Lithium in LMC Carbon Stars

D. Hatzidimitriou,1 D.H. Morgan,2 R.D. Cannon,3 B.F.W. Croke4

1 Department of Physics, University of Crete, Heraklion, Greece
2 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
3 Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia
4 Integrated Catchment Assessment and Management Centre, Centre for Resource and Environment Studies, Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

Nineteen carbon stars that show lithium enrichment in their atmospheres have been discovered among a sample of 674 carbon stars in the Large Magellanic Cloud. Six of the Li-rich carbon stars are of J-type, i.e., with strong $^{13}$C isotopic features. No super-Li-rich carbon stars were found. The incidence of lithium enrichment among carbon stars in the LMC is much rarer than in the Galaxy, and about five times more frequent among J-type than among N-type carbon stars. The bolometric magnitudes of the Li-rich carbon stars range between $-3.3$ and $-5.7$. Existing models of Li-enrichment via the hot bottom burning process fail to account for all of the observed properties of the Li-enriched stars studied here.

Key words: Galaxies: Large Magellanic Cloud, Stars: carbon

1 INTRODUCTION

Lithium is a sensitive indicator of nucleosynthesis and convective dredge-up in stars, as it is easily produced as well as easily destroyed in stellar interiors.

It has been known for a number of decades (e.g. Torres-Peimbert & Wallerstein, 1966) that some Galactic asymptotic giant branch (AGB) stars possess large surface lithium abundances, reaching values one or two orders of magnitude higher than the cosmic value. More recently, Li-rich AGB stars have also been identified in other Local Group galaxies, namely the Large and Small Magellanic Clouds (LMC and SMC) and M31. The great majority of Li-rich AGB stars discovered to date in the Magellanic Clouds have oxygen-rich rather than carbon-rich atmospheres (Smith et al. 1995) (hereafter SPL95), although the opposite may be true in the Galaxy (Abia et al., 1993, Abia & Isern 1997).

The lithium enrichment of the atmospheres of oxygen-rich AGB stars (i.e., stars with C/O < 1) is relatively well understood within the framework of the hot bottom burning (HBB) process during which the bottom of the convective envelope of the star reaches the top layers of the hydrogen-burning shell. Sackmann & Boothroyd (1992) showed that in the intermediate mass range (4-6M$_\odot$) the Cameron-Fowler $^7$Be transport mechanism (Cameron & Fowler 1971) is very effective at producing $^7$Li (via the decay of $^7$Be) and can account for the super-Li-rich, oxygen-rich AGB stars found by Smith & Lambert (1990) in the Magellanic Clouds.

Carbon-rich AGB stars (C/O > 1), (i.e., carbon stars), also display enhanced lithium abundances. Very large equivalent widths ($W_{6707} \sim 10\AA$) of the Li I $\lambda 6707$ resonance doublet have been found in a few Galactic carbon stars: examples are WZ Cas and WX Cyg which are classified as N7 (C$_2$ 2) and J6 (C$_2$ 3') by Keenan (1993) and Barnbaum, Stone & Keenan (1996) respectively. However, most Galactic carbon stars have much weaker lithium lines with $W_{6707} < 0.5\AA$ and some have $0.5\AA < W_{6707} < 1\AA$ (Torres-Peimbert & Wallerstein 1966). In the Magellanic Clouds, on the other hand, carbon stars that display lithium-enriched atmospheres seem to be rarer and generally less extreme in terms of lithium abundance, compared with their Galactic counterparts or with the oxygen-rich AGB stars within the Clouds (e.g., SPL95) mentioned in the previous paragraph. In the most comprehensive study yet of Li-rich AGB stars in the Magellanic Clouds by SPL95, only four Li-rich carbon stars were recorded in the LMC and just two in the SMC.

The study of Li-rich carbon stars present difficulties both observationally and theoretically. On the observational side, severe measurement difficulties arise from the blending of the lithium lines with the complex array of lines in the red A $^2$II-$X^2$Σ CN system. This heavy line blanketing also means that equivalent width measurements are generally made relative to a pseudo-continuum rather than the true continuum. From the theoretical viewpoint, the coexistence of carbon and lithium in the atmosphere of an AGB star is difficult to achieve, at least in the hot-bottom-burning scenario, since the conditions required to ignite lithium production also lead to fast CNO processing at the base of the envelope, with the subsequent destruction of the $^{12}$C that was previously conveyed to the stellar
surface. Ventura, D’Antona & Mazzitelli (1999), however, showed that, for a certain range of stellar masses corresponding to a very narrow range in bolometric magnitude of $-5.95 < M_{bol} < -5.75$, carbon can survive long enough in the convective envelope to keep C/O $> 1$, despite the activation of the Cameron-Fowler mechanism. At the same time, the $^{12}\text{C}/^{13}\text{C}$ ratio increases and the star displays the spectral characteristics of a J-type carbon star which is also Li-rich. These models, however, cannot explain the existence of the fainter (by up to about one magnitude) Li-rich carbon stars found by SPLL95 in the Magellanic Clouds, as well as by Abia et al. (1993) in the Galaxy. Abia & Isern (1997) proposed an alternative mechanism to HBB, involving deep mixing, operating in low-mass carbon stars ($M < 2M_\odot$) which can account for the fainter Li-rich and Li-rich (J-type) carbon stars, found in the Galaxy and in the Magellanic Clouds. A more detailed description of the various models will be discussed later in the light of the new observations described in the present study.

