INFRARED EMISSION OF CARBON STARS

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Abstract.
This review addresses the infrared emission from the most important classes of carbon-rich objects: the N- and R-type carbon stars, the carbon dwarfs and the CH-stars. Examples of carbon rich objects in the Galactic halo and the Magellanic Clouds are discussed. Discrimination of carbon-rich objects against red oxygen-rich objects is investigated. The detectibility of N-type carbon Miras in the DENIS and 2MASS near-infrared surveys is discussed.

1. Introduction

The organisers had asked me to review the infrared emission of carbon stars. They may not have realised that this is a formidable task indeed as there are actually many types of carbon-rich objects. Here, I will not discuss the R CrB stars, hydrogen deficient carbon (HdC) stars and carbon-rich post-AGB stars. The latter two classes have no or very little present-day mass loss and their near-infrared emission (most important for the kind of infrared surveys that are the topic of this conference) is therefore dominated by the stellar photosphere. Instead, I will concentrate on the more well-known classes of carbon-rich objects, namely the N- and R-type carbon stars, the CH-stars and the carbon dwarfs. In particular, I would like to discuss the spectral characteristics of these classes of carbon-stars.

As will be discussed below, the near-infrared DENIS and 2MASS surveys have the potential to discover carbon stars with near-infrared emission to large distances. In addition, the related question how to distinguish the different types of carbon-rich objects amongst each other and from red oxygen-rich objects from the data of these surveys will be investigated using colour-colour diagrams.

2. Different kinds of carbon stars

2.1. THE N-TYPE CARBON STARS

The N-type carbon stars are formed on the Asymptotic Giant Branch (AGB) after one or more third dredge-up events where carbon is mixed into the convective envelope. For a comprehensive scenario see Groenewegen et al. (1995), for a general review on AGB stars, see Habing (1996).

Characteristic of this class of stars is their variability and heavy mass loss, which are related to each other. As is the case for oxygen-rich Miras, there are correlations between the pulsation period and luminosity (Feast et al. 1989, Groenewegen & Whitelock 1996), and period and mass loss rate (Groenewegen et al. 1997b) for carbon miras.

2.2. THE R-TYPE CARBON STARS

The R-type carbon stars are hotter and less luminous than the N-type (Scalo 1976) and can not be on the AGB. These, or very similar hot and low luminosity carbon stars, have been found in the Galactic bulge (Lloyd Evans 1985, Westerlund et al. 1991) and the Magellanic Clouds (Westerlund et al. 1992, 1995).

McClure (1997) monitored 22 R-stars and found no evidence for radial velocity variations in any of them.

The classical explanation for the formation of these carbon stars considers an extraordinary mixing event at the Helium core flash (e.g. Dominy 1984). Based on the lower than expected 20% binary frequency McClure (1997) proposes that these stars may be coalescing binaries.

Significant cold and hot dust is known in only one case (Parthasarathy 1991). For the general absence of significant IR excess in R-, CH- and Ba II-stars see Dominy (1986).

2.3. THE CH-TYPE CARBON STARS

These stars, recognised as a separate class by Keenan (1942), are typically metal-poor objects with the kinematics of Population II objects. They are in binary systems (McClure & Woodsworth 1990). They are hotter than the N-type, with equivalent spectral types in the range G-K. Their near-infrared colours are of photospheric origin.

2.4. THE CARBON DWARFS

Currently, there are nine of these peculiar objects known. Their space density exceeds that of N-type carbon stars (Green et al. 1992). The prototype carbon dwarf G77-61 was discovered twenty years ago (Dahn et al. 1977) and long remained the only example known. Then, eight more were discovered by Green et al. (1991, 1992), Heber et al. (1993), Warren et al. (1993) and Liebert et al. (1994). Three carbon dwarfa are known binaries; this was established for the prototype from radial velocity measurements, for the two others from composite spectra. In the latter cases the companion is a white dwarf. The absolute V-magnitude is in the range +9.7-10.8.

3. Carbon stars in different environment

3.1. HALO CARBON STARS

Carbon stars in the Galactic halo have been long known (Sanduleak 1980, Margon et al. 1984). They are sometimes designated faint high-latitude carbon (FHLC) stars. Margon et al. (1984), Mould et al. (1985), Bothun et al. (1991), Green et al. (1992) and Moody et al. (1997) contain in total 41 such stars, some of which turned out to be dwarf carbon stars (Green & Margon 1994), or are known CH-stars. Originally, the interest in them was as tracers of the outer halo.

