THE CHEMICAL COMPOSITION OF CARBON STARS. II. THE J-TYPE STARS

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Received 1999 November 8; accepted 2000 January 26

ABSTRACT

Abundances of lithium, heavy elements, and carbon isotope ratios have been measured in 12 J-type Galactic carbon stars. The abundance analysis shows that in these stars the abundances of s-process elements with respect to the metallicity are nearly normal. $^{13}$C is not present in most of them, although upper limits have been derived for WZ Cas and WX Cyg, perhaps two SC-type rather than J-type carbon stars. The Rb abundances, obtained from the resonance $^{8}$7800 Rb 1 line, are surprisingly low, probably owing to strong non-LTE effects in the formation of this line in cool carbon-rich stars. Lithium and $^{13}$C are found to be enhanced in all the stars. These results together with the nitrogen abundances and oxygen isotope ratios measured by Lambert et al. and Harris et al. are used to discuss the origin of J stars. The luminosity and variability class of the stars studied would indicate that they are low-mass ($M \leq 2$–$3 M_\odot$), less evolved objects than the normal carbon stars, although the presence of some luminous ($M_{bol} < -5.5$) J stars in our Galaxy (WZ Cas may be an example) and in other galaxies, suggests the existence of at least two types of J stars, with different formation scenarios depending upon the initial mass of the parent star. Standard evolutionary AGB models are difficult to reconcile with all the observed chemical characteristics. In fact, they suggest the existence of an extra mixing mechanism that transports material from the convective envelope down to hotter regions where some nuclear burning occurs. This mechanism would act preferably on the early-AGB phase in low-mass stars. Mixing at the He-core flash and the binary system hypothesis are also discussed as alternatives to the above scenario.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: carbon — stars: evolution

1. INTRODUCTION

The carbon content in the envelope of asymptotic giant branch (AGB) stars is believed to increase along the spectral sequence $M \rightarrow S \rightarrow C$ during this phase of stellar evolution. The origin of this carbon enhancement is the mixing of He-burning products with matter from the convective envelope through the third dredge-up (TDU) mechanism, which can happen after each thermal instability (pulse) of the He-shell (Iben & Renzini 1983). The recurrence of TDU episodes leads to the creation of a carbon (C) star, defined as an AGB star with a C/O ratio higher than unity in the envelope. Among the C stars there exists a significant group of stars ($\sim 15\%$) named J-type stars (Bougoure 1954) showing strong $^{13}$C-bearing molecule absorptions, which usually implies low $^{12}$C/$^{13}$C ratios ($<15$) (Lambert et al. 1986; Abia & Isern 1997; Ohnaka & Tsuji 1999).

The location of J stars in the above AGB spectral sequence is far from clear. In fact, some authors have located these stars in a different evolutionary sequence from that of the ordinary carbon stars (e.g., Chen & Kwok 1993; Lorenz-Martins 1996), or even outside the AGB phase. J stars have also been considered as the descendants of the late-R carbon stars, which have similar spectroscopic characteristics Lloyd-Evans (1986). Theoretically, it is not easy to obtain an AGB star with the chemical peculiarities presented by J stars. Low $^{12}$C/$^{13}$C ratios can be obtained in current AGB star models of $M \geq 4 M_\odot$ if hot H-burning takes place at the bottom of the convective envelope (the so-called hot bottom burning [HBB]; Lattanzio 1998; Sackmann & Boothroyd 1992). However, the performance of the CN cycle at the same time destroys $^{12}$C and, in consequence, the C/O ratio in the envelope is reduced and the star again becomes O-rich. Thus, a fine-tuning of the parameters of the AGB models (mass, mixing-length, mass-loss rate, metallicity, etc.), which determine the chemistry of the envelope, seems to be required to obtain a J star. Mixing at the He-core flash has also been proposed as an alternative scenario to form J stars. In this event an injection of carbon-rich material from the core into the hydrogen-rich shell may occur.

The presence of strong $\lambda 6708$ Li I lines is frequent in J stars. In a Li survey of galactic C stars, Boffin et al. (1993) found that among 30 Li-rich stars in a sample of 250 C stars $\sim 50\%$ are of J-type. This figure increases up to $\sim 70\%$ if the Li-rich phenomenon is considered only among the J-type C stars in the survey. Although a good statistic has not yet been obtained, Li-rich J-type stars have also been found in the Magellanic Clouds (Brewer, Richer, & Crabtree 1996). Interestingly, envelope burning models can simultaneously produce Li-rich and $^{13}$C-rich AGB stars in models with initial mass $M \geq 4 M_\odot$. However, observations indicate that the majority of C stars in the Galaxy are low-mass objects, $M \leq 2$–$3 M_\odot$ (see, for example, Claussen et al. 1987). For this mass range no envelope burning has been found in any AGB model.

On the other hand, another important consequence of the TDU episodes in the AGB phase is the enrichment of the envelope with s-process elements. These elements are believed to be synthesized during the period between thermal pulses, when a $^{13}$C-pocket (formed in the intershell
region) is burned radiatively and supplies the neutrons necessary to activate the \(^{13}\)C(\(\alpha\), \(n\))\(^{16}\)O reaction (Straniero et al. 1995). At the next TDU, the synthesized \(s\)-nuclei are mixed into the envelope. Thus, if J-type stars owe their \(^{12}\)C enhancement to the operation of the TDU, they should also show some \(s\)-process element enrichment. There are very few abundance analyses of J-type stars. The most extensive study is still that by Utsumi (1970). This pioneering study based, however, on low-dispersion (5–14 Å mm\(^{-1}\)) photographic plates, concluded that low-mass \(s\)-elements (Sr, Y, Zr) are in nearly solar proportions in J stars, while rare-earth elements are over-abundant by factors of 10–100. However, a further revision by Utsumi (1985) showed that in J-type stars, abundances of \(s\)-process elements with respect to Fe are nearly normal. Kistln (1975) derived Zr/Ti ratios in two J stars (Y CVn and RX Peg) and Dominy (1985), also using low-dispersion spectrograms, defined an abundance index by comparing the intensity of some lines of low-mass \(s\)-process elements with those of metals. Dominy drew similar conclusions to Utsumi with the possible exception of the star WZ Cas. Recently, Lambert et al. (1986) and Harris et al. (1987) have focussed their attention mainly on the determination of up-to-date model atmospheres, and atomic and molecular data. We focus our attention mainly on the determination of \(s\)-process element abundances. Our results, together with CNO and Li abundances determined in other studies, are contrasted with theoretical stellar models to find an evolutionary status for J-type stars.

2. OBSERVATIONS

The observations were made during 1997 and 1998 at two different observatories. At the Calar Alto observatory we used the 2.2 m telescope in 1997 October and 1998 July during three nights in each month. For these observations a fibre optics Cassegrain Echelle Spectrograph was used (FOCES; Pfeiffer et al. 1998). This instrument uses a 1024 × 1024 CCD with 24 μm pixel size. The FOCES image covers the visible spectral region from 0.38 to 0.96 μm in about 80 orders with full spectral coverage. The resolving power achieved was ~40,000 with a two-pixel resolution element. At La Palma observatory the 4.2 m WHT was used with the Utrecht Echelle Spectrograph during one night in 1997 December and 1998 May. The spectral range coverage with this instrument, using the 79.0 lines mm\(^{-1}\) grating, is from 0.43 to 1.0 μm, with some gaps between orders. The projected size of the slit in the 2048 × 2048 CCD was around two pixels (24 μm), which gave a resolving power of ~50,000. We observed a total of 43 Galactic carbon stars selected from the 2 μm sky survey by Claussen et al. (1987). Twelve J-type carbon stars of this sample are analyzed here (see Table 1). The analysis of the additional 31 normal (N type) carbon stars will be presented in a future work.

