model atmosphere that fixes the dynamic range of the synthesized spectrum (i.e., the relative flux between the highest and lowest points of the spectrum). This is our main source of error since this ratio completely determines the thermal structure of the atmosphere. In fact, a change of only $\Delta$(C/O) = $\pm 0.05$ implies a variation of $\mp 6$ in the $^{12}$C/$^{13}$C ratio. Fortunately, there are many spectrum points that are almost independent of the $^{13}$C abundance (mainly the deepest points in the spectrum), so the C/O ratio can be reasonably fixed before estimation of the $^{12}$C/$^{13}$C ratio. The C/O ratios (C = $^{12}$C + $^{13}$C) derived in our stars range from 1.0 to 1.2, with a mean value of C/O = $1.05 \pm 0.06$. This is

[2] For details about the observations and reduction of the Li spectra, see ABIR.

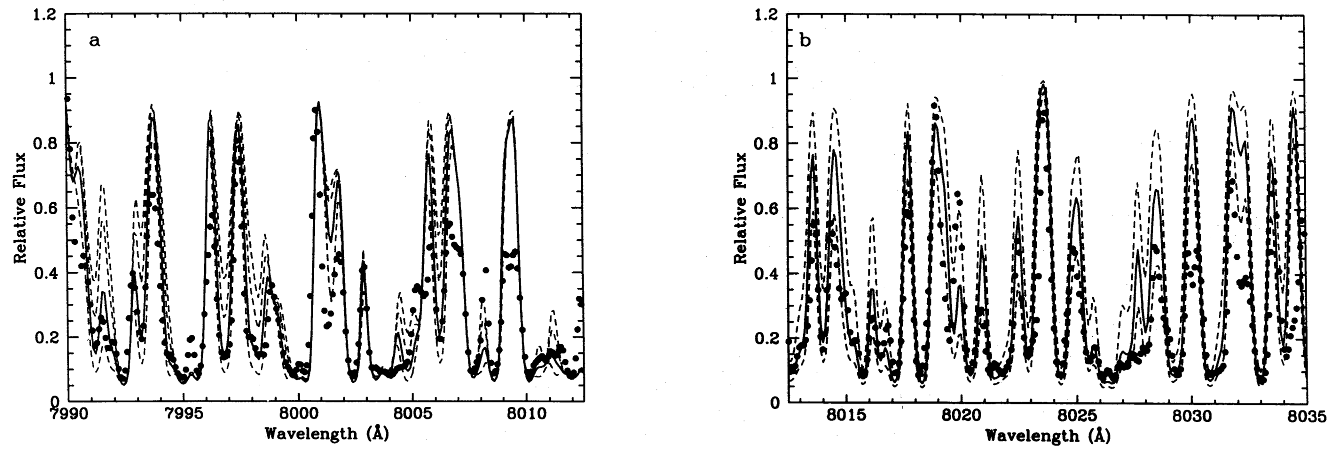


FIG. 1.—(*a*) Comparison of observed (*circles*) and synthesized (*solid and dashed lines*) spectra of VX And over the interval 7990–8012.5 Å. The synthesized spectra were calculated with $^{12}C/^{13}C$ isotopic ratios of 50, 25, 10, and 3. (*b*) As (*a*) but showing the effects of varying the absolute abundance of $^{12}C$, $\Delta$ [log ($^{12}C/H$)] = $\pm 0.35$ dex, for fixed C/O and $^{12}C/^{13}C$ ratios (1.2 and 8, respectively) over the interval 8012.5–8035 Å. The strong features where the calculated profiles coincide are $^{12}CN$ lines. Note the important difference between synthetic profiles in the weaker features.

in agreement with the idea that the C/O ratio in C stars is only slightly greater than 1 (see LGEH). The effective temperature scale for cool carbon stars is poorly known at present. The use of lunar occultations to derive angular diameters and the infrared-flux method seem to provide the best approach to deriving $T_{\rm eff}$ in these stars, but as far as we know, these kinds of measurements do not exist for the stars studied here. Therefore, we derived the $T_{\rm eff}$ parameter from infrared photometry, as noted above.