In a recent paper, Totten & Irwin (1997) present the results of an optical survey (a byproduct of the APM survey) for FHLC stars covering about 6500 sq. degrees. Thirty-two are definitely N-type, and some of them may be 'dusty'.

Interestingly enough, some FHLC stars are losing mass at a considerable rate. Two were serendipitously discovered by Cutri et al. (1989) and Beichman et al. (1990), namely IRAS 08546+1732 and IRAS 12560+1656. Both are Miras with a 390 day period (Joyce et al. 1997). A more detailed analysis is performed by Groenewegen et al. (1997a). From the period-luminosity relation of Groenewegen & Whitelock (1996) a luminosity of 5800 $L_\odot$ is derived for a period of 390 days, measured for both stars. A model fit with a dust radiative transfer model to the spectral energy distributions then gives the distances of 8.0 and 20 kpc from sun, and 7.8 and 11 kpc from the Galactic plane.

CO J = 2-1 emission was detected in the nearest object (IRAS 12560) after ten hours of integration using the IRAM 30m telescope. The expansion velocity is low at only 3.2 km s^{-1}, and stellar LSR velocity is +88 km s^{-1}. Combining the CO and dust observations and the modelling, Groenewegen et al. (1997a) derive for this star a mass loss rate of 1.3×10^{-6} $M_\odot yr^{-1}$, and a dust-to-gas ratio of 0.0014. The abundance of CO w.r.t H_2 is found to be 2×10^{-4}, indicating an underabundance of oxygen by –0.7 dex. w.r.t. solar.

The colours of these two stars are as follows: $M_\mathrm{K} = -6.8$ and -7.6, $I_\mathrm{C} =$ 14.3 and 18.7, $J = 10.4$ and 14.0, $H = 8.6$ and 11.8, $K = 7.0$ and 9.7. With such colours and a K-survey down to 14th magnitude one could probe the

