Carbon Stars in the *Infrared Telescope in Space* Survey

T. Le Bertre
LERMA, UMR 8112, Observatoire de Paris, 61 Avenue de l’Observatoire, F-75014 Paris, France; Thibaut.LeBertre@obspm.fr

M. Tanaka, I. Yamamura, and H. Murakami
Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

AND

D. J. MacConnell
Science Programs, Computer Sciences Corporation, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Received 2004 November 8; accepted 2004 December 7; published 2005 February 10

ABSTRACT. We have identified 139 cool carbon stars in the near-infrared spectrophotometric survey of the *Infrared Telescope in Space* (*IRTS*) from the conspicuous presence of molecular absorption bands at 1.8, 3.1, and 3.8 μm. Among them, 14 are new bright (*K*-4.0–7.0) carbon stars. We find a trend relating the 3.1 μm band strength to the color index, which is known to correlate with mass-loss rate. This could be an effect of a relation between the depth of the 3.1 μm feature and the degree of development of the extended stellar atmosphere where dust starts to form.

Online material: extended table, extended figure

1. INTRODUCTION

Carbon stars have traditionally been searched for in optical surveys with objective-prism plates. They were selected either through initially C2 bands in the blue (Secchi 1868) or later, through CN bands in the “photographic infrared” (Nassau & Velghe 1964). More recently, carbon stars have been selected from spectroscopic data obtained in the optical range in the course of the Sloan Digital Sky Survey (Margon et al. 2002).

Carbon stars have also been searched for in the *IRAS* survey, on the basis of an emission feature visible at 11.3 μm in the low-resolution spectra and attributed to silicon carbide (Volk & Cohen 1989; Epchtein et al. 1990). A method to find carbon stars undergoing mass loss by combining *IRAS* and near-infrared (1–5 μm) color indices has been proposed by Epchtein et al. (1987). This method has been successfully used by Guglielmo et al. (1993) to discover new infrared carbon stars.

Carbon stars have also been found by selecting candidates from near-infrared color indices and then performing optical spectroscopy (Mauron et al. 2004).

The formation processes of our Galaxy have left traces at large distances from the Sun, which are best seen in the form of evolved stars. The fraction of carbon stars among evolved stars is an indicator of the metallicity in the original population, and there is evidence that this fraction is increasing with galactocentric distance (Guglielmo et al. 1993). Inventories of cool carbon stars are of special interest, because these objects are evolved and thus can be used to trace matter at large galactocentric distances out to the Magellanic Clouds (Ibata et al. 2001).

The latest published version of the General Catalog of Galactic Carbon Stars (CGCS) has 6891 entries (Alksnis et al. 2001); most of them have been found on objective-prism photographic plates.

In the present work, we examine the potential for finding carbon stars by using near-infrared spectrophotometric surveys. For that purpose, we use the data provided by the Japanese space experiment *IRTS*.

2. NEAR-INFRARED SPECTROPHOTOMETRY WITH THE *IRTS*

The *Infrared Telescope in Space* (*IRTS*) is a 15 cm diameter cooled telescope that operates in space and has surveyed, by continuous scanning, ~7% of the sky (2700 deg²) with four infrared instruments (Murakami et al. 1996). The Near-Infrared Spectrometer (NIRS) is a grating spectrometer that covers two spectral ranges (1.4–2.5 and 2.8–4.0 μm), with a spectral resolution ranging from ~20 at short wavelengths to ~40 at the long wavelength end. The instrument was mainly designed to study the extended infrared emission and has an entrance aperture of 8′ × 8′. However, more than 14,000 point sources were also detected as peaks (“events”) over this extended emission. Their spectra are useful to probe the physical properties of late-type stars (e.g., Matsuura et al. 1999). We have also exploited them to study the contribution of mass-losing asymptotic giant
branch (AGB) stars to the Galactic cycle of matter (Le Bertre et al. 2001, hereafter Paper I; and 2003, hereafter Paper II).

