Very Large Telescope Spectra of Carbon Stars in the Large Magellanic Cloud and Their Metallicity Dependence

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VERY LARGE TELESCOPE SPECTRA OF CARBON STARS IN THE LARGE MAGELLANIC CLOUD
AND THEIR METALLICITY DEPENDENCE


ABSTRACT

Very Large Telescope (VLT) L-band spectra of six carbon stars in the Large Magellanic Cloud are presented. The stars show absorption bands at 3.1 μm (HCN and C2H2), and 3.8 μm, which is probably due to C2H2. Two LMC stars show strong 3.5 μm HCN absorption. The equivalent widths of the 3.1 μm and 3.8 μm bands are systematically larger in LMC carbon stars than in carbon stars in the solar neighborhood. Moreover, the ratio of the equivalent widths of the 3.8 and 3.1 μm bands is much larger in the LMC, suggesting a higher ratio of n(C2H2)/n(HCN). The stronger absorption bands are in contrast to the assumption that if the elemental abundances are scaled from the carbon star’s abundances in the solar neighborhood, the abundances of these molecules are less at lower metallicity. We argue for a systematically larger C/O ratio in LMC carbon stars. In the Galactic carbon stars n(C)/n(O) ≈ 1.05–1.1 on average; our chemical model shows that the stronger molecular bands in the LMC carbon stars could be explained with n(C)/n(O) > 1.2. The higher C/O ratio can also explain the higher ratio of n(C2H2)/n(HCN) in LMC stars than in the solar neighborhood.

Subject headings: infrared: stars — Magellanic Clouds — stars: abundances — stars: AGB and post-AGB — stars: atmospheres — stars: carbon

1. INTRODUCTION

Carbon atoms are synthesized in asymptotic giant branch (AGB) stars via helium burning. During the third dredge-up the newly synthesized atoms are carried from the bottom to the surface of the convective envelope. At low metallicity, evolution models of AGB stars with an initial mass of 2.0–2.5 M☉ predict that carbon is enriched efficiently in the atmosphere, with the number of oxygen atoms remaining approximately constant (e.g., Vassiliadis & Wood 1993) but not completely constant; Péquignot et al. 2000). For the most massive AGB stars, nitrogen may also be enhanced due to the onset of hot bottom burning, converting the new carbon into nitrogen via the CNO cycle (e.g., Marigo & Girardi 2001).

This suggests that the elemental abundances at different metallicities are not simply scaled from the solar abundance. The effect can be studied in the Large Magellanic Cloud (LMC), where the metallicity is about a factor of 2 less than in the solar neighborhood. In the atmospheres of AGB stars in the LMC, carbon, and possibly nitrogen as well, is generally expected to be more abundant relative to oxygen. The ratio of carbon-rich stars with respect to oxygen-rich stars is indeed expected to be higher in the LMC than in the solar neighborhood. There is also tentative observational evidence for enhanced molecular abundances: Lançon & Wood (2000) suggested that two “oxygen-rich” LMC supergiants show relatively stronger CN absorption bands than galactic supergiants.

To investigate the metallicity dependence of the atmospheres of AGB stars, we obtained infrared spectra of carbon stars in the LMC. We find that the equivalent widths of molecular bands are systematically larger in LMC carbon stars than in Galactic carbon stars. The observed spectra and chemical models indicate that the abundance of especially C2H2 is enhanced.

2. OBSERVATIONS

Spectra in L-band of six carbon stars in the LMC were obtained with the Infrared Spectrometer And Array Camera (ISAAC) at the Very Large Telescope (VLT) of ESO Paranal, Chile, on 2001 December 12–14. The sky condition was photometric on December 13 and partly cloudy on December 12 and 14. The sample is selected from Trams et al. (1999a) and van Loon, Zijlstra, & Groenewegen (1999).

The wavelength resolution of the ISAAC observations was λ/Δλ ~ 600. As telluric standards, B dwarfs and giants from the Hipparcos catalog were observed after every target observation. The spectrum of the telluric standard is assumed to be a blackbody of the effective temperature based on the spectral type from the Hipparcos catalog. The data were reduced using the Eclipse package and IDL. An exposure of the twilight sky was used for flat-fielding. The wavelength calibration is based on exposures of an Ar + Xe arc lamp with the same wavelength setting as the target observations. The flux error is estimated from ten nearby sky pixels in the image.