For Li-rich carbon stars, the derivation of reliable lithium abundances, the acquisition of adequate statistics of their occurrence, as well as an understanding of their exact evolutionary stage, are all outstanding and open issues which are important not only for late-stage stellar evolution and nucleosynthesis, but also for modelling the present-day lithium abundance in our Galaxy and other galaxies (e.g., Travaglio et al. (2001), Ventura et al. (2000), Romano et al. (2001)). It must be emphasized that the study of lithium production in external galaxies such as the Magellanic Clouds is particularly important in this respect, since lower metallicity and a different evolutionary history would affect the yield of lithium on galactic scales.

Following the completion of a catalogue of 7760 carbon stars in the Large Magellanic Cloud by Kontizas et al. (2001) (see also Dapergolas et al. (1996)), an extensive programme of spectroscopy of carbon stars has been started (Cannon et al. 1999) using the 2dF multi-object spectroscopic facility on the Anglo-Australian Telescope (AAT) (Lewis et al. 2002). The subject of the present paper is the detection of the $\lambda 6707$ resonance doublet in the spectra of 19 out of the 674 carbon stars studied. This is the first time that such a large homogeneous spectroscopic sample of carbon stars has been studied in the context of lithium enrichment in any galaxy. Having homogeneous spectra for such a large sample of carbon stars, all at practically the same distance and with little reddening, provides a firm basis for making stronger statistical statements about the LMC carbon stars than can be done for (current) Galactic, or other Magellanic Cloud samples. The paper is organized as follows: Section 2 describes the observations, Section 3 describes the basic characteristics of the spectra obtained, while Section 4 outlines the method used to identify and measure the equivalent widths of the $\lambda 6707$ resonance doublet. In Section 5, the photometric properties of the identified Li-rich carbon stars are investigated, while in Section 6, the results are compared with those of previous studies, and some theoretical implications are discussed.

2 OBSERVATIONS

Most of the carbon stars observed were selected from the Kontizas et al. (2001) catalogue of LMC carbon stars: SIMBAD identifier – KDM. This catalogue was constructed by identifying the strong (1,0) and (0,0) $^{12}\text{C}$ Swan bands (at 4737Å and 5165Å respectively) in carbon stars seen in low-dispersion spectra on an objective-prism survey taken in the blue–green with the 1.2-m UK Schmidt Telescope.

The spectroscopic observations were obtained at the AAT on 21 and 22 January 1998, using the 2dF multi-fibre spectroscopic facility, which enables up to 400 spectra to be recorded simultaneously, in a pair of identical fibre-fed spectrographs fitted with TEK 1024 CCDs (Lewis et al. 2002) – see http://www.aao.gov.au/2df/. The target stars covered four 2° diameter fields. The spectra were centred on the $\Delta \nu = +2$ Swan bands near 6200Å and covered the wavelength range 5675–6785Å. Subsequent 2dF observations of more Magellanic Cloud carbon stars were taken over a slightly different wavelength range which included the strong (0,1) Swan band at 5635Å but excluded the Li$\lambda 6707$ line.

The 1200R gratings were used, yielding spectra with a 1.1Å per pixel or an effective resolution of $\sim 2.5\text{Å}$. Several exposures were taken for each field, typically 3 $\times$ 900s or 2 $\times$ 1200s, together with offset sky, arc and flat field exposures. The data were reduced with the AAO’s 2dFDR data reduction package (Bailey et al. 2001) and the IRAF package and yielded spectra with signal-to-noise ratio (S/N) usually around 30 per pixel. Full details of the observations are given by Cannon et al. (in preparation).

Relative radial velocities of all the stars were obtained by using a cross-correlation technique in FIGARO. The high signal-to-noise ratio (S/N) usually attained for most stars and the large number of spectral features resulted in an internal precision of about 1/20 pixel though with external accuracies closer to 1/10 pixel.

3 SPECTRAL ANALYSIS

3.1 General considerations

The spectra have remarkable similarities due to the abundance of CN lines. They can be classified, however, in four main groups, which will be used to aid the analysis. These are: (1) typical N5-type carbon stars, with strong Swan bands and CN bands, (2) stars with weak Swan bands near 6200Å due to higher temperature and/or lower carbon abundance, (3) stars with very weak carbon features, (4) J-stars with strong $^{13}\text{C}^{12}\text{C}$ and $^{13}\text{C}^{14}\text{N}$ bands as well as the normal $^{12}\text{C}^{12}\text{C}$ and $^{12}\text{C}^{14}\text{N}$ bands. As noted earlier, identification of the J-type stars is important in the context of the theories of lithium enrichment in carbon stars. Details of the precise method used to identify the J stars are given by Morgan et al. (2003); but it is sufficient here to note that the method selects stars with a similar level of $^{13}\text{C}$ to the standard definition of a J star, which is equivalent to $^{12}\text{C}^{13}\text{C} < 15$ (Abia & Isern 1997). Allocation of the other stars to the first three groups was made by simple visual inspection. Exams of the spectral groups can also be found in Barnbaum et al. (1996). (1) TV Lac; 2: BD +2$^\circ$3336 and Z Psc; 3: HD 123821 and HD 76846; 4: HD 10636 and EU And). Each observed star (with sufficient S/N) was assigned to one of these four
The numbers of stars in the four groups were 486, 92, 23 and 66 respectively making a total number of 674 stars. The spectral range used in the following analysis was limited to 6690–6730Å. Each spectrum was corrected for its radial velocity using a grid of interpolated wavelength points to allow this to be done to the sub-pixel accuracy of the velocities. It was then normalized using mean counts in bands at 6695–6703Å and 6712–6720Å. A mean spectrum was constructed for each one of the four spectral groups. The mean spectra of N and J stars (Groups 1 and 4) are shown in Figs 1a & 1d respectively. The mean spectra of the carbon-weak stars (Groups 2 and 3) are like that for Group 1 but with weaker features. The J-star combined spectrum is clearly different from the N-star spectrum because of the presence of $^{13}\text{CN}$ bands. The spectrum of the LMC carbon star BMB R-46 taken from SPLL95 is shown in Fig. 1b; the similarity between it and the N-star spectrum of Fig. 1a is striking. The Galactic carbon star SY Eri, which is classified by Barnbaum et al. (1996) as N5 ($C_2$ 5), is shown at a higher resolution in Fig. 1c (Abia et al. 1993) and is again similar to the combined N-star spectrum. However, there are differences: Ca $\text{I} \lambda 6717$ is strong in SY Eri but is not apparent in either of the LMC stars and there are more features in the region 6702–6710Å of the Galactic star. These differences are due in part to the lower resolution of the LMC spectra and also to the lower metallicity of the LMC. Indeed, the strength of the calcium line in SY Eri is consistent with solar abundance (Abia et al. 1993).