We used standard IRAF packages and procedures to perform bias-level, dark-current, and scattered-light subtraction and to prepare a normalized flat-field image to remove pixel-to-pixel sensitivity fluctuations. A Th-Ar comparison lamp gave enough lines in all the echelle orders to perform an accurate wavelength calibration. We carefully identified nonsaturated Th-Ar emission lines and adjusted third–fourth order polynomials to obtain a calibration fit better than 10 mÅ in the residuals. The calibrated spectra were then divided by the spectrum of a hot, rapidly rotating star located in the sky as close as possible to the target star to eliminate telluric absorptions. We note however, that most of the lines used in the abundance analysis are not affected by terrestrial features. Finally, different images of the same object were co-added after extraction and calibration to obtain the final spectrum. The S/N ratio achieved in the final spectra varies from the blue to the red orders. At ~4500 Å the S/N is 40–50, while at ~8000 Å the S/N frequently exceeded 400. In contrast, below ~4400 Å the S/N ratios are poor because at these wavelengths carbon stars (J and N) are very difficult to observe. The reason for this flux depression is still a matter of controversy. In J stars, particularly rich in \(^{12}\)C, the absorption of

### TABLE 1

**The Program Stars**

| Star       | Type  | Var | Period \(^a\) | \(\pi\) \(^b\) | \(M_\text{bol}\) \(^b\) | Epoch \(^c\) | Observatory  |
|------------|-------|-----|--------------|---------------|-----------------|-------------|--------------|
| WX Cyg     | C8, 2eJ | Mira | 399          | \(-1.41 \pm 1.98\) | \(-4.35\)          | 745         | Calar Alto   |
| WZ Cas     | C9, 1J, SC7/10 | SRa | 186          | \(1.27 \pm 0.70\) | \(-6.44\)          | 745         | Calar Alto   |
| VX And     | C5, 3J | SRa | 369          | \(3.56 \pm 1.28\) | \(-3.61\)          | 745         | Calar Alto   |
| UV Cam      | C5, 3J | SR | 294          | \(0.17 \pm 0.98\) | \(-8.70\)          | 745         | Calar Alto   |
| Y CVn      | C5, 4J | SRb | 154          | \(4.59 \pm 0.73\) | \(-4.46\)          | 1015        | Calar Alto   |
| FO Ser      | C4, 5J | Lb  | ...          | \(2.74 \pm 1.21\) | \(-3.05\)          | 1016        | Calar Alto   |
| BM Gem      | C5, 4J | Lb  | ...          | \(1.83 \pm 1.24\) | \(-3.39\)          | 791         | La Palma     |
| RY Dra      | C5, 4J | SRb | 172          | \(2.05 \pm 0.65\) | \(-5.30\)          | 947         | La Palma     |
| RX Peg      | C4, 5J | SRb | 629          | ...            | ...              | 1017        | Calar Alto   |
| V614 Mon    | C3, 5J | SRb | ...          | \(3.23 \pm 0.96\) | \(-2.84\)          | 791         | La Palma     |
| V353 Cas    | C4, 5J | SRa | 365          | ...            | ...              | 746         | Calar Alto   |
| T Lyr       | C6, 5J | Lb  | ...          | \(1.58 \pm 0.75\) | \(-5.65\)          | 947         | La Palma     |

\(^a\) Data taken from the ASTRID database.

\(^b\) Bolometric magnitudes are obtained from mean K values and Hipparcos parallaxes (see text).
triatomic carbon compounds can become nearly continuous at the shorter wavelengths. On the other hand, Johnson, Luttermoser, & Faulkner (1988) have pointed out that at the low temperatures of these stars, the resonance lines of some atoms become so wide that they depress broad areas of the continuum. This makes it almost impossible to observe the interesting Ti resonance lines at \( \sim 4250 \) Å in C stars.

2.1. Individual Stars

The spectral types shown in Table 1 are based on the C-system classification by Keenan & Morgan (1941) revised by Yamashita et al. (1977). Our stars fulfill the criteria for the C stars: a ratio of \( ^{12}\text{C}/^{13}\text{C} \lambda 4744 \) to \( ^{12}\text{C}/^{13}\text{C} \lambda 4737 \) in blue; ratios of \( ^{12}\text{C}/^{13}\text{C} \lambda 6191 \) to \( ^{12}\text{C}/^{13}\text{C} \lambda 6168, \lambda 6102 \) to \( ^{12}\text{C}/^{13}\text{C} \lambda 6122, \) and \( ^{13}\text{C}/^{12}\text{C} \lambda 6260 \) to \( ^{12}\text{C}/^{12}\text{C} \lambda 6206. \) However, for some of them the spectrum is misleading, which might produce to a problematic spectral classification. For instance, WZ Cas shows weaker CN and C\(_2\) band absorptions than the other J stars in the sample. It also shows very strong Na D lines and its spectrum does not look as crowded as the rest of the J stars. In fact, atomic lines in WZ Cas are more easily identified. Indeed, this happens when the C/O ratio in the atmosphere is very close to unity, a characteristic that defines a SC-type carbon star. Since our C/O estimate in this star is \( \sim 0.1, \) we believe that WZ Cas has to be considered a SC star rather than a typical J star. Furthermore, it is the most luminous star in our sample (\( M_{\text{bol}} \sim -6.44 \)), which could indicate that WZ Cas belongs to a different population (massive) of C stars or that it is in a different evolutionary status (more evolved) than the rest of the J stars in our sample. However, Lorenz-Martins (1996) argues that it is difficult to separate J-type stars and SC stars only by spectroscopy results. Modeling the dusty envelope of this star he concludes that WZ Cas could be a J-type carbon star. Less obviously, the same peculiarities are observed in the spectrum of WX Cyg. In fact, Ohnaka & Tsuji (1996) considered this star to be SC type although, as far as we know, no other work in the literature classifies this star as SC-type. For this star we do not have a clear opinion. On the other hand, FO Ser is also classified in the literature as a late R type carbon star Stephenson (1989). We consider it a typical J star, but we note that it presents \( H\alpha \) in absorption that is not seen in other J stars or in N or late R stars.

2.2. Luminosities of the Stars

To estimate absolute bolometric magnitudes \( M_{\text{bol}} \) of our stars (Table 1) we have used the empirical relationships between \( M_{\text{bol}} \) and \( M_K - M_V \) for C stars obtained by Alksnis et al. (1998). Infrared absolute magnitudes \( M_{\text{bol}} \) are frequently used in connection with distance determinations where it is assumed that all AGB stars have the same \( M_K \sim -8.1 \) (Frogel, Persson, & Cohen 1980). To obtain \( M_K \) and \( M_V \), the \( K \) and \( V \) average values (the stars studied are variable!) quoted in the SIMBAD database were used. \( K \) and \( V \) magnitudes were corrected for interstellar extinction according to the galactic extinction model by Arenal, Grenon, & Goméz (1992). Distances were derived from parallax measurements by Hipparcos. Note that some parallaxes have considerable errors (see Table 1); for instance, the large uncertainty in the parallax for UV Cam produces an unlikely value for \( M_{\text{bol}} \) in this star. Thus, the bolometric magnitudes in Table 1 have to be considered as average values and only indicative.