Representative spectra of LMC carbon stars are shown in Figure 1. Several molecular bands are seen:  
1. C2H2 and HCN bands at 3.1 μm;
2. HCN band at 3.5 μm;
3. a band at 3.8 μm, tentatively identified as C2H2.

In Figure 2 a spectrum of an LMC carbon star, IRAS 04496–6958, is compared with that of a Galactic carbon star, V Cyg, with similar K–L color. All of the 3.1, 3.5, and 3.8 μm bands are deeper in IRAS 04496–6958 than in V Cyg.

1 Based on observations obtained at the European Southern Observatory, Chile (proposal 68.D-0660).
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We discuss the difference in equivalent widths of these molecular bands between the LMC and Galactic carbon stars in the following sections.

The identification of the 3.8 μm absorption band as C₂H₂ was made by Goebel et al. (1981), using a KAO spectrum of the carbon star V CrB. The 3.8 μm feature in the ISO/SWS spectra of the Galactic carbon star R Scl is also identified as C₂H₂ by Hron et al. (1998). The feature in V Cyg is similar. However, the shape of the feature in the LMC carbon star IRAS 04496−6958 looks slightly different. The deepest wavelength is 3.8 μm in IRAS 04496−6958, while it is 3.9 μm in R Scl and V Cyg. A difference in excitation temperature or column density could produce such a wavelength shift, but there is no proof for this. The identification of the 3.8 μm feature in LMC carbon stars as C₂H₂ is therefore tentative but will be assumed in the discussion below.

3. EQUIVALENT WIDTHS OF THE MOLECULAR BANDS

Figure 2 suggests that the molecular bands are stronger in LMC carbon stars than in Galactic carbon stars. The equivalent widths (W) of these three major bands are measured as summarized in Table 1. The results are shown in Table 2. The errors on the equivalent width are estimated from the flux errors.

The equivalent widths of the 3.1 μm band are plotted against K−L in Figure 3. The K- and L-band magnitudes of the LMC carbon stars are taken from Trams et al. (1999a), except for LI-LMC 1813, which is taken from J. Th. van Loon et al. (2002, in preparation). The equivalent width of the 3.1 μm band and K−L colors for additional carbon stars are taken from Groenewegen, de Jong, & Geballe (1994) (Galactic) and van Loon et al. (1999) (LMC, some objects are in common with our sample). van Loon et al. (1999) used 2.9 and 3.3 μm as the continuum level. Some ISAAC spectra are slightly affected by terrestrial atmospheric lines at 3.3 μm, and we use 3.35–3.40 μm instead. On average, this change affects the equivalent width by less than 0.002 μm, but some are affected by up to 0.02 μm.

Additional reference spectra of Galactic carbon stars are taken from the ISO/SWS data archive. These were studied by Yamamura et al. (1997), Aoki, Tsuji, & Ohnaka (1998), and Loidl et al. (1999a, 1999b). The K- and L-band magnitudes of these stars are taken from Le Bertre (1992) and Gezari, Schmitz, & Jaylee (1993). Within these samples, stars with colors 1 < K−L < 3 mag are not sampled. We therefore included stars with this color range from Noguchi et al. (1981) and obtained SWS data from the ISO archive.

Table 2 shows that the equivalent widths of the 3.8 μm band in the LMC carbon stars are larger than those in Galactic carbon stars. In ISO/SWS spectra published by Yamamura et al. (1997), Aoki et al. (1998), and Loidl et al. (1999a, 1999b), there are only four stars that show the 3.8 μm feature: R Scl, V Cyg, RU Vir, and T Dra. In contrast, all the LMC carbon stars exhibit the 3.8 μm feature. Assuming the 3.8 μm band is due to C₂H₂, Table 2 thus shows a large column density of C₂H₂ in LMC carbon stars—assuming that the excitation temperature is the same.