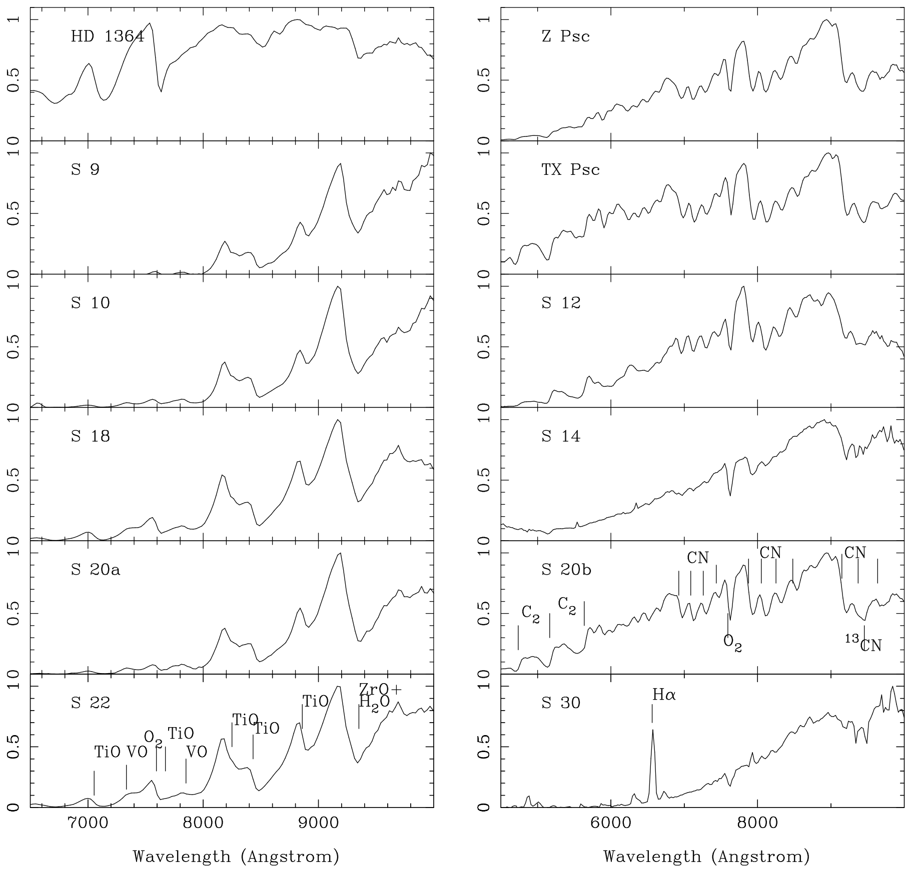

Figure 1. Optical spectra of AGB stars in the SMC (identified by S <number>), the M3.5 IIIa MK standard star HD 1364 and the known carbon stars TX Psc and Z Psc. Well known lines are identified, including telluric O_2 and H_2O lines. From Groenewegen & Blommaert (1997).

halo out to distances of at least 150 kpc. It is expected that 2MASS and DENIS will identify many more mass-losing halo carbon stars.

3.2. CARBON STARS IN THE MAGELLANIC CLOUDS

This is a long standing research topic dating back to the first surveys in the 1960's by Westerlund (1960). I had the opportunity to review this subject recently, including a discussion of the first ISO results on AGB stars in the Magellanic Clouds (Groenewegen 1997b). I will therefore be brief on this topic. Just as a reference: the total estimated number of carbon stars in the LMC is about 11 000 (Blanco & McCarthy 1983), while about 2 900 are known in the SMC (Blanco & McCarthy 1983, Rebeirot et al. 1993).

The last few years saw a number of interesting papers (WEG: taking a look at this subject) from the point of view of IRAS detected AGB stars in the Clouds (Whitelock et al. 1989, Reid et al. 1990, Reid 1991, Wood et al. 1992, Groenewegen et al. 1995, Zijlstra et al. 1996, van Loon et al. 1997a, b, Loup et al. 1997, Groenewegen & Blommaert 1997). The first and last paper in this list specifically deal with the SMC, the other papers concentrate on the LMC. The important outcome of these papers is that mass-losing AGB stars exist in the Clouds. However, as the 12 μm fluxes are close to the detection limit, the IRAS view is far from complete. For a given mass loss rate, the IRAS detection probability increases with increasing luminosity, and vice versa. An almost complete census of AGB stars in the Clouds will be provided by DENIS and 2MASS.

4. Spectral characteristics of carbon stars

In this section I will describe the emission and absorption features one can observe in carbon stars, starting in the optical and then turning to the near- and mid-infrared.

In the optical the absorption bands that identify a carbon star are the C_2 bands at e.g. 4737, 5165 and 5636 Å, and the stronger CN bands longwards of 7000 Å. As an example, Fig. 1 shows low resolution optical spectra of carbon (and oxygen-rich AGB stars for comparison) stars in the SMC, together with some well known objects (Groenewegen & Blommaert 1997).

A comprehensive atlas of carbon star spectra can be found in Barnbaum et al. (1996; at moderate resolution) and Barnbaum (1994; at high resolution).

Although one could have thought that the optical spectra of carbon stars are well understood almost a century since their discovery, the recent paper by Sarre et al. (1996) provides the first accurate vibrational band assignments of the SiC_2 molecule. This molecule has prominent bands in the 4750-5050 Å region (also called Merrill-Sanford bands). Figure 2 is an adaptation of Fig. 1 of Sarre et al. (1996) where details can be found. See Barnbaum et al. (1996) for more examples.

Green et al. (1992) find unusually strong C_2 6191 Å bandheads in the carbon dwarfs, which is not seen in any of the other FHLC stars they observed, and suggest this may be a spectroscopic way of identifying carbon dwarfs.

Moving towards the near-infrared there are two prominent absorption bands that identify carbon stars: a C_2 band at 1.77 μm at the edge of the H-band, and a blend of HCN and C_2H_2 lines (see Ridgway et al. 1978 for a high resolution spectrum) near 3.1 μm at the edge of the L-band.