For the stars WZ Cas and VX And, $T_{\rm eff}$ was taken from LGEH, where it is derived from at least three independent infrared indices. In any case, the uncertainty in the effective temperature in our stars is high: $\Delta T_{\rm eff} = \pm 250$–300 K. Nevertheless, the synthesized spectra are not very sensitive to moderate changes in $T_{\rm eff}$. In fact, it is difficult to discriminate between two theoretical spectra that differ by $\pm 200$ K. However, the $^{12}C/^{13}C$ ratio is sensitive to the effective temperature of the model employed. This is because the line-forming layers for $^{12}CN$ and $^{13}CN$ lines are different: $^{12}CN$ lines are mostly saturated and form in the upper layers, where the thermal structure does not change significantly in response to a change of $\Delta T_{\rm eff} = \pm 250$ K in the model atmosphere. The weaker $^{13}CN$ lines form at the deepest layers and are more sensitive to temperature changes. In summary, a variation of $\Delta T_{\rm eff} = \pm 300$ K introduces an uncertainty of $\mp 3$ in the $^{12}C/^{13}C$ ratio, or $\mp 6$ in the stars with weak $^{13}CN$ features.

On the other hand, the synthetic spectra were calculated using atmospheric models with log $g = 0.0$. However, masses and luminosities of Galactic carbon stars are not well known (see § 3), and the gravities are consequently uncertain as well. Johnson et al. (1982) showed, in a study similar to this, that an order-of-magnitude change in the gravity was equivalent to a change by $\sim 0.02$ in the C/O ratio, but the isotopic ratio appeared to change very little. In consequence, we believe that our main conclusions are not modified by uncertainties in the gravity. As noted above, we adopted a microturbulence parameter between 4 and 6 km s$^{-1}$. Comparison with the observations over the entire wavelength interval suggests an optimum value of $\sim 5$ km s$^{-1}$. Synthetic spectra are rather sensitive to this parameter. This is due to the high line density in this region of the spectrum (60–70 CN lines Å$^{-1}$) and because a variation of $\xi$ by approximately $\pm 2$–3 km s$^{-1}$ will roughly double the number of CN lines that contribute to the opacity at a given wavelength. However, an uncertainty of $\pm 2$ km s$^{-1}$ can be immediately rejected because it would either result in CN lines that are too narrow and free of significant blending with adjacent lines or produce extreme saturation effects. It is important to note that the microturbulence parameter can be inferred from spectral regions that either are almost free of $^{13}CN$ lines or in which the $^{13}CN$ lines are very faint (log $gf < -4$). Hence, the dependence of the derived isotopic ratio on the choice of $\xi$ is not as important as Figure 1 suggests. Furthermore, the effect of variations in $\xi$ may also be distinguished from that of variations in the C/O ratio since the former deepen and become broader and more blended with the neighboring features. The observed spectrum thus provides a way to discriminate between the effects of variations in the C/O ratio and microturbulence.

Another important source of error is the absolute abundance of C adopted in the synthesis. We obtain a carbon abundance slightly greater than solar for most of the stars (see Table 1). However, consistent determinations of CNO abundances in cool carbon stars do not yet allow an accuracy better than $\pm 0.2$–0.3 dex in log $\epsilon$(CNO/H) (see LGEH). In our case, such variation in the carbon abundance (for a fixed C/O ratio) does not significantly modify the dynamic range of the global spectrum. The reason for this is that most of the $^{12}CN$ lines are saturated and, in consequence, are not very sensitive to changes in the abundance of carbon. However, such variations do affect the intensity of many weak $^{12}CN$ lines adjacent to the $^{13}CN$ lines that are used as $^{13}C$ abundance indicators. For example, a variation of $\Delta$[log $\epsilon$(C/H)] = $\pm 0.3$ dex means an uncertainty in the isotopic ratio of $\mp 6$–8 (see Fig. 1*b*). We note that this effect is only evident if an extensive line list is used in the synthetic-spectra calculation, as is the case in this work. Uncertainties at the same level in the nitrogen abundance are not relevant where the $^{12}C/^{13}C$ ratio is concerned. Finally, if the adjustments to the $^{12}C/^{13}C$ ratio contributed by the estimated uncertainties of the physical parameters and the composition are added in quadrature, including the uncertainty introduced by the continuum-placing ($< \pm 5\% \rightarrow < \pm 3$ in $^{12}C/^{13}C$), we estimate an