3. ANALYSIS

3.1. Effective Temperatures

For the majority of the stars studied here the effective temperature is derived by Ohnaka & Tsuji (1996, 1999). These authors derived effective temperatures for C stars using the infrared flux method. The \( L' \)-band (3.7 \( \mu \)m) is used as infrared flux and \( T_{\text{eff}} \) values are obtained from the calibration log \( f_{\text{bol}}/f_L \) versus \( T_{\text{eff}} \), where \( f_{\text{bol}}/f_L \) is the ratio of observed bolometric flux to infrared flux. The \( T_{\text{eff}} \) values in Table 2 marked with an asterisk are derived in this way. For the rest of the stars we used the \( (J - D)_K \) versus \( T_{\text{eff}} \) calibration also described by Ohnaka & Tsuji (1996). Infrared photometry for our stars is taken from Noguchi et al. (1981) and Fouquè et al. (1992). Effective temperatures for J stars derived in this way do not differ significantly from those derived in N- and SC-type carbon stars. The estimated error in \( T_{\text{eff}} \) is \( \pm 150 \) K (see Ohnaka & Tsuji 1996 for details).

3.2. Model Atmospheres

The set of models used in this analysis was computed by the Uppsala group (see Eriksson et al. 1984 for details). The models cover the \( T_{\text{eff}} = 2500-3500 \) K, \( C/O = 1.0-1.35 \) range, and all have the same gravity \( \log g = 0.0 \). The input elemental abundances adopted for the J star models were the solar values, with the exception of C, N, and O, which were assumed to be altered relative to the Sun. The CNO abundances in the model atmosphere for a given star were taken from the literature (Lambert et al. 1986; Abia & Isern 1997). For each star a model atmosphere was interpolated in \( T_{\text{eff}} \) and C/O ratio in this grid. A typical microturbulence velocity for AGB stars \( \xi = 3 \) km s\(^{-1}\) was adopted or taken from the literature when available (Lambert et al. 1986). Table 2 shows the atmosphere parameters used in the analysis.

3.3. Identification of the Atomic Lines

The greatest difficulty in the analysis of atomic lines of carbon stars lies in the heavy blend effect of molecular

| Table 2: The Atmosphere Models for Program Stars |
| Star | \( T_{\text{eff}} \) (K) | \( \xi \) (km s\(^{-1}\)) | C/N/O\(^\ast\) | \(^{12}\text{C}/^{13}\text{C}\)\(^\ast\) |
| WX Cyg | 2940 | 3 | 8.93/7.99/8.92 | 4.5 |
| WZ Cas | 3140* | 2.2 | 8.932/7.99/8.92 | 4 |
| VX And | 2890* | 3 | 8.49/7.45/8.24 | 6 |
| UV Cam | 3350 | 3 | 8.65/7.69/8.62 | 4 |
| Y CVn | 2860 | 2.5 | 8.56/7.87/8.52 | 3 |
| FO Ser | 2600 | 3 | 8.96/7.99/8.92 | 13 |
| BM Gem | 3000* | 3 | 8.94/7.89/8.92 | 9 |
| RY Dra | 3010* | 2.4 | 8.61/7.94/8.54 | 2 |
| RX Peg | 2890 | 3 | 8.96/7.99/8.92 | 8 |
| V614 Mon | 2850 | 3 | 8.93/7.99/8.92 | 8 |
| V353 Cas | 2810 | 3 | 8.96/7.99/8.92 | 7 |

\(^\ast\) The adopted solar values are \( \log \epsilon(C) = 8.55 \), \( \log \epsilon(N) = 7.99 \), and \( \log \epsilon(O) = 8.93 \).

\(^\ast\) Isotopic ratios taken from Abia & Isern 1997 are corrected according to the \( T_{\text{eff}} \) values adopted here.
bands. The problem of blending is even more serious in J stars because of the strong C₂ and CN band absorptions. For this reason, identification of spectral lines in carbon stars (particularly of J-type) are very faint, so that very long time exposures are needed to obtain good S/N spectra. Wallerstein (1989) (7 Å mm⁻¹) and Barnbaum, Stone, & Keenan (1994) (≈3 Å mm⁻¹) identified atomic lines in SC and C stars, respectively, in a more crowded region (λ ≈ 5000–8000 Å). The accuracy in their line identifications ranges from 0.03 to 0.08 Å depending on the line intensity. Basically, we have used these three atlases for atomic line identification.

As a first step, we corrected the spectra for the stellar radial velocity using the wavelengths of some easily recognized features: the two Na D lines, the Li resonance line at 6708 Å, and C stars, respectively, in a more crowded region.
6708 Å, and the K I line at 7698 Å, together with a few intense Fe I and Ca I lines. The standard deviation around the mean Doppler shift obtained from these features was less than ±0.1 Å. This was the maximum wavelength shift allowed between measured and expected wavelengths to consider a feature as a good identification. Next, we followed the same criteria as in Abia & Wallerstein (1998) (hereafter Paper I) to consider an identification as useful for abundance analysis; namely, first, the line should not present a clear visual blend with any adjacent line and, second, the local continuum around the line should be reasonably placed within ~5% of uncertainty. Of course, in no way is it possible to establish the real continuum in our stars. We can only define a local or pseudocontinuum connecting the highest flux points near the line of interest. We also tried to use the weakest possible lines, log \( \frac{W(\lambda)}{\lambda} \) ≤ −4, although in most of the stars this was not possible. When applying these criteria we immediately realized that even our spectral resolution is not enough to clearly resolve most of the atomic features in the spectra. In fact, the majority of the atomic identifications in Utsumi’s list are clear blends. Therefore, most of the equivalent width measurements by Utsumi (1970) are overestimations, and the corresponding atomic line is not useful for analysis. This explains the s-process element overabundances derived by this author. The atomic identification list by Wallerstein (1989) and Barnbaum et al. (1994) covers a very crowded region in J stars and only a few of the atomic lines there were considered good candidates in our stars. In this way we drew up a first atomic line list. Finally, each line was checked for possible atomic and/or molecular contributions not clearly seen in the spectra as a blend. When any feature was suspected of contributing to the atomic line selected, we estimated its contribution by computing theoretical equivalent widths using the model atmosphere parameters shown in Table 2. If the estimated contribution was to be higher than ~15% of the total equivalent width measured, the line was ruled out for analysis.

The final atomic line list is shown in Table 3. As can be seen, very few lines were found to be useful for analysis. Note that several hundred atomic lines were searched in each star using the above selection criteria. For some species only one line was found. Table 3 also shows the total equivalent widths measured. To do this we used the SPLOT program of the IRAF package. In some cases only upper limits are derived since, even when the line appears to be free of blends, we believe the uncertainty in the location of the continuum near the line could be higher than 5%. We estimate the error in the equivalent width from the theoretical expression given by Cayrel (1988) (see also Paper I). The uncertainty ranges from \( \Delta W(\lambda) = 10 \) to 35 mÅ, according to the line intensity and to the S/N of the spectrum, with the main uncertainty being introduced by the continuum placing.