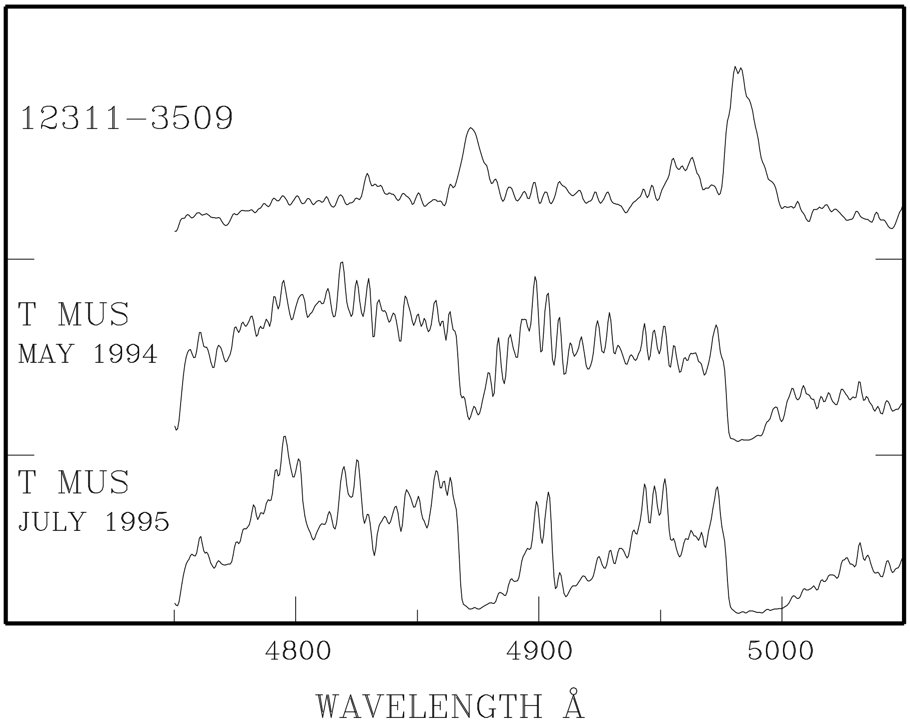

Figure 2. Spectra between 4750 and 5050Å of IRAS 12311-3509 and the semiregular variable T Mus in May 1994, when the SiC_2 absorption spectrum was abnormal, and July 1995. The spectra are flux-calibrated on an arbitrary intensity scale. The absorption bands at 4872, 4911 and 4982 Å are clearly visible in the bottom spectra. The spectrum of 12311–3509 illustrates that these bands can also be observed in emission. Adopted from Sarre et al. (1996), where more details can be found.

An example of the 1.77 μm feature is shown in Fig. 3 (from Lançon & Wood 1997). More near-infrared spectra of carbon stars are shown in Lázaro et al. (1994).

An example of the shape of the 3.1 μm feature is shown in Fig. 4 (from Groenewegen et al. 1994; also see Yamamura et al. 1997b). Substructure is clearly visible due to the fact that this feature is a blend. More 3 μm spectra of carbon- and oxygen-rich stars can be found in Merrill & Stein (1976a,b,c).

Recently, the Japanese IRTS and ESA's ISO satellite provided a wealth of new information, because of the coverage of wavelengths not observable from the ground, and the higher spectral resolution. IRTS/NIRS-MIRS spectra of carbon stars are shown in Fig. 5 (adopted from Yamamura et al. 1997a). ISO SWS spectra are shown in Fig. 6 (adopted from Yamamura et al. 1997b). The following lines can be identified: HCN + C_2H_2 features