Hereafter, we use the 2002 data release (NIRS Point Source Catalogue [PSC], ver. 1), which is described in Yamamura et al. (2003). For each event, a spectrum was constructed from the flux measurements in every channel by fitting the scan signal templates. Then the spectra corresponding to the same point source were identified and averaged. Errors are estimated from the errors on each measurement and the scatter of the data points.

3. COOL CARBON STARS IN THE NIRS POINT SOURCE CATALOG

Cool carbon stars are known to show molecular absorption bands in the near-infrared range. A NIRS spectrum of the bright carbon star Y Tau is presented in Figure 1. Clearly visible are a C$_2$ band at 1.8 µm, a band attributed to C$_2$H$_2$ at 3.8 µm, and a blend at 3.1 µm, due to C$_2$H$_2$+HCN (Ridgway et al. 1978), as are the CO bands at 1.6 and 2.3 µm. The C$_2$H$_2$ band at 3.8 µm may not be visible in all carbon stars; Yamamura et al. (1997) show that it is seen preferentially in the intermediate mass-losing stars of the class III stars defined by Groenewegen et al. (1992). Its presence may also depend on the phase of variability; for instance, it is visible in all ISO Short Wavelength Spectrometer (SWS) spectra of V CrB, except the one obtained close to maximum (see Fig. 9 in § 4.2), possibly an effect of the strong dependence of the C$_2$H$_2$ abundance on the stellar effective temperature (Matsuura et al. 2002). CN also contributes to the steep decline at the shortest wavelengths (∼1.4 µm).

In general, the 3.1 µm blend is much deeper than the C$_2$ band. However, we caution that in the NIRS spectra, the spectral resolution around 1.8 µm is lower than around 3.1 µm, which may lead to an underestimation of the corresponding C$_2$ band depth, the C$_2$ band width being about 0.05 µm (Lançon & Wood 2000). In addition, since the entrance aperture was larger than the point sources, the individual spectra may have been displaced slightly over the detector array, hindering the perception of this C$_2$ band. This band can be useful when the signal-to-noise ratio (S/N) is marginal, in the range of 2.8–4.0 µm (Fig. 2). Furthermore, it is reassuring to detect it, since the presence of C$_2$ absorption bands is the defining characteristic of C stars in the 0.4–0.6 µm region.

The 3.1 µm blend is seen even in highly reddened sources (Fig. 3), although it tends to be obliterated by circumstellar dust emission.

To identify carbon stars in the NIRS PSC, we use the 3.1 µm index defined in Paper II. This index gives the depth of the band (at 3.1 µm) relative to the continuum (taken at 2.9 and 3.3 µm); the maximum depth is obtained for an index value

---

2 The IRTS data and explanations are available via the DARTS archive at http://www.darts.isas.jaxa.jp.
CARBON STARS IN IRTS SURVEY 201

![Graph showing the distribution of 3.1 μm index for AGB stars.](image)

**Fig. 4.**—Histogram of the 3.1 μm index for the sample of AGB mass-losing stars studied in Paper II: 126 C-rich stars (thick line) and 563 O-rich stars (thin line). For clarity, the histogram has been truncated.

of 0.0, whereas a value ∼0.5 indicates a flat spectrum. The strength of the 3.1 μm feature has been found to be a very sensitive indicator of the C/O abundance ratio (Catchpole & Whitelock 1985).

In Paper II we have used this index to discriminate oxygen-rich stars from carbon-rich ones in a sample of 689 mass-losing AGB stars. A histogram of this sample is presented in Figure 4. Most of the carbon stars have an index smaller than 0.45 (only three sources have an index >0.45); the median value is at 0.34. On the other hand, the oxygen-rich stars have, in general, an index at around 0.5.