When possible, \( gf \) values were derived from identification and equivalent width measurements in the Solar Atlas by Moore, Minnaert, & Hootgast (1966), using solar abundances from Anders & Grevesse (1989). We used the solar model atmosphere by Holweger & Müller (1974) with parameters \( T_{\text{eff}} = 5780 \) K, \( \log g = 4.44 \) and micro-turbulence variable with optical depth. Note that the possibility of using the Sun as a standard to derive astrophysical \( gf \)-values is greatly limited by the weakness of the lines used here in the solar spectrum. Specific references for individual lines are given in Table 3, otherwise we used the \( gf \)-values given in the VALD database (Piskunov et al. 1995). Finally, we considered the hyperfine structure using such information as was available: McWilliam (1998) for Ba; for Tc and Rb lines see the discussion in Paper I and references therein. Broadening by radiation damping was calculated as in Edvardsson et al. (1993), when not given explicitly by VALD. Finally, the classical van der Waals damping constant of the atomic lines was considered, also following Edvardsson et al.

4. ABUNDANCE RESULTS

4.1. Lithium

All our stars show a strong \( \lambda 6708 \) Li I absorption (see Fig. 1). In WZ Cas and WX Cyg the equivalent width of this spectral feature is certainly larger than 1 Å. Abia, Pavlenko, & de Laverny (1999) discuss the formation of Li I lines in C-rich atmospheres considering also N-LTE effects. They conclude that among the Li lines available for analysis in AGB stars (\( \lambda 4603, \lambda 6104, \lambda 6708, \) and \( \lambda 8126 \)), the subordinant line at 8126 Å is probably the most reliable, on the basis of high S/N spectra and spectral synthesis. This line forms deep enough in the atmosphere where the uncertainties in the model atmosphere structure of AGB stars are smaller. N-LTE effects for this line are also weak (\( \sim 0.2 \) dex) and the continuous opacity coefficient seems to be well reproduced by model atmospheres in this wavelength range. Unfortunately, in our stars, except WZ Cas and WX Cyg, the \( \lambda 8126 \) Li I line is weak and very crowded with strong CN absorptions in such a way that synthetic fits to this line differing by \( \sim 0.2–0.3 \) dex in the Li abundance do not significantly alter the quality of the fit. Thus, we decided to use the \( \lambda 6708 \) line, which is much more sensitive to abundance variations, except for the stars WX Cyg and WZ Cas. For these two stars we used instead the \( \lambda 8126 \) Li I line. In any case, all the Li abundances were derived by spectrum synthesis and corrected by N-LTE effects according to Abia et al. (1999) (see this paper for details). However, one has to be
very careful when interpreting the Li abundances derived from the resonance Li i line. The presence of a circumstellar component in the $\lambda$6708 Li absorption would lead us to overestimate the Li abundance when derived from this line. In fact, VX And, BM Gem, and W614 Mon show weak blueshifted Na D line absorptions, probably indicating the presence of a circumstellar envelope in these stars. This circumstellar absorption is, however, not observed in the strong $\lambda$7698 K i resonance line which should form at about the same depth in the atmosphere than the Li resonance line (see Barnbaum 1992). The lack of K i circumstellar absorption probably rules out significant contamination of the photospheric feature.

Final Li abundances are shown in Table 4 in the scale $\log(\epsilon(\text{Li}) = 12 + \log(\text{Li}/\text{H})$, where Li/H is the abundance of Li by number. From Table 4 it is clear that all the stars have unusual Li abundances [$\log(\epsilon(\text{Li}) > 1$], larger than the typical value found in normal C stars [$\log(\epsilon(\text{Li}) \sim 0.0$], but significantly smaller than those found in the so-called super Li-rich. WX Cyg and WZ Cas are certainly super Li-rich stars, although these stars may not be J-type stars (see above). The formal uncertainty in Li abundances of Table 4 ranges from 0.3–0.4 dex. Figure 2 shows the correlation of Li abundances versus $^{12}\text{C}/^{13}\text{C}$ ratios found in J- (this work) and N-type carbon stars (Abia & Isern 1997). J-type stars are all Li-rich and note that there are also some Li-rich N-type stars. The formal error in the $^{12}\text{C}/^{13}\text{C}$ ratios in Figure 2 is $\pm 6$ (see Abia & Isern 1997).

4.2. Technecium

The presence of Tc in the atmosphere of AGB stars (in fact $^{99}\text{Tc}$) is commonly interpreted as evidence of the operation of the s-process within stars. This study is the first detailed search for the presence of this element in J-type stars. As mentioned above, the three resonance Tc i lines near 4250 Å are inaccessible in C stars because of the strong flux depression in these stars below $\lambda \sim 4400$ Å. Therefore we have used, as in Paper I, the intercombination and weaker Tc line at 5924.47 Å. We followed the same procedure in the analysis as in Paper I. The reader is referred to this paper for a detailed discussion of the identification of the Tc blend and the choice of the $gf$-value and the hyperfine structure of this line. As in Paper I, the $\lambda$5924 Tc blend is not well reproduced by synthetic spectra, in particular the red wing of the line. Thus, although in some stars the Tc blend was apparently well reproduced, we prefer to be cautious and record the Tc abundance as “equal to or less than.” Figure 3 shows a clear example of this in the star WZ Cas. Tc may be present in this star, but the poor fit to the red part of the line prevents us from asserting a definitive detection. We place an upper limit of $\log(\epsilon(\text{Tc}) \leq 1$. For WX Cyg, the other possible detection, we set $\log(\epsilon(\text{Tc}) \leq 0.7$. Note that these two possible detections are of the same level as the Tc upper limits set for the sample of SC stars analyzed in Paper I. In the remaining stars, the best fit to the Tc blend is compatible with no-Tc, i.e., a synthetic spectrum with no-Tc does not differ from another one computed with a small Tc abundance. For these stars we quote a “no” entry in Table 4, meaning that Tc, very probably, is not present. An example of this is shown in Figure 3 for the star

![Graph showing Li abundances versus $^{12}\text{C}/^{13}\text{C}$ ratios in J stars in this work (circles) and N stars (squares) from Abia & Isern (1997). All the J stars are Li-rich. Note that there are some Li-rich N stars with low carbon isotope ratios.](https://example.com/graph.png)