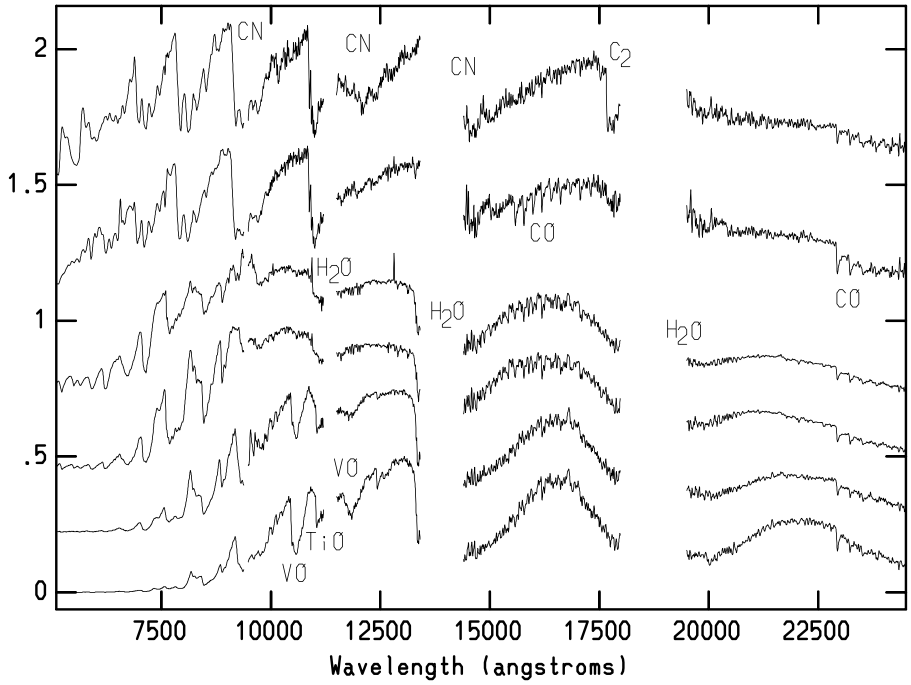

Figure 3. Near-infrared spectra of a carbon star (top spectrum) compared to oxygen-rich spectra. Note the strong C_2 absorption at 1.77 μm. From Lançon & Wood (1997).

at 3.1 μm (see above), 3.9 μm (also observable from the ground, e.g. Bregman et al. 1978), 7.5 μm and 13.7 μm, a C_3 feature at 5.2 μm, and the well-known silicon carbide (SiC) dust emission feature at 11.3 μm. I will not discuss features longward of 20 μm. The SiC feature can be observed from the ground (e.g. Treffers & Cohen 1974, Speck et al. 1997) and is present in the wavelength range covered by the IRAS low resolution spectrograph, and is thus studied extensively (e.g. Lorentz-Martins & Lefèvre 1994, Groenewegen et al. 1997b)

The SWS spectra have revealed so much detail that the theoretical interpretation is lacking behind the observations at the moment. Recent attempts to remedy this, and e.g. to predict the strength of the various absorption features as a function of phase in the pulsation cycle, can be found in Loidl et al. (1997) and Hron et al. (1997).

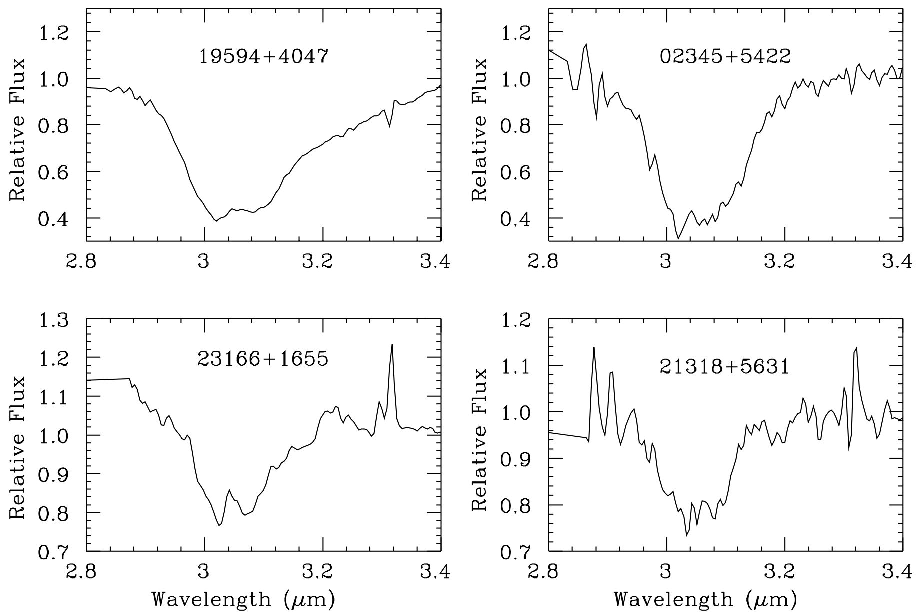

Figure 4. Normalised 3 μm spectra of carbon stars. IRAS names are indicated. From Groenewegen et al. (1994).

5. Carbon stars in relation to DENIS and 2MASS

Let us first estimate to which distances carbon Miras can be detected in the DENIS and 2MASS surveys. As the K-band seems the most suitable filter in terms of sensitivity and intrinsic brightness of the objects in question, I concentrate on that filter. In Groenewegen & Whitelock (1996) the following period-K-relation is derived from stars in the LMC, scaled to the galaxy: $M_{\rm K} = -3.56 \log P + 1.14$.