3.2 Identification of Li $\text{I} \lambda 6707$

The Li $\text{I}$ resonance doublet at 6707.8Å lies in a spectral region which is heavily affected by many atomic and molecular features. These are mainly CN lines, but molecular lines of $C_2$ and TiO are also present near the Li doublet. However, the $C_2$ lines are of minor importance compared with the CN lines since at all optical depths the CN concentration is a factor of 7 to 100 times higher than the $C_2$ concentration (Abia et al. 1993). Moreover, since $C/O > 1$, CO formation is favoured against TiO. The presence of strong CN bands makes it difficult to use simple visual means to select stars with enhanced lithium, and even harder to measure the strength of the line.

The method chosen here to identify the lithium line in a particular star was to subtract the mean observed spectrum (described above) of the spectral group appropriate for the star in question, scaled according to the strength of the CN bands in the individual spectrum. The scaling factor was determined by minimizing the difference between the spectrum and the scaled mean. The subtracted spectrum is mainly that of CN, but includes contributions from metal lines and other molecular bands. The subtraction process is designed to reveal only those features that deviate significantly from the scaled mean spectrum. Fig. 2 shows examples of this process for three stars: two typical N stars (Group 1), one with and the other without a lithium line, and a J star (Group 4) with a strong lithium line. The relative smoothness of the residual spectra beyond the bounds of the lithium line and seen throughout the entire upper panel shows that this is a valid procedure which takes account of the strong star-to-star variations in the overall strengths of the CN bands, presumably depending on both temperature and carbon and nitrogen abundances.

Residual spectra such as those shown as solid lines in Fig. 2 were constructed for every observed star. Lines in the residual spectra were then sought as follows: a second-order polynomial was fitted to the residual spectrum using the least-squares method in order to define the ‘continuum’ and all maxima and minima (potential emission and absorption lines respectively) about this fit were identified. A gaussian, superimposed on the quadratic fit, was then fitted to each maximum and minimum allowing its central wavelength ($\lambda_{cen}$), height and full width at half maximum ($\text{FWHM}$) to vary. The equivalent widths of the identified (both emission and absorption) lines ($W_\lambda$) were then measured. It should be emphasized that these equivalent widths should be used in a relative sense only, due to their strong dependence on the way the continuum is defined. Other au-

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**Figure 1.** Spectra in the region around Li $\text{I} \lambda 6707$. (a) mean spectrum of Group 1 (~N5) stars; (b) LMC star BMB R-46 from SPLL95; (c) Galactic star SY Eri (type N5($C_2$ 5)) from Abia et al. (1993); (d) mean spectrum of Group 4 (J) stars.
Figure 2. Normalized spectra of three carbon stars. The dashed line is the spectrum of a star, the dotted line is the mean spectrum of all stars in the same spectral group and the solid line is the difference between the spectrum and the scaled mean spectrum. (a), the N star (Group 1) KDM 3863 which has no lithium line; (b), the N star KDM 1792 which does show a lithium line; (c), the J star (Group 4) KDM 2832 which has a strong lithium line. The scaling factors applied to the mean spectra were 0.6, 1.0 and 0.9 respectively.

The authors use a pseudo-continuum, so equivalent widths from different sources are not directly comparable.

Clearly, a spectrum with poor signal-to-noise ratio will generate random ‘lines’. It turns out that the number of detected lines starts to rise significantly once the count level falls below ~500 counts per pixel. Consequently, 53 stars with fewer than 500 counts per pixel were excluded from further consideration.

The derived $W_\lambda$ are plotted against $\lambda_{\text{cen}}$ in Fig. 3. What appears as a gap around $W_\lambda = 0$ is merely a consequence of the limit applied to the line search procedure. Absorption features appear in the lower part of the figure; emission features appear in the upper half. The fairly uniform distribution of points with $|W_\lambda| \lesssim 0.25$Å demonstrates the noise level of the identification procedure, which results from the S/N in the original spectra, the spectral mismatch between star and template and/or velocity errors. Most of the features in this region of the diagram have $W_\lambda = 0$ and are indeed unlikely to correspond to true absorption (or emission) features given the spectral resolution of 2.5Å. However, there are a few outlying points, both below (absorption) and above (emission) this band, which have $|W_\lambda| \gtrsim 0.3$Å and which were selected for further investigation. In particular, there is a peak in the distribution of absorption features at 6708Å and emission peaks at 6717Å and 6706Å.