**TABLE 4**

| Species | WX Cyg | WZ Cas | VX And | UV Cam | Y CVn | FO Ser | BM Gem | RY Dra | RX Peg | V614 Mon | V353 Cas |
|---------|--------|--------|--------|--------|-------|--------|--------|--------|--------|----------|----------|
| Li ...... | 4.4    | 4.8    | 2.6    | 3.0    | 0.7   | 1.2    | 1.5    | 1.3    | 1.5    | 1.3      | 2.7      |
| Tc ...... | <0.7   | <1.0   | no     | no     | no    | no     | no     | no     | no     | no       | no       |
| [M/H] ... | 0.3    | 0.0    | 0.05   | 0.2    | 0.0   | 0.1    | 0.2    | -0.05  | 0.4    | -0.1     | 0.3      |
| [Rb/M] ... | -0.35  | -0.55  | -1.15  | -1.10  | -1.60 | no     | -1.60  | no     | -1.25  | no       | -0.90    |
| [Sr/M] ... | <0.7   | 0.3    | <0.5   | <0.7   | ...   | <0.5   | <0.3   | <0.3   | <0.3   | <0.3     | ...      |
| [Y/M] ... | -0.45  | -0.1   | ...    | -0.05  | <0.6  | 0.25   | <0.7   | 0.3    | 0.1    | 0.16     | 0.20     |
| [Zr/M] ... | -0.3   | 0.2    | ...    | -0.15  | 0.2   | 0.0    | 0.15   | ...    | -0.3   | ...      | ...      |
| [Nb/M] ... | <1.1   | 0.15   | 0.17   | ...    | ...   | ...    | <0.5   | ...    | 0.10   | ...      | ...      |
| [Ba/M] ... | 0.0    | 0.4    | 0.25   | -0.07  | 0.3   | 0.1    | -0.2   | 0.1    | -0.4   | 0.27     | ...      |
| [La/M] ... | -0.25  | -0.1   | ...    | 0.3    | ...   | ...    | ...    | ...    | ...    | ...      | ...      |
| [Ce/M] ... | 0.3    | 0.15   | 0.25   | ...    | ...   | ...    | ...    | 0.05   | ...    | ...      | ...      |
| [Pr/M] ... | 0.2    | 0.15   | ...    | ...    | ...   | ...    | ...    | ...    | ...    | ...      | ...      |
| [Nd/M] ... | 0.05   | ...    | 0.3    | 0.4    | 0.5   | 0.1    | 0.35   | 0.0    | <0.6   | 0.15     | ...      |
| [Sm/M] ... | ...    | ...    | ...    | ...    | <0.5  | ...    | <0.5   | 0.1    | ...    | ...      | ...      |
| [Gd/M] ... | <0.6   | ...    | ...    | ...    | ...   | ...    | ...    | ...    | ...    | ...      | ...      |
| [(h)/M] ... | -0.06  | 0.16   | 0.20   | 0.09   | 0.3   | 0.2    | 0.02   | 0.25   | -0.08  | 0.17     | 0.17     |
4.3. Rubidium

The Rb abundance is a monitor of the neutron density at which the s-process operates in AGB stars. Therefore the derivation of Rb abundances in these stars is extremely important, specifically the abundance ratios between Rb and its neighbors in the periodic table (Zr, Sr). We have used the resonance line at 7800.23 Å to derive Rb abundances. The other accessible line at 7947 Å is much weaker and very crowded with CN lines in cool stars. Nevertheless, the resonance line is also blended, and so Rb abundances have to be derived from spectral synthesis. We have used the same atomic and molecular line list in the Rb spectral region as in Paper I with the addition of some C$_2$ lines (including the $^{13}$C isotope) computed by P. de Laverny (1999, private communication). We refer again to Paper I for a discussion of the identification of the atomic and molecular lines contributing to the 7800 Å blend. The Rb line is represented by the hyperfine structure components of both isotopes $^{85}$Rb and $^{87}$Rb in a terrestrial ratio ($^{85}$Rb/$^{87}$Rb = 2.59) with $gf$-values taken from Wiese & Martin (1980). Only in three stars (WX Cyg, WZ Cas, and V353 Cas) does the Rb line appear clearly as a prominent absorption in the background of CN lines. In the remaining stars, the Rb line is not distinguished from the background of lines (see Fig. 4). Table 4 shows the Rb abundance derived in our stars relative to their mean metallicity [M/H].

We adopt here the usual notation $[X] = \log (X)_B - \log (X)_0$ for any abundance quantity $X$. 

UV Cam. In fact, for this star, Y CVn, and RX Peg we were able to obtain spectra in the 4250 Å region with a high enough S/N ratio to check for the presence of the Tc resonance lines. We have not quantitatively analyzed these spectra because we lack the appropriate atomic and molecular lines in this spectral region, but a careful search for the resonance lines confirmed the absence of technetium in these three stars. We agree with the previous finding by Little, Little-Marenin, & Hagen (1987) in Y CVn. Barnbaum et al. (1991) report the possible detection of Tc in two J stars, EU And and BM Gem (star studied here). Their argument is based on the presence of a strong absorption at 6085 Å, which is partially due to the $\lambda$6085.22 Tc I line. From these authors, the fact that the $\lambda$6085 absorption appears with such intensity only in those carbon stars where Tc has been detected unambiguously using the blue lines, supports the identification of the feature at 6085 Å as Tc. Our quantitative analysis of the $\lambda$5924 Tc feature in BM Gem is, however, compatible with a nondetection. We note that the $\lambda$5924 Tc feature is a factor $\sim$2 more intense than the $\lambda$6085 one (Garstang 1981); therefore the presence of Tc in BM Gem in any measurable amount should have appeared in our analysis. Furthermore, the $\lambda$6085 Tc feature is strongly blended with a Ti I line of moderate intensity ($\chi = 1.05$ eV, log $gf = -1.35$) and some CN and C$_2$ absorptions, which necessarily requires a spectral synthesis analysis to confirm the detection. Leaving apart the possible presence of Tc in BM Gem for a further and accurate analysis and the upper limits set for WZ Cas and WX Cyg, possible SC-type stars, we can conclude that most of J stars do not show Tc.
adopt the solar photospheric Rb abundance by Anders & Grevesse (1989): $\log e(\text{Rb}) = 2.60 \pm 0.15$. If the meteoritic Rb abundance is preferred, the $[\text{Rb}/\text{M}]$ values in Table 4 have to be increased by 0.2 dex.

From Table 4 it is apparent that the $[\text{Rb}/\text{M}]$ ratios derived are remarkably low. For some stars the best fit is compatible with no Rb. Nevertheless, we believe that our Rb abundances could be, and in some cases are, lower limits. The are several reasons for this: first, some metallic lines (Fe, Ni) near the Rb line are best fitted by theoretical spectra assuming abundance values that are systematically lower by $\sim 0.2$–0.3 dex than that of the mean metallicity of the star derived from other metallic lines (see Table 3). Thus, the $[\text{Rb}/\text{M}]$ ratios should be increased by this factor if $[\text{M}/\text{H}]$ is derived from the atomic lines near Rb. On the other hand, our synthetic spectra typically give a very strong $\lambda 7800$ Rb I absorption even for very low Rb abundances. We found the same figure when deriving abundances from other resonance or very low-excitation energy lines of elements with a similar ionization potential to Rb (4.18 eV). Consider, for instance, the resonance $\lambda 6708$ Li I (5.39 eV) and $\lambda 7698$ K I (4.34 eV) lines, two alkali elements with a similar atomic structure. In fact, synthetic fits to the K I line give low potassium abundances (under solar). No nuclear mechanism able to destroy potassium in stars is known. This effect with K however, was not found by Plez, Smith, & Lambert (1993) in M giants of the Magellanic Clouds. Non-LTE effects (overionization) could be the reason for this as in the case of the strong resonance Li I line in some C stars (Abia et al. 1999). N-LTE corrections on this line might extend to until +0.6 dex in the sense of N-LTE minus LTE abundances. Similar unexpected low $[\text{Rb}/\text{M}]$ ratios were also derived by Plez et al. (1993) and Lambert et al. (1995). However, these authors conclude that NLTE effects on Rb are probably weak, from analysis of the Rb line in Beltegeuse and Aldebaran, two Galactic M supergiants whose atmospheres are presumed to be similar to those of the O-rich AGB stars they studied. A quantitative N-LTE study of the formation of the Rb line in cool C-rich atmospheres is needed before this question can be answered. Typical maximum uncertainties in the atmosphere parameters ($\Delta T_{\text{eff}} = \pm 200$ K; $\Delta \log g = \pm 1$ km s$^{-1}$; $\Delta \text{CNO}/\text{H} = \pm 0.3$ dex; $\Delta \text{C}/\text{O} = \pm 0.05$ dex) and $\sim 5\%$ in the continuum added quadratically, represent a maximum uncertainty of $\sim 0.4$ dex in the absolute abundance of Rb derived. The formal uncertainty concerning the $[\text{Rb}/\text{M}]$ value is probably less than this, because some of these sources of uncertainty affect the $[\text{M}/\text{H}]$ values in a similar way. Thus, when deriving the $[\text{Rb}/\text{M}]$ ratio, many errors would be canceled out. However, we avoid to estimate neutron densities in the $s$-process site from the derived Rb/Zr or Rb/Sr ratios because of the uncertain Rb abundances as mentioned above.