In Table 1 the relevant numbers are collected for a typical 'short' period of 200 days, an 'average' period of 400 days and a typical 'long' period of 700 days. The respective absolute K-magnitudes based on the P-K-relation are listed, as well as the range in distances carbon miras can be observed based on saturation and 10σ detection limits for DENIS (Epchtein 1997) and 2MASS (Skrutskie et al. 1997). The conclusion is that the near-IR surveys have the potential to detect carbon stars out to several hundred kpc.

Can the different types of carbon-rich objects be distinguished from each other, and from oxygen-rich objects?

Figure 7 shows IJK and JHK colour-colour diagrams from Groenewegen (1997a). Oxygen-rich and carbon-rich AGB stars are compared to

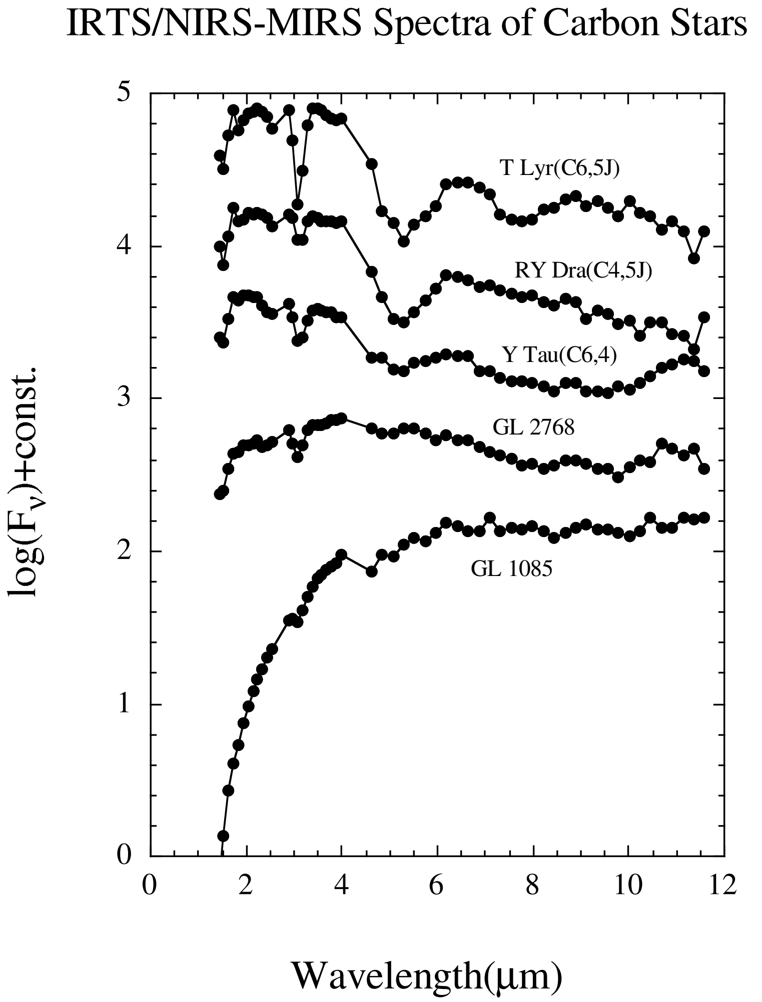

Figure 5. IRTS spectra of carbon stars. Note the strong features at 3.1 μm and 5.2 μm. Adopted from Yamamura et al. (1997a).

galaxies, M-dwarfs, Herbig Ae/Be stars and T Tau stars. For the construction of these samples see Groenewegen (1997a). Note that the sequence for the oxygen-rich AGB stars (the filled squares) does not appear continuous. This is an artifact of the type of templates used.