The emission features at 6717Å are due to [S II] λ6717, most probably originating in line-of-sight nebulosity in the LMC. This supposition is corroborated by the fact that the same stars also show strong Hα emission, as one would expect. The occasional appearance of nebular emission lines in the 2dF data is not surprising because there is patchy nebulosity across the LMC field, but the sky subtraction was done using the mean signal from a relatively small number of sky fibres chosen to lie in clear areas. However, the [S II] λ6717 emission lines do help place limits on the acceptable values of the gaussian FWHM. Most of these have $2 \AA < \text{FWHM} < 3$Å, and none has $\text{FWHM} < 2$Å or $\text{FWHM} > 4.5$Å. Consequently, all detections with $\text{FWHM} < 2$Å were excluded from further consideration. In practice, no features rejected in this way were

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close to the position of the lithium line. Since small spectral mismatches in the region around the lithium line can affect the wings of the detected lithium feature, as is the case with the strong line shown in Fig. 2c, an upper limit for the line width was set at $\text{FWHM} \leq 5\text{Å}$.

Another way to study these results is to consider Fig. 4 which shows histograms of the identifications plotted in Fig. 3 which lie in the range $2\text{Å} \leq \text{FWHM} \leq 5\text{Å}$. The 40Å wavelength range is divided into 2Å-wide bins. The three left-hand panels are for absorption features and the three right-hand panels are for emission features. The individual histograms are for identifications with $W_\lambda > 0.4\text{Å}$, $0.3 < W_\lambda < 0.4\text{Å}$ and $W_\lambda < 0.3\text{Å}$. The predominance of the peak at 6708Å in the stronger absorption features is obvious (Fig. 4a); it contains eleven stars, one of which, KDM 2832, has a very strong absorption line at 6707Å and stands out clearly from the rest in Fig. 3. Its spectrum is plotted in Fig. 2c and shows a Li $\lambda$6707 that is strong enough to be seen even without the subtraction of the template spectrum.

Of the remaining three features in Fig. 4a, one appears at 6691Å in star KDM 2379, another is the blend of two smaller features at 6717Å in star KDM 3389 and the third is the consequence of a bad pixel. Since none of the bins in Fig. 4a apart from the 6708Å bin has more than one star, it is reasonable to assume that no more than one of the eleven stars in the 6708Å bin is there by chance. With only two out of 18 bins having single stars, the likelihood that this is happening is only $\sim 0.11$.

The same peak can be seen in the weaker lines of Fig. 4b, but here there are also significant numbers of lines in the two neighbouring bins at lower wavelengths. Nevertheless, the histogram certainly reflects a non-random distribution. It is unlikely that the detections shortward of 6708Å are due to enhancements of individual metal lines because related metal lines are found in other wavelength bins as well (Barnbaum 1994) and are relatively weak in LMC stars. It is more likely that they are associated with a general spectrum characteristic which also produces the relatively high numbers of weak lines found (Fig. 4c) at the same two bins and also gives rise to a number of emission features at 6706Å (Fig. 4e). This could be due to differences in the relative strengths of the $^{12}\text{C}^{12}\text{C}$, $^{13}\text{C}^{12}\text{C}$, $^{12}\text{C}^{14}\text{N}$ and $^{13}\text{C}^{14}\text{N}$ molecular bands between some stars and the mean spectrum. In contrast, very few very weak lines are found at 6708Å. Nor are many emission lines found at 6708Å. If, as is likely, the weak lines give a measure of how errors in the method generate lines, two of the ten lines in the 6708Å bin in Fig. 4b are expected to have been caused in this way. If they do not, then the number of false detections at 6708Å (at $0.3 < W_\lambda < 0.4\text{Å}$) could be as high as the number seen in the neighbouring bin at 6706Å, i.e., five out of the ten detections at 6708Å could be false.

Fig. 5 is an example of a J star with a modest detection of Li $\lambda$6707 with $W_\lambda = 0.48\text{Å}$. (This can be compared with the strongest lithium line detected in our sample, shown in Fig. 2c.) The superimposed lines show the quadratic 'continuum' and the fitted gaussians. This particular example includes gaussians fitted to two broad shallow absorption features and two narrow emission features; all these have $\text{FWHM}$ values that are inappropriate for real lines. Although very clear in this figure, the line at 6707Å cannot be seen directly in the original spectrum, but is manifested as a low

![Figure 4. Histograms of 'lines' detected in the residual spectra. Panels (a), (b) and (c) are for absorption 'lines' with $W_\lambda > 0.4\text{Å}$, $0.3 < W_\lambda < 0.4\text{Å}$ and $W_\lambda < 0.3\text{Å}$ respectively; Panels (d), (e) and (f) are for emission 'lines' in the same three ranges of $W_\lambda$.](image-url)
Table 1a gives the final sample of carbon stars with absorption features within 0.75 Å of Li $\lambda 6707.8$, with $W_{6707} > 0.3$ Å and with 2.0 Å $\leq$ fwhm $\leq$ 5.0 Å. As seen in the previous section, features with $W_{6707} > 0.4$ Å are likely to be due to Li $\lambda 6707$ at the 90 per cent confidence level, while those with 0.3 $< W_{6707} < 0.4$ Å are likely to be due to Li $\lambda 6707$ at the 50–70 per cent confidence level. Column 1 gives the identification number of the star in the Kontizas et al. (2001) catalogue, column 2 gives the spectral group assigned to each star (see Section 3.1), columns 3 to 6 give various photometric measurements which will be explained in Section 4, columns 7 and 8 give the $W_{6707}$ (equivalent width) and fwhm measurements of the line at 6707 Å, column 9 gives the J-index taken from Morgan et al. (2003) and column 10 provides cross references to Blanco, McCarthy & Blanco (1980): BMB, Blanco & McCarthy (1990): BM, Hughes (1989): SHV, and Westerlund et al. (1978): WORC.