4.4. Metallicity and Heavy Elements

The abundances of metals were derived from the usual method of equivalent width measurements and curves of growth calculated in LTE. Ca, V, Fe, and Ti abundances were used as a measure of the metallicity of the stars. The $[\text{M}/\text{H}]$ value shown in Table 4 is the mean metallicity obtained from these elements. The upper limits in Table 3 were not considered when deriving $[\text{M}/\text{H}]$. In the star Y CVn we were not able to identify any metallic line useful for abundance analysis. For this purpose, we adopted the metallicity obtained by Lambert et al. (1986) from several Fe and Ca lines. Note that the number of metallic lines analyzed per star is rather low: minimum, one and maximum, eight for WZ Cas. This star is the only one for which a reasonable statistic with Fe lines (five) can be performed. We found a mean dispersion of $\pm 0.1$ dex around the mean iron abundance derived, which is compatible with the error introduced by the uncertainty in the equivalent width measurements. On the other hand, the elements having isotopes formed by neutron captures have very few useful lines in the visible spectra of J stars. Note the significant number of empty entries or upper limits in Table 3. WZ Cas is again the sole star where it is possible to detect a significant number of heavy element lines. A resolving power of $\sim 10^5$ is needed to perform an accurate analysis of these stars. This means that abundance analyses in C stars based on intermediate- to low-resolution spectra and/or on the visual intensity of spectral lines can lead to important errors. For example, the $\lambda 4607.34$ Sr I, $\lambda 4554.04$ Ba II, and $\lambda 6709.49$ La I features, used by Dominy (1985) to define an abundance index of these $s$-process elements, appeared in our spectra as very crowded blends. At these wavelengths many CN and C$_2$ lines contribute significantly in C stars. Therefore, a high intensity of such lines does not necessarily mean an enhancement of Sr, Ba, or La. This kind of analysis is only useful in relative abundance studies between stars, not to derive absolute abundances.

Figure 5 compares the strength of the Ba II line (4934.07 Å) found in three J-type stars. To establish a wider comparison, the spectrum of a normal (N) C star (Z Psc), presumed to be rich in Ba, Utsumi (1985), is included. All the spectra in Figure 5 were obtained in the same way with echelle spectrographs. The Ba II line is clearly strong in Z Psc, reflecting its probable Ba overabundance, but among the J stars this line is not so intense. Since in general few lines are available, it is not practical to examine the distribution of abundance against atomic number or even the mean differ-

![Comparison of \(\lambda 4934.07\) Ba II line strengths in three J stars (top to bottom: V614 Mon, BM Gem, and Y CVn) and a normal N-type carbon star Z Psc (bottom).]
ence between low-mass (Sr-Y-Zr) and high-mass (Ba-La-Ce-Nd-Sm) s-elements star by star. Instead, we derive the mean heavy-element enhancement \( \langle h \rangle / M \) shown in Table 4. To derive this we did not consider upper limits or the uncertain Rb abundances.

As in Paper I, an estimate was made of the theoretical errors concerning the derived metal abundances because of the uncertainties in the atmosphere parameters of the stars. The formal error due to errors in \( T_{\text{eff}} \), microturbulence, CNO abundances, the C/O ratio in the atmosphere, equivalent width measurements, and the location of the continuum, added quadratically, is \( \pm 0.3-0.6 \) dex, depending mainly on the intensity and excitation energy of the line as well as on the ionization state of the line considered. The microturbulence parameter is also an important source of uncertainty since most of the abundances are derived from strong lines, in the flat part of the curve of growth. For example, a variation of \( \Delta \xi = \pm 1 \) km s\(^{-1}\) produces a change of \( \pm 0.4 \) dex in the barium abundance derived from the strong Ba II line at 4934 Å. Unfortunately, given the large uncertainties in the equivalent width measurements and the few number of lines identified (§ 3.3), it was impossible to estimate \( \xi \) using the requirement that individual abundances derived from lines of different intensity have to be nearly equal.

Taking the error bar above into account our results in Table 4 show that J-type C stars are of near solar metallicity \([M/H] = 0.12 \pm 0.16\) and do not show the sizable heavy element enhancements typical of S or SC stars (Smith & Lambert 1990; Abia & Wallerstein 1998). The mean heavy element enhancement among the J stars in the sample is \( \langle h \rangle / M = 0.13 \pm 0.12 \), which is compatible with non-enrichment. Considering individual stars (see Table 4), in some of them there is a hint of a heavy-element enrichment, but given the small number of lines analyzed and the large errors, this has to be considered with caution.

Comparison with the results obtained by Utsumi (1985) for the stars in common (UV Cam, WZ Cas, Y CVn, and RY Dra) is difficult because of the different methods used in the analysis. Furthermore, Utsumi uses only Ti as the metallicity indicator and refers all the abundances to this element. Instead, we have used Fe, Ca, V, and Ti to obtain the metallicity \([M/H]\). However, the abundance ratios found here agree with those of Utsumi in the stars in common between the error bars (Utsumi estimated an accuracy of about 0.4 dex).

5. EVOLUTIONARY CONSIDERATIONS

J-type carbon stars are not rare, amounting to \( \sim 15\% \) of C-rich giants, and therefore they should represent a stage of evolution that is available to a significant fraction of stars, and are not the result of anomalous initial conditions or statistically unlikely events. The chemical abundances found in the present and other studies offer constraints to certain scenarios that have been offered to account for the existence of these C stars. In the following paragraphs, we use these abundance results to discuss the evolutionary status suggested and to propose new ones.

First, let us recall the chemical properties of J stars: (1) they are certainly carbon stars (\( C > O \)) and show very low carbon isotope ratios (<15). In many of them the \( ^{12}\text{C}/^{13}\text{C} \) ratio is equal to the CNO cycle equilibrium value. (2) An important fraction (\( \sim 75\% \)) have enhanced Li \([\log \epsilon(\text{Li}) > 1]\) although the majority are Li-rich rather than super Li-rich objects. (3) They are solar metallicity stars. (4) They do not show Tc or s-process element enhancements in their atmospheres. Obviously, exceptions to these figures can be found, but we are only discussing these stars on the basis of their most common properties. For instance, the carbon star UV Aur (a symbiotic star) is classified as J-type, although it shows Tc (Little et al. 1987) and does not present Li (Boffin et al. 1993). Unfortunately, we could not include this star in the present study.