Additional information comes from Green et al. (1992, their Fig. 1) who present a colour-colour diagram which includes the carbon dwarfs. It appears that in a $(J-H),(H-K)$ diagram they are off-set with respect to other FHLC-stars and the low luminosity carbon stars in the Galactic

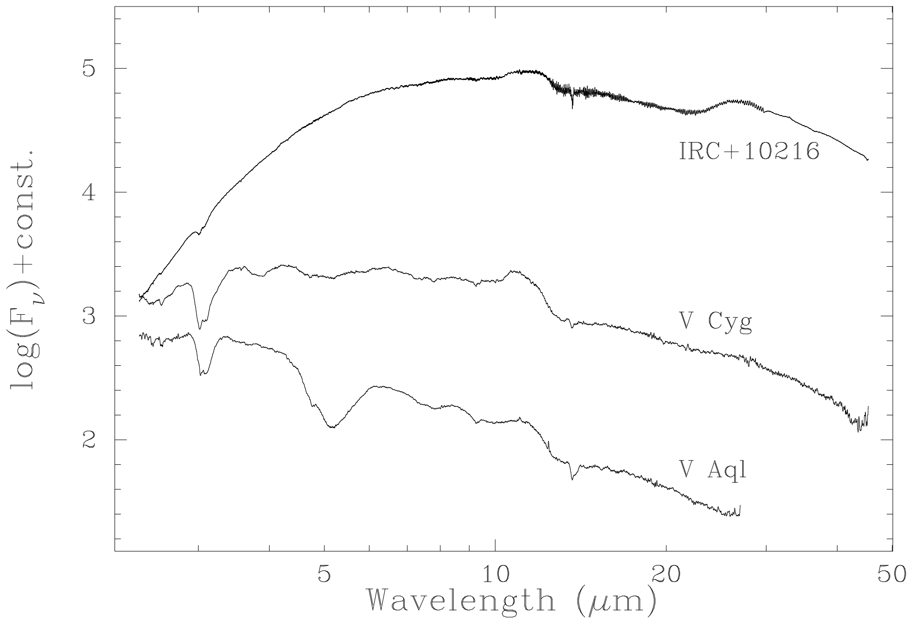

Figure 6. ISO SWS spectra of carbon stars. Adopted from Yamamura et al. (1997b).

TABLE 1. How far can carbon miras be detected ?

	survey	P = 200	400	700 days
$M_{\rm K}$		–7.05	–8.12	–8.95
Range	DENIS[(a)]	5.1-90	8.4-145	12.5-220
(kpc)	2MASS[(b)]	1.6-190	2.7-300	3.9-450

[(a)]Based on a saturation limit of K = 6.5 and a 10σ detection limit of 12.7. Interstellar extinction is neglected.
[(b)]Based on a saturation limit of K = 4.0 and a 10σ detection limit of 14.3. Interstellar extinction is neglected.

bulge. The colours of the carbon dwarfs are blue: 0.25 $\lesssim(H-K)\lesssim$0.36, 0.35 $\lesssim(J-H)\lesssim$0.65.

Furthermore, Feast & Whitelock (1992, their Fig. 5) present a $(J-H),(H-K)$ colour-colour diagram that includes CH-stars in the LMC, carbon dwarfs in dwarf spheroidals, Galactic CH- or related stars, CH-stars in ω Cen and the dwarf carbon stars. Apart from the dwarf carbon stars that stand out as mentioned above, there is a large overlap between the classes. They also show that there is a significant overlap with normal oxygen-rich giants.

For comparison, Fig. 8 shows colour-colour diagrams for a relatively

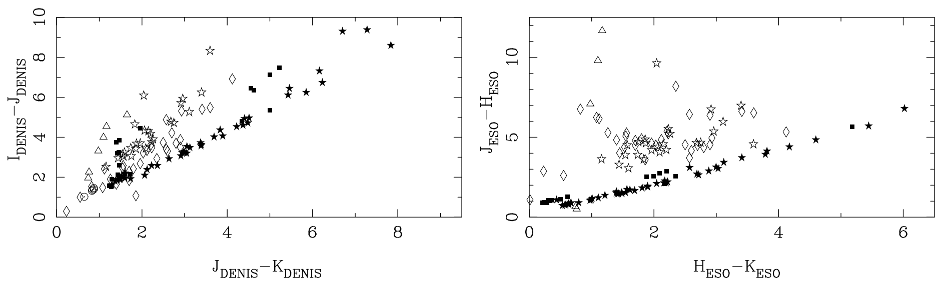

Figure 7. IJK and JHK colour-colour diagram. Symbols: carbon stars = filled stars; oxygen-rich AGB stars = filled squares; galaxies = open circles; M-dwarfs = open triangles; He Ae/Be stars = open diamonds; T Tau stars = open stars. The limits of the IJK plot are set based on the saturation and 5σ detection limits of DENIS; very red AGB objects outside the plot limits do exist. For the AGB stars the colours are dereddened. From Groenewegen (1997a).

unbiased sample of carbon stars in the LMC (Costa & Frogel 1996). The larger scatter in the bottom panel is in all likelihood due to the fact that the I- and JK photometry was not taken simultaneously.