Table 1b provides a list of LMC and SMC carbon stars with identification of Li $\lambda 6707$ recorded in the literature and makes a noteworthy comparison with Table 1a. SPLL95 reported four Li-rich LMC carbon stars and a further 31 carbon stars for which lithium could not be detected. Richer, Olander & Westerlund (1979) and Richer (1981) detected the lithium line in two out of 52 stars and two out of 25 stars respectively. With one in each of the two pairs common to SPLL95, the total number of stars is six. SPLL95 also note two Li-rich SMC stars. These are both members of the Rebeirot, Azzopardi & Westerlund catalogue (Rebeirot et al. 1993) and both are J stars as seen in other 2dF data (Cannon et al., in preparation). They are also included in Table 1b.

3.4 Comparison with other work

First there is the question of commonality between the 2dF-selected and previously known Li-rich stars. It turns out that not one of the six known Li-rich stars were included in the 2dF sample. Nor were any of the stars reported by SPLL95 as having no lithium detection included in the 2dF sample. However, five of the other stars observed by Richer et al. (1979) (WORC54 $\equiv$ KDM1490, WORC78 $\equiv$ KDM1814, WORC106 $\equiv$ KDM2518, WORC192 $\equiv$ KDM5314, WORC196 $\equiv$ KDM5426) and three of those observed by Richer (1981) (BMB BW31 $\equiv$ KDM2117, BMB BW41 $\equiv$ KDM2148, BMB BW54 $\equiv$ KDM2197) are in the 2dF sample. Whereas Li $\lambda 6707$ was not noted by these authors as being present in any of these eight stars, it was found in one of the 2dF spectra (KDM 2197); none of the others has a line anywhere near the limit for inclusion in Table 1a. In fact, the line identified in KDM 2197 is at the lowest limits of both $W_{6707}$ and fwhm for inclusion in the table. It is likely that this strength is below the limit for identification by Richer (1981).

The equivalent widths, $W_{6707}$, recorded in Table 1a range between 0.3 Å and 0.6 Å with one stronger line at 1.4 Å. Torres-Peimbert and Wallerstein (1966) found similar strengths for $W_{6707}$ of $\sim$ 0.4–0.5 Å in fourteen of the sixteen Galactic carbon stars in which they detected lithium. The other two were the well known super-Li-rich stars WZ Cas and WX Cyg. However, in the more recent studies by SPLL95 in the Magellanic Clouds and by Boffin et al. (1993) in the Galaxy, significantly higher values $W_{6707}$ have been reported. In fact, three of the four Li-rich LMC carbon stars described by SPLL95 are in the super-Li-rich category. Part of the discrepancy between levels of $W_{6707}$ is due to the different methods used. SPLL95 used a pseudo continuum fitted near 6700 Å and did not attempt to correct their values of $W_{6707}$ for a CN contribution. It is worth stating that the $W_{6707}$ levels determined by Torres-Peimbert and Wallerstein (1966) and noted above as being similar to those of Table 1a were corrected for a contribution from CN, though through a method different to the one used here. Inspection of Fig. 2c shows that this technique would give a larger equivalent width than the one quoted in Table 1a. Tests on the 2dF spectra of J stars imply differences of 0.4–0.5 Å between the two methods. However, this level of discrepancy is not sufficient to explain why no super-Li-rich carbon stars were discovered in the 2dF sample.

4 PHOTOMETRY

Infrared photometry of sources in much of the LMC is now available through the Second Incremental Data Release of the Two Micron All Sky Survey – (2-MASS) (Skrutskie et al. 1997) and is available on-line at http://irsa.ipac.caltech.edu/. 2-MASS JHK measurements were extracted for the stars in the 2dF sample by matching catalogue coordinates. Whenever 2-MASS data were
Table 1. Magellanic Cloud carbon stars with Li i λ6707