Figure 2 also shows a tendency for a systematically stronger 3.1 μm band in LMC carbon stars with respect to Galactic stars with the same color. This is consistent with van Loon et al. (1999), who found 3.1 μm band in LMC carbon stars is at least as strong as the one in Galactic stars. Two molecular species contribute to the 3.1 μm absorption: HCN and C₂H₂. Aoki et al. (1998) estimated that in the star WZ Cas, HCN is the dominant source of opacity in this band, with C₂H₂ contributing only up to 10%. The strong 3.8 μm band suggests that this ratio may be different for the LMC stars. This is illustrated in Figure 4, where the equivalent widths of the 3.1 and 3.8 μm bands are plotted against each other. With only a single exception, the LMC stars fall above the Galactic stars. WZ Cas, with its negligible C₂H₂ content, is located in the bottom right corner. This figure suggests that the fractional C₂H₂ contribution to the 3.1 μm feature can be systematically larger in the LMC carbon stars.

It is not clear that C₂H₂ is the sole cause for the larger 3.1 μm equivalent width evident in Figure 3. The error on W₁,₃, a measure of the HCN band, is similar to the strength of the feature in Galactic stars. The data still allow for the possibility of a somewhat higher HCN abundance, which could contribute to the stronger 3.1 μm feature. But the values for W₁,₃ are mostly

![Image](image_url)

**Fig. 1.—Example of LMC carbon star spectra. In IRAS 04496−6958 the HCN and C₂H₂ bands at 3.1 μm, the HCN 3.5 μm band, and the 3.8 μm band are seen. Atmospheric lines remain, especially around 2.9 and 3.3 μm.**

**Fig. 2.—Comparison of the LMC star IRAS 04496−6958 and the Galactic star V Cyg, whose K−L colors are similar. There are differences in the depth of the molecular features at 3.1 and 3.8 μm. Due to the different wavelength resolution, small features in IRAS 04496−6958 are more prominent.**

**Table 1**

<table>
<thead>
<tr>
<th>Name</th>
<th>Molecules</th>
<th>Measured Region (μm)</th>
<th>Continuum (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W₁,₃</td>
<td>HCN, C₂H₂</td>
<td>2.95–3.35</td>
<td>2.90–2.95, 3.35–3.40</td>
</tr>
<tr>
<td>W₃₈</td>
<td>C₂H₂</td>
<td>3.60–4.00</td>
<td>3.50–3.60, 4.00–4.10</td>
</tr>
</tbody>
</table>

**Note.**—The continuum level is linearly interpolated from the wavelength region in the last column.
upper limits, and a lower median HCN abundance in the LMC can also not be excluded.

In Table 2, a large $W_{3.5}$ is found in two LMC carbon stars, LI-LMC 1813 and IRAS 04496–6958. LI-LMC 1813 will be discussed separately by J. Th. van Loon et al. (2002, in preparation). A high value is found for IRAS 04496–6958, a possible silicate carbon star (Trams et al. 1999b), which would be a good candidate for hot bottom burning.

All equivalent widths show a decrease with redder $K-L$. This is probably due to filling of the molecular absorption bands with continuum dust emission. For stars with $K-L$ larger than unity this color is a measure of dust excess (absorption and emission), rather than the effective temperature of the star, and is related to the dust mass-loss rate. Although the same $K-L$ relates to similar dust mass-loss rates for both LMC and Galactic carbon stars, the correlation with the gas mass-loss rate will be affected by the different gas-to-dust ratio (van Loon 2000).

4. CHEMICAL EQUILIBRIUM MODELS

For lower elemental abundances, the molecular abundances will also be affected by the lack of metals (e.g., seen in Fig. 4 of Marigo 2002). The equivalent widths of molecular bands are thus expected to be smaller in the LMC.

To quantify this, we calculate chemical models for the stellar atmospheres. We assume local thermodynamic equilibrium to compute the relative molecular abundances (Markwick 2000), for a range of temperatures and metallicities. Figure 5 shows the abundances, in terms of the relative partial pressure, for HCN and C$_2$H$_2$. [Z/H] and C/O ratio, the HCN and C$_2$H$_2$ abundances at

![Image](fig3.png)

**Fig. 3.—**The 3.1 $\mu$m equivalent width is plotted as a function of the $K-L$ color. The lines are least-squares fits for the LMC sample (solid line) and the Galactic sample (dashed line).