TABLE 1

DATA AND ABUNDANCES FOR PROGRAM STARS

| Star | $T_{eff}$ (K) | C/N/O | $^{12}C/^{13}C$ | log $\epsilon$(Li) | Comments |
|---|---|---|---|---|---|
| BM Gem ....... | 3000 | 8.93/7.99/8.92 | 9 | 1.5 | Silicate-rich |
| BS Per .......... | 2958 | 8.935/7.99/8.92 | 27 | 0.0 | ... |
| EL Aur ......... | 2600 | 8.93/7.99/8.92 | 33 | 0.3 | ... |
| UV Cam ........ | 3000 | 8.65/7.69/8.62 | 6 | 2.2 | *s*-elements–rich; $H_\alpha$ emission |
| V353 Cas ....... | 2800 | 8.96/7.99/8.92 | 7 | 2.5 | ... |
| V614 Mon ...... | 3100 | 8.94/7.99/8.92 | 5 | 1.7 | ... |
| VY And ........ | 3000 | 8.928/7.99/8.92 | 4 | 1.8 | ... |
| VX And ........ | 2700 | 8.44/7.45/8.24 | 8 | 2.0 | ... |
| S Aur ........... | 2610 | 8.926/7.99/8.92 | 28 | 0.5 | $H_\alpha$ emission |
| SY Per .......... | 2600 | 8.95/7.99/8.92 | 47 | −1.0 | $H_\alpha$ emission |
| WZ Cas ........ | 2850 | 8.993/7.99/8.99 | 5 | 5.1 | *s*-elements–rich |

uncertainty of $\pm 8$–12. With a typical measurement having an uncertainty of $\pm 2$–5 arising from the fit itself, the final uncertainty for a typical star is about $\pm 9$–13, i.e., the stronger the intensity of the $^{13}$CN lines, the lower the error. (A more complete discussion of the sources of error can be found in Johnson et al. 1982.)

With the $^{12}C/^{13}C$ ratios derived in this way as an input, we reanalyzed the spectra of the same stars as taken by ABIR in the Li I 6708 Å spectral range. The lithium abundances we derived for the stars S Aur, BM Gem, BS Per, EL Aur, and SY Per were different from those of ABIR. The mean difference found was $\Delta[\log \epsilon(\mathrm{Li})] = -0.25 \pm 0.30$. The typical error in log $\epsilon$(Li) is $\pm 0.4$ dex (see ABIR). Table 1 shows the $^{12}C/^{13}C$ ratios and Li abundances determined for our stars.

## 3. RESULTS: CLUES FOR Li PRODUCTION IN C STARS

First, it should be emphasized that, because of the interplay of all the parameters ($T_{eff}$, abundances, $\xi$, continuum placing), the convergence toward final Li abundances and $^{12}C/^{13}C$ ratios requires careful exploration of the parameter space. The set of parameters that gives a good match to the observed and synthetic spectra in both the Li and 0.8 $\mu$m spectral regions is not unique. Furthermore, non-LTE effects in the formation of the Li resonance line and the CN molecule in cool stars are under scrutiny and still not well known. In addition, the stars analyzed here are variable stars, so the existence of waves, shock fronts, and inhomogeneities would be the rule rather than the exception in their atmospheres. We do not know how these phenomena affect the abundance determinations in these stars (see Gustafsson & Jørgensen 1994 for a discussion). Definitely, all of these factors lead to large uncertainties in the abundances derived in C stars, as noted above. However, keeping this in mind, our results for the Li abundance and the $^{12}C/^{13}C$ ratio can be used to test current models of AGB stars.