We should note at this stage that there is, in principle, a difficulty with some S stars with a C/O abundance ratio close to 1, and in particular the SC stars. If such S/SC stars show the 3.1 μm absorption band, with our procedure, they would be recognized as C stars, although strictly speaking they are only somewhat enriched in carbon. The SC class refers to stars that show ZrO bands and also CN bands. Some show the 3.1 μm absorption band (Catchpole & Whitelock 1985), in addition to a band attributed to CS around 4 μm (Aoki et al. 1998). They constitute a rare group (only 14 SC stars are in the General Catalog of S Stars; Stephenson 1984), forming a continuous sequence from S to C stars. In principle, they do not show C2 bands (Stephenson 1984). As most of our sources show the C2 band at 1.8 μm, and as SC stars are rare, we do not expect a significant contamination. On the other hand, the discovery of more such rare objects would be of interest. In the IRTS survey, we found only one source (NIRS 19505+5332 = BS Cyg = CGCS 4543) that belongs to this class. Its spectrum, for which only the odd-numbered channels were transmitted, clearly shows the absorption band at 3.1 μm (Fig. 5). It is classified as SC8/8 by Keenan & Boeshaar (1980), but does not appear in Stephenson (1984). Catchpole & Whitelock (1985) note that the SC star BH Cru, which has an absorption feature at 3.1 μm, may occasionally show charactersitics of a CS star (Lloyd Evans 1985). This is supported by the recent discussion of this star by Zijlstra et al. (2004), who interpret such changes as a temperature effect.

Finally, we note that some S stars show a weak absorption band at 3.1 μm. Two such cases have been observed by ISO with the SWS: W Aql and S Cas. The near-infrared part of their spectra is shown in Figure 6, along with that of a carbon star, R Scl. The 3.1 μm blend is clearly visible in R Scl and W Aql and also seems present in S Cas. The latter source has been observed by the IRTS, but the 3.1 μm band is not visible in the NIRS spectrum (see Fig. 4 in Paper I). The source W Aql is not in the NIRS PSC; the 3.1 μm index measured on the ISO spectrum is ∼0.46. On the other hand, the C2H2 band at 3.8 μm is present in the spectrum of R Scl, but not in the spectra of the two S stars. There is an absorption from 4.0 to
4.2 μm, due to SiO in the spectrum of S Cas and perhaps W Aql, but not in R Scl. At the present stage, we conclude that some S-type stars may show the 3.1 μm absorption band, and we suspect that they do not show the band of C₂H₂ at 3.8 μm. For these stars, the 3.1 μm seems to stay weak, and we expect that a limit of 0.45 on the index value keeps them out of our selection.

We have considered the 8879 NIRS sources for which the data are of sufficiently good quality to estimate their K and L magnitudes in the ESO photometric system (see Paper II). Among them, we obtained 471 sources with a 3.1 μm index ≤0.45. Each corresponding spectrum was examined visually. We found 139 sources that unambiguously show a C₂ band at 1.8 μm and/or the blend at 3.1 μm, and 220 that are very probably not carbon-rich. The former are reported in Table 1. Most of these carbon stars can be associated with an IRAS and a CGCS source. However, these associations should be viewed with caution, because the entrance aperture of the NIRS on the sky was ∼6′. In addition, the accuracy of the pointing reconstruction is ∼2′ rms.

Some carbon stars may have been missed, for instance among the remaining 112 sources for which the NIRS spectra do not have a S/N sufficient to characterize them. We also note that some carbon stars may have a 3.1 μm index above 0.45; three such cases were identified in Paper II (see also Fig. 4). For clarity, we have added these three cases at the end of Table 1. The majority of the 220 sources that we have rejected have a 3.1 μm index in the range of 0.40–0.45. In addition, there are sources that show an emission band at 3.3 μm attributed to polycyclic aromatic hydrocarbons (PAHs). This emission raises the flux at 3.3 μm relative to 3.1 μm, which mimics an absorption. These “PAH” sources, which often have a large K − L, are readily identified from their NIRS spectra. Finally, it is worth noting that we did not find carbon stars with a K − L color smaller than 0.4.

M. Tanaka et al. (2005, in preparation) have developed a similar but slightly different method. They use five parameters to separate M, C, and S stars. Applying this method to 4002 good quality NIRS spectra, they find 91 carbon stars. With our procedure, we have obtained all their carbon stars but one (NIRS 07281−1216 = IRAS 07280−1217 = CGCS 1735). This source shows a weak 3.1 μm absorption band (3.1 μm index = 0.46), which explains why we could not select it. For completeness, we have added this source at the end of Table 1. The incidence of carbon stars in their sample is about 0.023 (91/4002), whereas it is about 0.016 (139/8879) in our sample. This confirms that we miss some carbon stars at low S/N.