| Star  | Gp  | J   | K   | Mbol | Teff | W6707 | fwhm | j-index | Other      |
|-------|-----|-----|-----|------|------|-------|------|---------|------------|
| a. 2dF stars |
| 1310  | 1   | 11.37 | 9.99 | -5.48 | 3230 | 0.49  | 3.0  |
| 1393  | 4   | 12.58 | 10.74 | -4.46 | 2670 | 0.50  | 4.0  | 5.9      |
| 1402  | 1   | 11.79 | 9.86 | -5.32 | 2580 | 0.40  | 3.0  |
| 1608  | 4   | 13.54 | 12.46 | -3.34 | 3740 | 0.33  | 2.5  | 3.6      |
| 1792  | 1   | 12.52 | 10.97 | -4.37 | 2990 | 0.60  | 4.0  |
| 2155  | 4   | 12.61 | 10.83 | -4.39 | 2730 | 0.48  | 3.5  | 6.0      |
| 2197  | 1   | 11.58 | 9.76 | -5.44 | 2690 | 0.30  | 2.5  | BMB BW54  |
| 2364  | 4   | 13.04 | 11.20 | -4.00 | 2670 | 0.30  | 3.5  | 5.3      |
| 2400  | 1   | 12.86 | 11.34 | -4.02 | 3030 | 0.45  | 4.0  |
| 2406  | 1   | 11.37 | 9.77 | -5.53 | 2930 | 0.35  | 3.0  |
| 2832  | 4   | 11.76 | 10.34 | -5.09 | 3170 | 1.42  | 5.0  | 5.6      |
| 3344  | 1   | 11.24 | 9.62 | -5.67 | 2910 | 0.31  | 3.0  | WORC 138  |
| 3495  | 2   | 12.53 | 10.91 | -4.38 | 2910 | 0.44  | 2.5  |
| 3525  | 1   | 13.29 | 12.10 | -3.56 | 3530 | 0.30  | 3.0  |
| 4404  | 1   | 12.53 | 10.84 | -4.42 | 2830 | 0.35  | 4.5  |
| 4141  | 4   | 12.06 | 10.56 | -4.81 | 3140 | 0.49  | 3.5  | 5.4      |
| 4626  | 4   | 12.82 | 10.84 | -4.33 | 2530 | 0.36  | 5.0  | 4.8      |
| 4850  | 2   | 12.54 | 11.19 | -4.31 | 3270 | 0.48  | 3.0  | SHV 0534304-720850 |
| 5455  | 1   | 12.65 | 11.13 | -4.23 | 3030 | 0.59  | 3.5  | BM 35-15  |
| b. Published stars |
| 1604  | 4   | 11.80 | 10.36 | -5.00 | 3140 | 4.43  | WORC 65  |
| 2041  | 4   | 13.30 | 11.72 | -3.56 | 2960 | BMB BW9 |
| 2809  | 12.33 | 10.91 | -4.47 | 3170 | 1.71  | HV 5680 |
| 11.98 | 9.65 | -5.60 | 2250 | 6.41  | BMB R46 SHV 0521050-690415* |
| 0     | 11.48 | 10.23 | -5.29 | 3430 | 8.33  | BMB BW89* |
| 2     | 12.10 | 9.35 | -6.22 | 1980 | WORC 186* SHV 0535323-710211 |
| 4     | 12.64 | 10.98 | -4.71 | 2817 | 2.45  | RAW 1296* |
| 4     | 13.02 | 11.29 | -4.37 | 2740 | 1.55  | RAW 1329* |

W6707 and fwhm are in Å
W6707 values given in brackets were determined by a different method (see text)

*: Gp 0 represents an SC star (Richer & Frogel 1980)
#: Gp 2 for WORC 186 is assumed from data by Richer et al. (1979)
**: BMB R46 is also F4488 as recorded by SPLL95
*: RAW 1296 and RAW 1329 are SMC members
unavailable, JK measurements were taken from the Deep Near-Infrared Survey of the southern sky – DENIS (Cioni et al. 2000) which is available on-line from the CDS at Strasbourg (http://cdsweb.u-strasbg.fr/denis.html). The magnitudes from the DENIS database were corrected in the way described by Morgan et al. (2003) to bring them into alignment with the 2-MASS data.

The J and K magnitudes were subsequently used to derive bolometric magnitudes (Mbol) and effective temperatures (Teff) by applying the relations Mbol = K_o - dm + 0.69 + 2.65(J-K)_o - 0.67(J-K) and Teff = 7070/[J - K]_o + 0.88, derived by Wood, Bessell & Fox (1983) and Bessell, Wood & Lloyd Evans (1983), respectively. A distance modulus value of 18.45 was adopted (Westerlund 1997) and a mean reddening of E(J-K) = 0.07 (Costa & Frogel 1996). Small deviations from the adopted value of the reddening do not significantly affect the derived values of Teff and Mbol. The resulting values of Teff and Mbol are listed in Columns 5 and 6 of Table 1. It must be pointed out that the use of these parameterizations for Mbol and Teff may not be fully applicable to the specific stars studied here and must be treated with caution. Formal errors for Mbol and Teff are ±0.2 mag and ±0.7 K.

The bolometric magnitudes of the Li-rich stars identified in the 2dF sample lie in the range −3.3 to −5.7 which includes fainter stars than the range of −4.6 to −5.7 occupied by the four Li-rich LMC stars identified by SPLL95. Similarly faint Li-rich carbon stars have been found in the SMC (SPLL95), in M31 (Brewer et al. 1996), and in the Galaxy where −3.5 < Mbol < −6.0 (Abia & Isern 1997).

Figure 6 shows the location of the Li-rich carbon stars of Table 1a on the Hertzsprung-Russell Diagram. For comparison the location of all carbon stars observed are shown on the same diagram. Their bolometric magnitudes and effective temperatures were derived in the same way as those of the stars in Table 1, based on the data in Cannon et al. (2003; in preparation). The six Li-rich stars listed in Table 1b are also included in this plot. The distribution of the Li-rich stars in Fig. 6 is clearly not the same as that of the normal carbon stars. Of the stars plotted as triangles, the two 'coolest' (WORC 186 and BMB R46) are both extreme colours, and the 'warmest' (BMB BW89) is actually an SC star (Richer & Frogel 1980) and perhaps should not be included. Two of the 2dF Li-rich stars are fainter and cooler than the others and lie near the tip of the red giant branch.
Figure 6. A plot of $M_{\text{bol}}$ against $T_{\text{eff}}$ for LMC carbon stars. The circles are the Li-rich stars of Table 1a and the triangles are other Magellanic Cloud stars known to have strong Li\textsc{i} $\lambda$6707 (SPLL95).