Figure 2 presents the main result of this work: the stars with low carbon isotopic ratios ($^{12}C/^{13}C < 15$, *J-type* stars) have large Li abundances, log $\epsilon$(Li) > 1.0. The remainder of the stars in the sample have $^{12}C/^{13}C$ ratios and Li abundances as expected in the AGB phase ($^{12}C/^{13}C \gtrsim 30$, log $\epsilon$(Li) $\approx$ 0.0). Although the correlation outlined in Figure 2 awaits confirmation by more observations, it seems apparent that the Li enrichment of Galactic C stars implies a corresponding $^{13}$C enrichment. This is similar to the figure derived from observations in the Small Magellanic Cloud (Plez, Smith, & Lambert 1993), although some important differences between the properties of the two sets of AGB stars must be noted (see below). What mechanism can simultaneously enrich a C-star in Li and $^{13}$C? The standard theory in the AGB phase says that, during thermal pulses, fresh $^{12}$C but not a significant amount of $^{13}$C or $^{16}$O is added to the convective envelope and, hence, to the atmosphere. Assuming that the base of the envelope is cool so that hydrogen burning through the CN cycle does not convert $^{12}$C to $^{13}$C and $^{14}$N, the surface $^{12}C/^{16}O$ and $^{12}C/^{13}C$ ratios are predictable, given the envelope's composition prior to the dredge-up of $^{12}$C. These predictions are shown in Figure 3 (*lines*). It can be seen in this figure that the Li-rich stars fall outside these lines. Conversely, the Li-normal C stars are between them. We might conclude that some $^{12}$C burning through the CN cycle has occurred in our Li-rich stars, transforming $^{12}$C into $^{13}$C. Current models of Li production (Sackmann & Boothroyd 1992; Mowlavi 1995) find the Li-rich phenomena and HBB only in high-mass AGB models, $M \geq 5\ M_\odot$. Li-rich stars are produced in these models when convective-envelope base temperatures ($T_{base}$) exceed $5 \times 10^7$ K. After $\sim$10 pulses, high lithium abundances [log $\epsilon$(Li) $\sim$ 4.5] are found that persist for $10^4$–$10^5$ yr and decline slowly thereafter.

On the basis of these models, a lithium abundance of log $\epsilon$(Li) $\approx$ 2, as typically derived here, would indicate that our stars are either in transition to becoming superrich Li stars or have already passed this phase, or simply could indicate a different $T_{base}$ and/or $^3$He content (the seed of $^7$Li) in the envelope. Low carbon isotopic ratios ($^{13}C/^{12}C \lesssim 15$) due to $^{12}$C burning are found in the same models with $T_{base}$ reach-

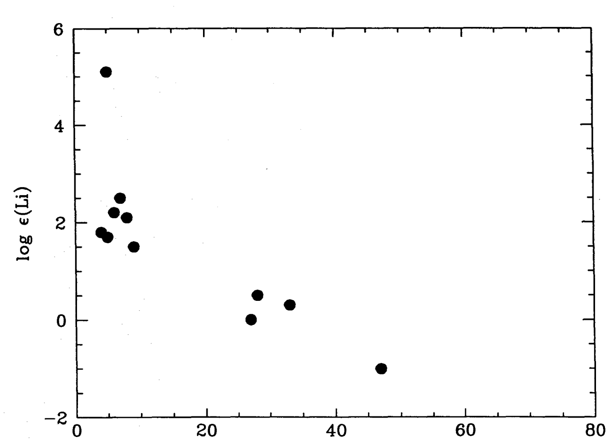


FIG. 2.—Lithium abundances vs. $^{12}C/^{13}C$ for program stars

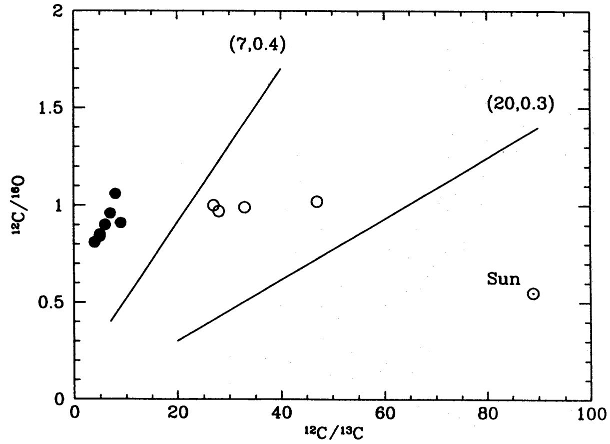


FIG. 3.—The $^{12}C/^{16}O$ and $^{13}C/^{12}C$ ratios for program stars. Filled circles refer to the Li-rich stars. Open circles are Li-normal C stars (see text). The lines illustrate two simple models (taken from Fig. 40 of LGEH) of the dredge-up in which pure $^{12}C$ is added to initial envelope compositions representative of a red giant prior to the third dredge-up. Adopted initial compositions of these red giants are indicated within the figure.

ing (6–8) × $10^7$ K. For higher temperatures HBB will prevent the formation of a C star. In fact, a luminosity range is predicted in which a C star can also be a lithium-rich star, $-6 \leq M_{bol} \leq -6.5$. For higher luminosities an AGB star can be Li-rich; however, it is then not a C star but an S star. This luminosity range is in rather good agreement with the findings in the SMC (Smith & Lambert 1990; Plez et al. 1993) but not with that in the Galaxy: following the analysis by Claussen et al. (1987), our stars would be in the range $-5.5 \leq M_{bol} \leq -4.8$, outside the predicted luminosity range above (although this is probably a weak point because of the difficulty in determining the distance for the Galactic stars). Furthermore, the majority of Galactic AGB Li-rich stars are C stars (but see also Plez & Smith 1995).