Figure 6 shows the position of our J stars in an observational H-R diagram, including some Galactic R-type and N-type carbon stars with absolute magnitudes also derived from the Hipparcos parallaxes (see Alksnis et al. 1998). From this figure, one might consider J stars as transition objects between R stars and N stars. This is reinforced considering the fact that most J stars are irregular or semi-irregular variables (very few Miras are found among them) with not very large pulsation periods, which is a characteristic of the less evolved carbon stars. Furthermore, on average the envelopes of J stars are thinner than those of ordinary carbon stars (Lorenz-Martins 1996), which could also suggest that this class of objects is in the very early stages of carbon star evolution.

Current AGB models (Sackmann & Boothroyd 1992; Lattanzio 1997; Blöcker 1998) can obtain C-rich \((C/O > 1)\) envelopes and low carbon isotope ratios in stars with initial mass \( M \gtrsim 4 M_\odot \), through the successive He-shell flashes and TDU episodes coupled with the operation of HBB at the base of the convective envelope. These stars can also be, for a long period of time, Li-rich AGB stars with peak Li abundances in the range \( \log \epsilon(\text{Li}) \approx 3-4 \). However, the operation of HBB leads to the transformation of \( ^{12}\text{C} \) into \( ^{14}\text{N} \); thus nitrogen is expected to be enhanced in the envelope of these stars. The nitrogen abundances derived in some J stars (Lambert et al. 1986) show a normal N/O ratio, much lower than that expected on the basis of the CNO cycle operation in HBB. The \( ^{17}\text{O}/^{16}\text{O} \) and \( ^{18}\text{O}/^{16}\text{O} \) ratios measured in J stars (although with an important error bar)
also argue against a pure CNO cycle interpretation of the J star’s chemical anomalies (Harris et al. 1987). Models by Lattanzio & Forestini (1998) can obtain only a C-rich, Li-rich, $^{12}\text{C}/^{13}\text{C}$ low, and N/O < 1 AGB star in a very narrow range of stellar masses ($M \sim 5 \, M_\odot$), with a specific metallicity ($Z \sim Z_\odot/3$) and for a very short period of time ($\lesssim 10^4$ yr). In this context, the number of J stars expected would be very low, which is in contrast with the significant number observed. On the other hand, these objects would be fairly luminous ($M_{\text{bol}} < -6$), and should present some s-process element enhancement (at least of low-mass Sr-Zr-Y, see Vaglio et al. 1998). None of this is observed (see Tables 1 and 4). Thus, standard AGB models for masses $M \geq 4 \, M_\odot$ are very difficult to reconcile with the observed properties of J stars. Note in addition that there is observational evidence indicating a low-mass ($M \lesssim 2 - 3 \, M_\odot$) progenitor star for most of the J stars studied here (e.g., Claussen et al. 1987). Most of our stars are not very luminous objects ($M_{\text{bol}} > -5$). Their luminosity is of the order of the predicted value for low-mass stars during or near the AGB phase.

Although the formation of low-mass C stars has recently been found to be possible (Straniero et al. 1997), HBB is not found in low-mass AGB models because of the low temperatures reached at the base of the convective envelope. One has to advocate, therefore, the existence of a non-standard mixing mechanism that transports material from the bottom of the convective envelope into deeper and hotter regions (basically the H burning shell) where cool processing might occur. This hypothetical mixing mechanism, perhaps induced by meridional currents, was proposed by Wasserburg, Boothroyd, & Sackmann (1995) and has been shown to reproduce the CNO isotope anomalies found in some low-mass red giants (Boothroyd & Sackmann 1999). Under certain conditions, it can also create $^7\text{Li}$ via the Cameron and Fowler mechanism (Cameron & Fowler 1971), thus accounting for the recent discovery of surprisingly high lithium abundances in some low-mass red giants (Brown et al. 1989; Wallerstein & Sneden 1982; de la Reza et al. 1997). Boothroyd & Sackmann (1999) suggest that this extra mixing and cool bottom processing could also occur in low-mass AGB stars and account for the $^{13}\text{O}$ depletion and low $^{12}\text{C}/^{13}\text{C}$ ratios found in the J stars analyzed by Harris et al. (1987). The operation of this mechanism on the early-AGB or just after the onset of the helium shell flashes is preferred since cool bottom processing appears to become weaker as the star ascends the AGB phase. This point might be compatible with the suggestion (see Fig. 6) that J stars are not very evolved AGB stars but are just on the verge of becoming normal N-type carbon stars. In that case, little or no s-process element enhancement would be expected, as a significant number of TDU episodes are needed. This might also be compatible with the abundance results presented here. A quantitative analysis of the operation of this extra mixing and cool bottom processing and the subsequent envelope chemist on the AGB is currently in progress (Sackmann & Boothroyd 2000, in preparation).

With the above AGB scenarios encountering difficulties in explaining the existence of J stars, we examine a scenario outside the AGB phase: the mixing at the He core flash. This mechanism has already been proposed to explain the evolutionary status of the R stars (Dominy 1985). Note that as far as the chemical composition is concerned, R stars and J stars only differ in the presence of Li and slightly lower $^{12}\text{C}/^{13}\text{C}$ ratios in the latter. Thus, there is the suspicion that R stars may be the ancestors of J stars (see Fig. 6) after an additional mixing event (second dredge-up?). Very few studies of the core He-flash have been published. In an off-center core flash hydrodynamic calculation, Deupree & Cole (1981, 1983) show that a bubble of low density and high temperature ($T \sim 4 	imes 10^8$ K) can form and mix the He-core and H-shell matter. If in some red giant stars the core flash does introduce C-rich material into the H-burning shell, there is reason to believe that the results of He-burning and CN-processing may reach the convective envelope and ultimately the surface. The main question is whether the He-flash is able to produce and mix enough $^{12}\text{C}$ into the envelope to transform the star into a C star. Investigations by Mengel & Gross (1976) of noncentral flashes (in fact, near the core boundary) within a rapidly rotating core show that a series of flashes could occur and build up the C abundance in the envelope through successive flash and mixing events. Recently, Deupree & Wallace (1996) have reexamined the He-core flash performing helium flash calculations of different intensity. The violence of the flash is mainly governed by the degree of degeneracy where the explosion occurs. The authors estimate the surface abundance anomalies produced by the different He flashes. They show that the primary material mixed into and above the hydrogen shell in all cases is $^{12}\text{C}$. The other major products are the result from hot $\alpha$ captures that occur during the flash ($^{20}\text{Ne},^{24}\text{Mg},^{28}\text{Si}$, and $^{32}\text{S}$) and, if the hydrogen shell is penetrated at reasonably high temperature, some $^{14}\text{N}$. Observable enhancements of $^{12}\text{C}$ in the envelope are favored in very metal poor, low-mass envelope red giants. For moderate peak temperatures of the flash ($\sim 9 \times 10^8$ K) important $^{12}\text{C}$ enhancements (by a factor of 70) can also be obtained in solar metallicity stars, in such a way that the star might become a carbon star. However, in order to account for the observed chemical peculiarities of J stars, fine tuning of the models is required. First, on the way, $^{13}\text{C}$ must be exposed to protons and much of it be converted to $^{13}\text{N}$ to get a low $^{12}\text{C}/^{13}\text{C}$ ratio in the envelope. In addition, to prevent the release of neutrons via the $^{13}\text{C}(\alpha, n)$ reaction and so the creation of s-process nuclei, the temperature in the mixing zone must not exceed $\sim 10^5$ K (interestingly, Deupree & Wallace claim that their flash computations do not produce s-process elements). Finally, Li production would require temperatures not exceeding $\sim 5 \times 10^7$ K in the processing zone. At least the last temperature requirement appear rather difficult to attain (Lattanzio, 1999, private communication). Perhaps, Li can be produced after the He-flash by an additional mixing event between the convective envelope and the H-shell. Obviously, the He-flash scenario merits further hydrodynamic (three-dimensional) studies. Note, the He-flash occurs in low-mass and low-luminosity objects such the stars studied here.