![Image](fig4.png)

**Fig. 4.—**The 3.8 $\mu$m equivalent width as a function of the 3.1 $\mu$m equivalent width. 3.8 $\mu$m nondetected stars are marked with an arrow if they have a positive value of $W_{3.8}$. 

### Table 2

<table>
<thead>
<tr>
<th>Name</th>
<th>$W_{3.1}$ ($\times 10^4$ $\mu$m)</th>
<th>$W_{3.8}$ ($\times 10^4$ $\mu$m)</th>
<th>$W_{3.5}$ ($\times 10^4$ $\mu$m)</th>
<th>K−L</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I 04286–6937</td>
<td>7.27 ± 0.23</td>
<td>6.67 ± 0.03</td>
<td>(1.2 ± 6.3)</td>
<td>2.15</td>
</tr>
<tr>
<td>I 04496–6958</td>
<td>15.41 ± 0.02</td>
<td>6.07 ± 0.02</td>
<td>7.8 ± 1.8</td>
<td>1.80</td>
</tr>
<tr>
<td>I 04539–6821</td>
<td>8.20 ± 0.10</td>
<td>4.60 ± 0.02</td>
<td>(1.8 ± 3.2)</td>
<td>3.00</td>
</tr>
<tr>
<td>I 04557–6753</td>
<td>13.92 ± 0.07</td>
<td>6.67 ± 0.02</td>
<td>(0.5 ± 3.4)</td>
<td>2.85</td>
</tr>
<tr>
<td>I 05112–6755</td>
<td>9.70 ± 0.14</td>
<td>2.03 ± 0.04</td>
<td>(5.9 ± 5.5)</td>
<td>3.20</td>
</tr>
<tr>
<td>LI 1813</td>
<td>11.39 ± 5.29</td>
<td>5.24 ± 0.04</td>
<td>15.5 ± 9.4</td>
<td>3.72</td>
</tr>
<tr>
<td>Galactic:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP And</td>
<td>4.36</td>
<td>(−0.46)</td>
<td>3.8</td>
<td>2.18</td>
</tr>
<tr>
<td>V Aql</td>
<td>10.50</td>
<td>(0.48)</td>
<td>(1.1)</td>
<td>0.79</td>
</tr>
<tr>
<td>WZ Cas</td>
<td>14.69</td>
<td>(−0.37)</td>
<td>9.9</td>
<td>0.33</td>
</tr>
<tr>
<td>V Cyg</td>
<td>12.62</td>
<td>3.44</td>
<td>10.0</td>
<td>1.18</td>
</tr>
<tr>
<td>T Dra</td>
<td>11.29</td>
<td>3.78</td>
<td>11.7</td>
<td>1.59</td>
</tr>
<tr>
<td>CW Leo</td>
<td>2.30</td>
<td>(−0.33)</td>
<td>1.1</td>
<td>4.33</td>
</tr>
<tr>
<td>TX Psc</td>
<td>7.67</td>
<td>(0.87)</td>
<td>2.3</td>
<td>0.32</td>
</tr>
<tr>
<td>R Scy</td>
<td>16.91</td>
<td>2.09</td>
<td>6.9</td>
<td>0.81</td>
</tr>
<tr>
<td>S Scy</td>
<td>11.47</td>
<td>(2.06)</td>
<td>4.2</td>
<td>0.43</td>
</tr>
<tr>
<td>RU Vir</td>
<td>7.60</td>
<td>1.50</td>
<td>6.9</td>
<td>1.00</td>
</tr>
<tr>
<td>GL 2392</td>
<td>7.63</td>
<td>(0.34)</td>
<td>7.3</td>
<td>1.99</td>
</tr>
</tbody>
</table>

**Notes.**—Because of the large error in the spectra at 2.9 $\mu$m, which is used as continuum, the error of $W_{3.5}$ is larger than that of $W_{3.1}$. In the first column, “I” is IRAS, “LI” is LI-LMC, and “GL” is AFGL. Parentheses show nondetection.
In conclusion, the elemental abundances of LMC carbon stars extrapolated from the simple scaling from the Galactic carbon stars are not appropriate to explain the infrared spectra of carbon stars in the LMC. As pointed out by Marigo (2002), the enrichment of elements in the atmosphere through the third dredge-up should be also considered.

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REFERENCES