On the other hand, concerning the masses of Galactic C stars, from the characteristic scale height above the Galactic plane ($z_0 \approx 200$ pc), Claussen et al. estimated that Galactic C stars have masses between 1.2 and 1.6 $M_\odot$. This seems to be in agreement with recent theoretical models by Groenewegen, van den Hoek, & de Jong (1995), which predict a mass range $1.5 \leq (M/M_\odot) \leq 4$ for a star to become a carbon star. For $M \geq 4\ M_\odot$ HBB prevents the formation of carbon stars. However, a recent study by Barnbaum, Kastner, & Zuckerman (1991) claims the existence of a more massive ($M \geq 2.5$–$4\ M_\odot$) population of Galactic C stars with a correspondingly lower value of $z_0$. To check the possibility that our stars are biased toward large masses, we have derived the $z$-values of our stars; no correlation was found between $z$ and the Li abundance. Therefore, we may conservatively assume that the typical mass of the Li-rich C stars analyzed here is $\sim 2\ M_\odot$, still well below the mass range for which high lithium abundances and low $^{12}C/^{13}C$ ratios are predicted by the current theoretical models.

Nevertheless, HBB has been found for $M \geq 1.2\ M_\odot$ (e.g., Sackmann & Boothroyd 1991) for an appropriate value of the mixing-length parameter ($\alpha \sim 2.1$). In these models HBB occurs for a short period after a pulse when the star reaches a peak luminosity of log $L \sim 4.25\ L_\odot$, or $M_{bol} \sim -5.8$. The existence of HBB for a given stellar mass model seems to be extremely dependent on the mixing-length parameter. Given the uncertainty in theoretical models and in the determination of the Galactic C stars' distance, the bolometric magnitudes of our stars are not too far from this luminosity limit. Definitive evidence favoring the existence of HBB in low-mass AGB stars could result from the search for $^{14}N$ enrichment at the surface. From our analysis we cannot assert this. None of the stars studied here appear to be $^{14}N$-rich. In fact, we derive for them a characteristic solar N abundance. However, we do not exclude this possibility since our N abundances are not derived independently of the C abundance and, thus, are not accurate enough. Another indication would be the study of the $^{18}O/^{17}O$ ratios in the $^{13}C$-rich stars, although it seems very improbable that $T_{base}$ is high enough to significantly alter this oxygen ratio in low-mass AGB stars. In any case, these kinds of analyses are of special interest with respect to Galactic Li-rich C stars.

The alternative to HBB for Li production is the plume-mixing model, which is also based on the operation of the Cameron & Fowler mechanism. Earlier models of this type (Scalo & Ulrich 1973) can form a Li-rich C star for both low ($\sim 1\ M_\odot$) and intermediate ($\sim 5\ M_\odot$) masses of both population compositions. C stars will show low $^{12}C/^{13}C$ ratios and $^{14}N$ enrichment depending on the duration of the mixing after the thermal pulse. The probable low-mass nature of the C stars studied here would favor the operation of this scenario. Certainly, the correlation found here between the $^{12}C/^{13}C$ ratio and Li in C stars remains to be confirmed by further observations, but in any case, whichever the mechanism driving the Li production in Galactic AGB stars, Figures 2 and 3 should encourage theoreticians to recalculate low-mass AGB star models. The observational counterpart should be the derivation of the stellar parallaxes of Galactic C stars in order to estimate accurate distances and, in consequence, bolometric magnitudes and masses. The *HIPPARCOS* mission will be of great help for this.

We thank an anonymous referee for constructive comments and criticism. We also thank R. García López and I. Domínguez for support during the observations. This work was partially supported by grants PB91-060, PS90-02224, and PB93-1162. The 2.5 m Isaac Newton Telescope and 2.5 m NOT are operated on the island of La Palma by the RGO in the Spanish observatory of El Roque de los Muchachos, maintained by the Instituto de Astrofisica de Canarias.

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