Finally, we consider the mass-transfer scenario in a binary system. The existence of S stars with no Tc, as predicted by the mass-transfer paradigm, is now well established (Jorissen, Frayer, & Johnson 1993). Whether this scenario can also be applied to C stars is not yet firmly demonstrated, although Barnbaum (1993) found 16 Tc-poor stars in a sample of 78 C–N stars with Ba excess. However, it is difficult to explain the absence of s-process element enhancement and the C/O ratios in our stars within this scenario. In principle, the accreted material must be
extremely carbon-rich; the donor star should be a normal C star with probably enhanced s-nuclei in the envelope. Dominy (1985) estimated a C/O $\gtrsim 5$ in the material accreted by a typical $\sim 1 M_\odot$ red giant when applying this scenario to explain the C/O $> 1$ ratios observed in R stars. The same figure can be applied in the case of J stars. This extreme C/O ratio is not observed in any C star. Furthermore, even assuming that the material transferred were Li-rich (some N-type carbon stars are Li-rich), it is unlikely that Li could survive during the mass-transfer and posterior mixing. In fact, extrinsic (binary, no Tc) C stars do not usually show the Li enhancements found here (Barbuy et al. 1992).

Nevertheless, a significant number of J stars (5%–10%; Lloyd-Evans 1991) show a very uniform 9.85 $\mu$m emission, which is believed to be due to the presence of a silicate dust shell (Little-Marenin 1986). Also the detection of H$_2$O masers in five J-type stars has been reported (Engels 1994). This is rather strange, because silicate emission and H$_2$O masers are usually associated with O-rich environments, while J stars are C-rich objects. It is difficult to interpret these observations. The circumstellar shell is assumed to be produced by mass loss from the central carbon star and should reflect the carbon-rich material of its photosphere. The transit time of material through the circumstellar shell is only of the order of years, which is shorter than the transit time ($\sim 10^5$ yr) from M $\rightarrow$ S $\rightarrow$ C. Thus, it is unlikely that we are observing very recently produced circumstellar material from a progenitor M star. Our stars were classified as J-type C stars over 50 years ago. It has been suggested (Little-Marenin 1986; Lloyd-Evans 1990, 1991) that the material expelled from the now carbon star, starting while it still had an oxygen-rich envelope, has accumulated in a disk (or common envelope) around an unseen hypothetical companion. Hinkle, & Smith (1990) discuss in detail the different possibilities for the nature and mass of the companion star, although the most probable situation is that the secondary is a low-mass star on the main sequence. In fact, Barnbaum et al. (1991) found radial velocity variations by 6 km s$^{-1}$ in BM Gem and by 5 km s$^{-1}$ in EU And over a 6 month interval. The small uncertainty in their radial velocity measurements ($\pm 1.5$ km s$^{-1}$) and the fact that the velocity has change of direction over this period of time point to a binary nature for these two J-type carbon stars. Although the binary hypothesis can probably explain the silicate emission in some J stars, unfortunately there are not other radial velocity variation studies nor a search for ultraviolet excesses (in the hypothesis that the companion is now a white dwarf) to test the binary scenario for all the observed J stars. Note that McClure (1997) found no evidence of binary motion in a sample of 22 R-type C stars (possible ancestors of J stars). He however, concluded that since it is very common to find binary systems ($\sim 20\%$) among normal late-type giants, it is likely that the R stars were once all binaries, but with separations so close that would not allow them to evolve completely up the giant and asymptotic giant branches without coalescing. The star with the smallest mass in the system was disrupted and engulfed by the now visible J star. Perhaps a strong nonstandard mixing event between the core and the envelope material at the He flash was induced by tidal forces in the actual J star. Whether this stellar merging or nonstandard

### 6. Concluding Remarks

Our most important conclusion is that heavy element abundances in J-type carbon stars are nearly solar with respect to their metallicity. We did not found Tc in these stars, although we set some generous upper limits for two of the stars studied. Considering all our abundance results, it is difficult to find an evolutionary status for J stars. Their average luminosity and variability types leads us to consider these objects as less evolved than normal (N) carbon stars. However, standard AGB models are unable to explain all their properties. On the contrary, the chemical peculiarities of J stars suggests the existence of a nonstandard mixing mechanism, similar to that proposed in the red giant branch to explain anomalous CNO isotopic ratios and Li abundances. This extra mixing mechanism, acting preferably in the early AGB phase of low-mass stars ($M < 2–3 M_\odot$), would take material from the convective envelope, transport it down to regions hot enough for some nuclear processing, and then transport it back up to the convective envelope. The expected stellar mass for the occurrence of this cool processing would be in agreement with the observational evidence suggesting a low-mass for most of the J stars studied here. Mixing at the He-core flash and the binary system hypothesis may well be alternative scenarios, although fine tuning is required to explain all the observed characteristics of J stars within these models. Nevertheless, these scenarios require further investigation.

On the other hand, the existence of rather luminous J stars ($M_{\text{bol}} < -5.5$) in our Galaxy, as well as in other galaxies (M31 and the Magellanic Clouds) (see Brewer et al. 1996; Smith et al. 1995; Bessell, Wood, & Lloyd-Evans 1983), suggests there could be two types of J stars depending upon the initial mass of the parent star. The low-mass J stars would be explained by a nonstandard mixing mechanism such as those mentioned above, while the high initial mass ($M \geq 4 M_\odot$) J stars (perhaps WZ Cas is an example of this) would be explained through the operation of HBB. This idea was previously proposed by Lorenz-Martins (1996). Note that current models of s-process nucleosynthesis (e.g., Busso & Gallino 1997) predict a strong metallicity dependence of s-nuclei enrichment. For solar metallicity and/or slightly metal-rich intermediate mass AGB stars, a small s-process element enrichment is predicted. This might be in agreement with the small [$^{3}$He]/$^{4}$He value that we have found in WZ Cas. The study of the presence of s-elements in the luminous J-stars of M31 and the Magellanic Clouds would be of a great interest.

Data from the VALD data base at Vienna were used for the preparation of this paper. E. Eriksson, and the stellar atmosphere group of the Uppsala Observatory are thanked for providing the grid atmospheres. The 4.2 m WHT is operated on the island of La Palma by the RGO in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. Based in part on observations collected at the German-Spanish Astronomical Centre, Carlar Alto, Spain. This work was partially supported by grant PB96-1428.