Figure 7. Relative frequency of carbon stars in $M_{\text{bol}}$ intervals of 0.5 mag. The left-hand panel is for N stars and the right-hand panel is for J stars. The open circles are for normal carbon stars and the solid squares are for the Li-rich stars in Table 1a.

rather than on the AGB; the rest lie among the main body of AGB stars but seem to be more widely distributed and relatively uncommon at the peak of the general distribution. Fig. 7 shows the distribution of Li-rich stars with bolometric magnitude (in 0.5-magnitude bins), separately for N and J types. For comparison, the distributions for normal carbon stars are superimposed. The normal N and J stars have clear single peaks at $M_{\text{bol}} = -4.75$ and $M_{\text{bol}} = -3.75$ respectively. Although the total number of J stars is small here, studies of a much larger sample show that the J stars are indeed fainter than the N stars (Morgan et al. 2003). The error bars shown in Fig. 7 are based on $\sqrt{n}$ statistical errors. There would not seem to be a significant difference between the distributions of the bolometric magnitudes of the Li-rich and normal J stars. However, the Li-rich N stars are absent from the $M_{\text{bol}} = -4.75$ bin which is the peak of the normal N-star distribution. There are, in fact, no Li-rich N stars in the range $-5.25 < M_{\text{bol}} < -4.5$.

5 DISCUSSION

5.1 Statistics

Of the 667 stars studied here, 53 were excluded as being of insufficient quality to allow the reliable non-detection (or detection) of Li\textsc{i} $\lambda$6707 to a limit of $W_{6707} \approx 0.3\AA$. Of the remaining 614 stars, nineteen (i.e. 3.1 per cent) have detectable Li\textsc{i} $\lambda$6707. Among the 614 stars there are 62 J stars, of which seven are Li-rich. This means that, to the detection limit of the present work, 11.3 per cent of the J stars are Li-rich compared with only 2.2 per cent of the non-J stars. So lithium enrichment seems to be about five times more frequent among J-type carbon stars. No super-Li-rich carbon stars were discovered in the sample of 614 stars. It is probably true to say that none was discovered in the full sample of 667 stars because most of the extra 53 stars could have revealed a very strong lithium line with $W_{6707} \sim 4\AA$.

These percentages are significantly lower than those recorded in the literature for the Galaxy and the Magellanic Clouds, although in the latter case in particular the samples are one or two orders of magnitude smaller than the present one. Boffin et al. (1993) found that in a sample of about 200 Galactic carbon stars $\approx 12.5$ per cent were Li-rich and 1.5 per cent were super-Li-rich. (The Boffin et al. (1993) results are updates of generally similar results based on smaller samples, presented in the earlier papers of Abia et al. (1991, 1993).) More recently, Abia & Isern (1997) made an extensive study of 44 Galactic carbon stars (28 of N type, 11 of J type, and 5 SC stars) and detected $^7$Li in 82 per cent of the J stars and in 15 per cent of the rest. In the Magellanic Clouds, SPLL95 found four Li-rich carbon stars out of a total of 35 LMC carbon stars in their sample (11.4 per cent) and 2 out of 25 (8 per cent) for the SMC.

Part of the difference in the frequencies of Li-rich carbon stars reported by the different authors may be related to actual differences between the carbon star populations in the parent galaxies (ages, masses, metallicities), but part of it may be due to the different approaches adopted for the lithium detection in the spectra, and, most importantly, the correction (or lack of it) for the CN contribution and the choice of continuum. The size of the sample considered in each case and its initial selection must also be taken into account.

5.2 Spectral properties

In order to gain some insight into the formation of the observed population of Li-enriched carbon stars, it is useful to investigate the possible existence of correlations between the equivalent widths $W_{6707}$ and other properties of the stars, such as bolometric magnitude, effective temperature, and spectral group (Groups 1–4 as shown in Table 1a). Figs 8a and 8b show $W_{6707}$ plotted against $M_{\text{bol}}$ for the 2dF results.
in Table 1a and the data from SPLL95 (Table 1b) respectively. The SC star, BMB 89, is considered to be too different in spectral type and is not shown. The two points in brackets are estimates of \(W_{6707}\) based on the Li-indices published by Richer et al. (1979) and Richer (1981). No statistically significant correlations can be found for the N stars in Fig. 8a, but the bimodality of the distribution can be seen again. Nor did Abia et al. (1993) find any correlation between bolometric magnitude and lithium abundance for their sample of Galactic carbon stars. However, if only J-type carbon stars are taken into account, a different picture seems to emerge with \(W_{6707}\) appearing to increase with bolometric magnitude. For the 2dF sample plotted in Fig. 8a, this conclusion is based on just one star and cannot be taken as more than tentative; but it is more striking for the SPLL95 sample plotted in Fig. 8b. As noted earlier, the apparent offset between the new data and the SPLL95 results can be partly explained by the different continua adopted. In interpreting these diagrams it should be remembered that some of the stars, especially those in the SPLL95 sample, are variables and could change in stars, especially those in the SPLL95 sample, are variables in these diagrams it should be remembered that some of the

\[M_{bol} = \text{bol} - 6.3\]

by Whitelock & Feast (2000). With these considerations in mind, it is clear that a larger statistical sample is needed to confirm this result.