The few sources (14) in Table 1 that have no CGCS counterpart can be considered as new cool carbon stars. Their NIRS spectra are given in Figure 7. It is surprising that new carbon stars are found that do not have an extreme color (K − L ≤ 1) and are still relatively bright (K ∼ 6). Perhaps they have been missed in previous surveys because they are variable. Some of these new carbon stars are in fields covered by near-IR objective-prism plates obtained by one of us (MacConnell 2003). These plates have been reexamined, and the results are given in the notes to Table 1.

4. DISCUSSION

4.1. Cool Carbon Stars

In the top panel of Figure 8, we present the 3.1 μm index as a function of K − L. Most of the 8879 NIRS sources with

![Figure 7](image-url)

**Fig. 7.—**NIRS spectra of new carbon stars. [See the electronic edition of the PASP for additional panels of this figure.]
available $K$ and $L'$ magnitudes are in a large clump around an index value of $\sim 0.50$ and a $K - L'$ color of $\sim 0.3$. There is a tail going horizontally to the right, composed mainly of oxygen-rich late-type stars. In addition, there is a "plume" going downward to the right, which is marked by a straight line in the figure. This plume is made of carbon stars, as can be seen in the bottom panel of the figure.

This feature shows that there is a relation between the 3.1 $\mu$m index that characterizes the carbon-rich stellar atmospheres and the $K - L'$ color in the range of 0.7 to 1.4. This color is known to be related to the present mass-loss rate of carbon stars (Le Bertre 1997). It is interesting to note that the same kind of plume is visible when plotting the 1.9 $\mu$m index (which characterizes O-rich late-type stars) versus $K - L'$, which, for these sources, characterizes their present mass-loss rate (Le Bertre & Winters 1998). The trend is not a perfect correlation, and sources are also found to the right of the plume. This might be an effect of dust emission filling in the 3.1 $\mu$m band in spectra of sources undergoing heavy mass loss. Groenewegen et al. (1994) have obtained 2.8–3.5 $\mu$m spectra for 16 carbon stars with a $K - L'$ index in the range of 2–7. They find that the 3.1 $\mu$m feature weakens with redder $K - L'$ color, and they also interpret this tendency as an effect of filling-in by dust emission.

A possible interpretation of the trend observed in Figure 8 is that the mass loss and the absorption band at 3.1 $\mu$m are both increasing with the degree of development of the extended stellar atmosphere where dust is likely to form. Winters et al. (2000) have shown that the mass loss of red giants is favored by a low effective temperature, a low stellar mass, a high luminosity, and a large pulsation amplitude. The synthetic spectra of carbon-rich AGB star atmospheres obtained by Loidl et al. (1999) from dynamic models show that the strengths of the $C_2H_2$ and HCN features increase in the same manner, because these molecules form preferentially at low temperatures ($T < 2500$ K) in the upper atmospheric layers.

We have found 14 new carbon stars in a sample of 139 sources. The $C_2$ band at 1.8 $\mu$m has been useful to confirm the carbon-rich nature of the sources in the cases for which the S/N at 3 $\mu$m is poor. Unfortunately, the spectral resolution of the NIRS around 2 $\mu$m ($\sim 20$) is not enough to define an index measuring the depth of this band.

The IRTS survey is limited in sensitivity to $K \sim 8$ and $L' \sim 7$. Furthermore, in some regions of the sky, close to the Galactic plane where the level of the extended emission is increased by confusion, the sensitivity was reduced by $\sim 2$ mag (Paper II). Most of the carbon stars that we have identified are probably at a distance of between 1 and 5 kpc from the Sun (see Fig. 7 in Paper II). Extrapolating to the whole sky, a survey such as the IRTS would reveal $\sim 2000$ cool carbon stars, with possibly 200 new ones. These estimates would rise greatly for a survey with better sensitivity and better spatial and spectral resolution.