The conclusion I draw from all these data is that, based on IJK and JHK colour-colour diagrams alone, (a) it is extremely difficult to separate unreddened carbon stars (mainly CH-stars, R-stars) from normal oxygen-rich giants, as exception possibly being the carbon dwarfs, (b) for moderate red colours there is the danger of overlap with other red sources. This danger appears to be less for the 2MASS system, (c) mass-losing AGB stars with very red colours are easily identified but this will be a minority of sources amongst the 10^8 that are expected to be detected, as demonstrated in Fig. 7.

As discussed in Groenewegen (1997a) additional information may be used to make a more clear-cut discrimination, e.g. optical colors or IRAS fluxes. However the latter only provides such information for a few 10^5 sources only.

6. Conclusions

Carbon stars display a rich absorption and emission spectrum. The recent satellite missions ISO and IRTS have unveiled parts of the spectrum that are inaccessible from the ground, the 5-8 μm and the $\gtrsim$20 μm region.

The upcoming near-infrared surveys have the potential to detect carbon stars out to large distances. However, except for the reddest sources, it will prove difficult to separate the different classes of carbon stars from colour-colour-diagrams alone and there is the potential of confusion with oxygen-rich sources, or other red sources. Conclusive identification could be done using narrow-band filters in the optical (e.g. Richer et al. 1984)

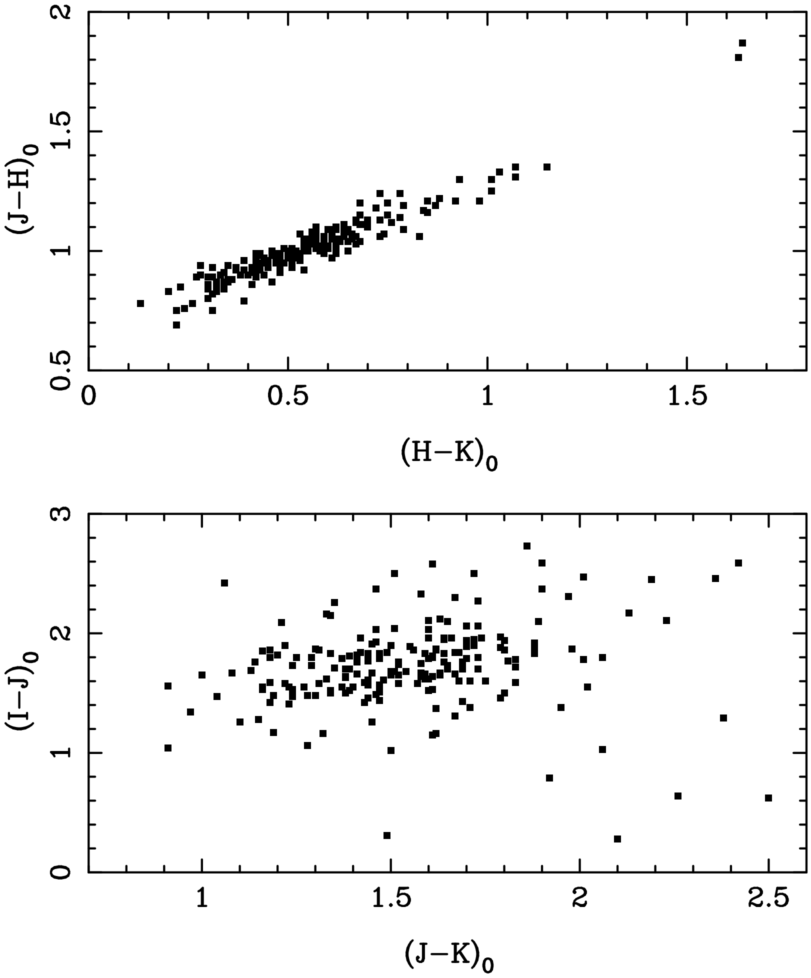

Figure 8. Colour-colour diagram for a sample of carbon stars in the LMC. Based on data from Costa & Frogel (1996).

or the near-infrared (not yet attempted). This should be possible even for distant objects with the new generation of 10m class telescopes.

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