So it would appear that J-type stars hold some special position in the Li-enriched carbon star sample: (i) it seems to be about 5 times more likely to get a Li-enriched carbon star if it is also of J-type and (ii) there seems to be a correlation between bolometric magnitude and equivalent width of the lithium line for these stars. It must also be emphasized that the highest equivalent width of the lithium line in the 2dF sample occurs in a J-type carbon star.

\(W_{6707}\) does not seem to display any obvious correlation with either \(T_{eff}\) or, for the J stars, with the j-index derived by Morgan et al. (2003) and listed in Table 1a. However, it must be remembered that the size of the sample of J-type Li-enriched stars is just seven.

5.3 Theoretical models

Given that for the first time the search for Li-enriched carbon stars has been conducted within such a large and homogeneous spectral sample, it is worth discussing the theoretical implications of the results presented here. Ventura et al. (1999) produced a self-consistent description of time-dependent mixing, overshooting and nuclear burning in AGB stars, and showed that there is a narrow range of stellar masses in which, despite the activation of the Cameron-Fowler mechanism, carbon can survive long enough in the convective envelope to keep the C/O ratio over unity as well as increasing \(^{13}\text{C}/^{12}\text{C}\), and that consequently these objects can be observed as Li-rich C stars for a non-negligible fraction of their AGB life. Their model can account for:

(i) the very rare luminous Li-rich carbon star with \(M_{bol} = -6.5\). No such star exists in either our or SPLL95’s sample of LMC Li-rich carbon stars.

(ii) Li-rich J-type carbon stars with \(M_{bol} \approx -5.75\) to \(-5.95\). The brightest J-type Li-rich star in our sample has \(M_{bol} = -5.1\), which is more than half a magnitude fainter than required, for its formation to be attributable to this mechanism.

(iii) Li-rich non-J carbon stars for short periods during thermal pulses. Although this scenario could explain some of the N-type Li-rich carbon stars, it cannot explain all of them, as the mechanism can operate successfully only for short periods. Not enough details are given by Ventura et al. (1999) to allow for a stronger statement. In any case, the faint J-type Li-rich carbon stars in our sample cannot be explained in this way. To summarize, it would seem that only very few, if any, of the Li-rich carbon stars of Table 1a can be accounted for by these models; the predicted overall distribution of Li-enriched stars is not a good match to the observations. It should be noted that the models which reproduce the characteristics of J-type stars suffer from another deficiency; they predict that these stars should show enhancements of the s-process elements because they are thermally pulsing AGB stars which suffer the third dredge-up, but no s-process enhancements are seen in J-type carbon stars in the Galaxy. Thus, there is a strong possibility that J-type stars are not in the AGB phase and their chemical peculiarities are due to a different atmospheric processes.

Travaglio et al. (2001) investigated the behaviour of AGB models – again in the framework of the HBB process – with masses in the range 4–6\(M_{\odot}\) and metal abundances between \(Z = 0.004\) and \(Z = 0.02\). They showed that the condition \(C/O > 1\) together with high \(^7\text{Li}\) \((\text{log}(Li) \approx 4)\) can only be achieved for the 4\(M_{\odot}\) \(Z = 0.004\) case, while much lower Li abundances \((\text{log}(Li) \approx 2)\) are found for the same mass, but for \(Z = 0.008\). However, their models are far too bright \((-7 < M_{bol} < -6)\), to be applicable for the cases of Table 1a. They do, however, mention that preliminary calculations showed that lithium enrichment of AGB atmospheres through the HBB process can operate at lower masses (and give lower \(M_{bol}\)) for low metallicities \((Z = 0.0001)\). This statement holds promise with regard to the faint Li-rich carbon stars in the Magellanic Clouds, but one has to await for more detailed models.

Abia & Isern (1997) found observational evidence that supports the existence of a deep mixing mechanism operating in low-mass AGB stars that could be responsible for the
creation of Li-rich, J-type, low-mass (and low luminosity) carbon stars. This mechanism could account for the fainter J-type, Li-rich stars of Table 1a, but cannot explain the equally faint N-type, Li-rich carbon stars found.

6 SUMMARY

The results of the present study can be summarized as follows:

(1) The incidence of lithium enrichment among carbon stars in the LMC is much rarer than in the Galaxy, and about five times more frequent among J-type than among N-type carbon stars: of the 614 stars studied here, 19 (3.1 per cent) have detectable Li λ6707. Among the 614 stars there are 62 J-type stars, 7 (11.3 per cent) of which are among the Li-rich stars found here. No super-Li-rich carbon stars were found.

(2) The equivalent widths of the Li λ6707 line were measured from spectra corrected in a statistical fashion for the contribution from (mostly) CN. The values derived are similar to the corrected equivalent widths for the lithium line in Galactic carbon stars derived by Torres-Peimbert & Wallerstein (1966) but significantly lower than the values derived by SPLL95 in the Magellanic Clouds (whose values were not corrected for CN contamination).

(3) The bolometric magnitudes of the Li-rich carbon stars range between −3.3 and −5.7. The distribution in $M_{\text{bol}}$ of the Li-rich N-type carbon stars seems to have two distinct peaks at $\sim -4.25$ and $\sim -5.25$ mag.

(4) J stars hold some special position in the Li-enriched carbon star sample, as they are about five times more likely to be Li-enriched. Also, there seems to be some correlation between bolometric magnitude and equivalent width of the lithium line for these stars.

(5) Existing models of lithium enrichment via the hot bottom burning process fail to account for the observed properties of the Li-enriched stars studied here. A different deep mixing mechanism operating in low-mass AGB stars seems to be required, especially for the faint N stars that do show Li-enrichment.

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