The advantages of searching for cool carbon stars by near-infrared spectrophotometric means are multiple. The effective temperature of N-type stars ranges from 1800 to 4000 K (Bergeat et al. 2001), and they reach the maximum of their energy distribution around 2 $\mu$m. Many of them are undergoing mass loss and are surrounded by circumstellar dust shells that shift their spectra toward long wavelengths ($\sim 3$ $\mu$m or more). As a result of the energy distribution, the infrared data also provide a more direct determination of the luminosity than those obtained in the optical. Furthermore, carbon stars are often variable, with an amplitude that decreases with wavelength; therefore, it is less likely to miss a star that is at minimum if the survey is done at a long wavelength. There is also a general advantage of the infrared range in detecting sources in regions of the Galaxy that are affected by dust extinction (“zone of avoidance”). Finally, as cool carbon-star spectra are characterized by wide molecular bands, a spectral resolution of $\geq 40$
is enough to clearly recognize them. With spectrophotometry, it is easy to build photometric indices targeted to specific classes of sources. On the other hand, our experience (§ 3) shows that the availability of a continuous spectrum over a large wavelength range is useful to identify the sources that contaminate the samples that are extracted on the basis of these photometric indices: the same data are used to select candidates and to confirm them.

4.2. Other Carbon Stars in the IRTS Survey

There are other categories of carbon stars, the majority being found in the R and CH classes. The R stars are a mix of giants with effective temperatures lower than $\sim 5000$ K and that in general are nonvariable, and of classical cool carbon stars (late R type/N type). The true R stars (excluding N type) are too faint to be on the AGB and do not show evidence of mass loss. They may owe their carbon enrichment to an He-core flash (Dominy 1984) and, perhaps, to a coalescence in a binary system (McClure 1997). They are more easily selected by isolating the early R0–R4 subtypes.

A search for R stars in the NIRS PSC was performed by cross-correlating the positions in the PSC with those in the CGCS catalog (Alksnis et al. 2001). We found several associations. The NIRS spectra of sources associated with early (R0–R4) type stars sometimes show CO absorptions at 1.6 and 2.3 $\mu$m, but no other distinctive features (Fig. 9, top). Later type R stars may show the $C_2$ band at 1.8 $\mu$m without the 3.1 $\mu$m absorption band (Fig. 9, bottom), confirming our suspicion that the latter is not sufficient to select all cool carbon stars. It thus appears again that the 1.8 $\mu$m band, as well as the 3.1 $\mu$m band, could be very useful for future surveys.

The Galactic CH stars are metal-poor carbon stars that are characterized in the optical range by strong CH bands. They are spectroscopic binaries and probably owe their carbon enrichment to mass transfer from a more evolved companion (Jorissen 1999). We have not identified any CH star in the NIRS PSC. However, at least three members of this class (V Ari, V CrB, and HD 189711) were observed by ISO with the SWS. Apart from the long-wavelength wing of the 2.3 $\mu$m CO band, no characteristic feature is visible in the (2.3–4.1 $\mu$m) spectra of V Ari and HD 189711; unfortunately, the region of the spectrum around 1.8 $\mu$m is missing in the ISO spectra. V CrB shows a strong absorption at 3.1 $\mu$m, and at some phases, an absorption at 3.8 $\mu$m (Fig. 10). However, this source is a Mira variable and therefore is probably not typical of the CH class. If objects like V CrB are in the NIRS PSC, they would be selected as cool carbon stars and would probably not be recognized as CH-types.

There are also the J-type stars, which are characterized by strong $^{13}$C bands, indicating a low ($\leq 10$) $^{12}$C/$^{13}$C ratio. We have identified three such cases in § 3 that were already selected: NIRS 07235+0354 (CGCS 1708), NIRS 12545+6615 (CGCS 3313, RY Dra), and NIRS 18306+3657 (CGCS 4038, T Lyr). All show strong molecular bands at 1.8 and 3.1 $\mu$m. At the

<table>
<thead>
<tr>
<th>NIRS Name</th>
<th>$K$</th>
<th>$K - L'$</th>
<th>IRAS Association</th>
<th>Other Association</th>
<th>Spectral Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>04166+5719 N</td>
<td>5.57</td>
<td>1.70</td>
<td>04166+5719</td>
<td>TW Cam</td>
<td>F8 Ib</td>
<td>SIMBAD</td>
</tr>
<tr>
<td>07284+0940 S</td>
<td>3.61</td>
<td>1.33</td>
<td>07284+0940</td>
<td>U Mon</td>
<td>K0 Ibvar</td>
<td>SIMBAD</td>
</tr>
<tr>
<td>18125+0510 N</td>
<td>5.19</td>
<td>1.07</td>
<td>18123+0511</td>
<td></td>
<td>G5</td>
<td>Mass (2003)</td>
</tr>
</tbody>
</table>
Fig. 10.—ISO SWS spectra of a CH star (V CrB, CGCS 3652) obtained at three different phases. Note that the 3.8 μm absorption is virtually absent (as is the 3.56 μm HCN band) close to maximum (thick line), but clearly present close to minimum (medium and thin lines).

low spectral resolution of the NIRS, it does not seem possible to isolate the J-type stars from the other cool carbon stars.

We found three NIRS sources that could be associated with RV Tauri stars (Table 2). It is known that some RV Tauri stars show a carbon-rich nature. Giridhar et al. (2000) have performed an abundance analysis of several RV Tauri stars: U Mon is O-rich (C/O ~ 0.8), whereas TW Cam is carbon-rich (C/O ~ 2). The O-rich character of U Mon is supported by its IRAS low-resolution spectrum (LRS class 26). Le Bertre et al. (2001) note that in a K – L’ versus 12–25 μm diagram, TW Cam falls in the “c” (carbon-rich) region of Epchtein et al. (1987). The NIRS spectra corresponding to TW Cam (Fig. 11) and U Mon are basically featureless, whereas the one of NIRS 18125+0510 shows an H₂O band at 1.9 μm and a CO band at 2.3 μm. The latter NIRS source is certainly not carbon-rich.

Finally, we could not identify R Coronae Borealis stars in the NIRS PSC, nor any known carbon-rich post-AGB stars. At the present stage, we do not see an easy way to pinpoint warm carbon stars directly in the IRTS survey.

5. CONCLUSION

We have identified 139 cool carbon stars in the IRTS/NIRS survey on the basis of the 3.1 μm absorption feature due to a blend of C₂H₂ and HCN bands. About 90% have been confirmed through cross-identification with the CGCS, and 14 are new, relatively bright (K ~ 3.9–6.9) C stars. This indicates that an important number of bright carbon stars are still missing from our inventories.

It is likely that there are more cool carbon stars in the Point Source Catalogue that were not selected either because the 3.1 μm band is weak or because a limited signal-to-noise ratio hampered an unambiguous classification. The spectral resolution of the IRTS was insufficient to fully exploit the important C₂ band at 1.8 μm; a spectral resolution of 40 or better would have been preferable. The C₂ band at 1.8 μm and the C₂H₂ band at 3.8 μm should be useful to separate C and S stars. An extension of the wavelength coverage beyond 4 μm to cover the SiO band would also have been helpful.

Sensitive near-infrared spectrophotometric surveys covering the range from ~1.5 to ~4.5 μm with a spectral resolution ≥40 therefore have the potential to reveal new carbon stars in the Galaxy and in its satellites, and also in other galaxies, and to provide useful information on their physical properties.

We thank Dr. N. Epchtein for useful advice and encouragement. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We thank an anonymous referee for helpful suggestions.

REFERENCES

Jorissen, A. 1999, IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lebre, & C. Waelkens (San Francisco: ASP), 437
MacConnell, D. J. 1979, A&AS, 38, 335
Yamamura, I., et al. 2003, Exploiting the ISO Data Archive—Infrared Astronomy in the Internet Age, ed. C. Gry et al. (ESA–SP 511: Noordwijk: ESA), 35