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Research Note

On the distance and mass-loss rate of carbon stars showing the silicon carbide emission feature

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Abstract. The distances and the mass-loss rates of carbon stars are in general very poorly known. The various estimates of the distances, taken from the general literature, show considerable discrepancies, while the evaluations of the mass-loss rates can be in error by more than an order of magnitude. In this work we have evaluated these two important stellar parameters for a previously selected sample of 55 carbon stars showing the 11.3 μm band, commonly attributed to silicon carbide (SiC) grains. To perform the calculation we have used the values of geometrical and physical parameters of these sources obtained from the best fits of their observed spectra. Using the distance values derived in this way and the 11.3 μm band intensity, we have evaluated the absolute band strength and we have found that, in agreement with other authors, there is a correlation between this quantity and the mass-loss rate. This correlation can be very useful to determine the mass-loss rate of other carbon stars not included in our sample, by means of the intensity of the SiC band, without using the usual technique based on CO observations. The same procedure can be conveniently applied to the same as well as to other carbon stars, whose spectra will be available to the community in the next future (i.e. the infrared spectra of sources observed by the Infrared Satellite Observatory, ISO).

Key words: stars: carbon – stars: circumstellar matter – stars: distances – stars: mass-loss

1. Introduction

Carbon stars are highly evolved stars which can be considered a direct evidence for evolution along the asymptotic giant branch (Chan & Kwok 1988, 1990; Willems 1988). Among their interesting features there is the characteristic ejection of large amounts of processed material into the interstellar medium (Knapp & Morris 1985) and for this reason they are often regarded as chief factories of interstellar dust grains. In particular the atmospheres of carbon stars are generally thought to be the place were carbon and silicon carbide (SiC) grains can easily condense (Tielens 1990).

To study the exact nature of the carbon grains (amorphous or crystalline) as well as of the SiC component (α-SiC or β-SiC; Borghesi et al. 1985), some years ago our group started a study of the observed infrared spectra of carbon stars in relation to the extinction properties, of both carbon and SiC submicron particles, measured in our laboratory (Borghesi et al. 1985, 1986; Bussoletti et al. 1987; Orofino et al. 1990, 1991; Blanco et al. 1994, 1998).

In particular, in the most recent paper (Blanco et al. 1998, hereinafter Paper I) the spectroscopic and photometric data relative to a sample of 55 carbon stars showing the 11.3 μm feature have been fitted in the wavelength range between 0.4 μm and 100 μm. This has been done by means of a radiative transfer model using the laboratory extinction spectra of amorphous carbon and silicon carbide grains. The transfer code allowed us to determine also, in a self-consistent way, the grain equilibrium temperature of the various species at different distances from the central star and all the relevant circumstellar parameters, which can be very important for the evolutionary study of carbon stars.

To get meaningful information on the nature and physical properties of the dust grains responsible for the 11.3 μm feature and the underlying continuum, the fitting procedure of the spectra has been applied individually to every single source. For this reason it has been possible to take into account not only any variation in position and shape of the SiC band, but also the general trend of the observed flux density of each individual object.

Our analysis has shown that all the sources, in addition to the amorphous carbon grains accounting for the continuum emission, need the presence of α-SiC particles while some of them require also β-SiC. Moreover, the presence of one or both types of SiC particles seems correlated neither with the total optical thickness nor with any other physical and geometrical parameter of the circumstellar envelope.

Our fitting procedure may be used, also, to derive the distances and the mass-loss rates which are in general very poorly known. The various estimates of the distances, taken from the general literature, show considerable discrepancies, while the evaluations of the mass-loss rates can be in error by more than an order of magnitude. The best-fit parameters found in Paper I

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have been already used to calculate the mass-loss rates from the central stars of our 55 carbon star sample (see Table 2 of Paper I). In this work we extend our analysis calculating the distances of the same sample of carbon stars by using the physical and geometrical parameters found in Paper I. In Sect. 2 we present the derived distances and describe the computational method which has the advantage of being, on the average, more accurate than those used for the same stars by other authors.

Using such distances and the mass-loss rates for all the 55 stars of our sample, we show that the correlation between the absolute band strength of the SiC feature and the mass loss-rates, already found by other authors with an independent method (Skinner & Whitmore 1988, hereinafter SW), still holds and it is statistically strengthened by the increased number of stars taken into consideration. This correlation, presented in Sect. 3, provides an easy method to derive the distance and/or the mass-loss rate of other carbon stars not included in our sample.

2. Evaluation of the distances

In absence of interstellar extinction, the flux density $F_\lambda(\mathrm{R_E})$ of the radiation at a wavelength λ emitted by a circumstellar envelope of outer radius $\mathrm{R_E}$, is related to the flux density $F_\lambda(d)$ observed at a distance d by the well known equation:

$$d = R_E \left[\frac{F_\lambda(R_E)}{F_\lambda(d)} \right]^{1/2} \tag{1}$$

which can be used to evaluate the distance of the object. The basic idea of our approach is the determination of the distance of a carbon star by using the best-fit values of the emitted flux at 10.6 μm and of the outer radius of the circumstellar envelope. We have chosen to work at the wavelength λ = 10.6 μm, since this value lies in the wavelength range of the observed IRAS Low Resolution Spectra (LRS, IRAS Science Team 1986) and because at this wavelength the interstellar extinction is completely negligible.

The best-fit parameters of the model discussed in Paper I are the optical thickness τ of the envelope at 0.55 μm, the star temperature $\mathrm{T_*}$, the two ratios $\mathrm{R_I/R_*}$ and $\mathrm{R_E/R_I}$ (where $\mathrm{R_I}$ is the inner radius of the envelope and $\mathrm{R_*}$ the stellar radius), and the percentages of the three dust components of the envelope (amorphous carbon, α-SiC and β-SiC). This means that, in order to derive $\mathrm{R_E}$ we have to know $\mathrm{R_*}$. In Paper I the stellar radius has been derived, starting from the best-fit values of $\mathrm{T_*}$, and using the semi-empirical formulas (Bergeat et al. 1978):

$$R_* = 183 R_\odot (T_*/2150)^{-4.55} \quad \text{for} \quad T_* \le 2150\,K \tag{2}$$

$$R_* = 183 R_\odot (T_*/2150)^{+3.5} \quad \text{for} \quad T_* \ge 2150\,K \tag{3}$$

However, when these values of $\mathrm{R_*}$, together with the best-fit values of $\mathrm{T_*}$, are used to obtain the stellar luminosity:

$$L_* = 4\pi R_*^2 \sigma T_*^4 \tag{4}$$

(σ is the Stephan-Boltzmann constant) we derive for many stars values of $\mathrm{L_*}$ which sensibly differ from the expected ones. To overcome this difficulty we have followed here a different approach. From the sample of carbon stars examined in Paper I it is possible to extract a subset of 10 Mira-like stars with well known period of variability. These stars constitute a very important group, since Feast et al. (1989), analysing a sample of 49 Mira variables in the Large Magellanic Cloud (LMC), found two distinct relations between the period and the bolometric luminosity of the star (P-L relation) which are valid for the 20 carbon-rich Miras and the 29 oxygen-rich Miras, separately. Since, as reported by Cohen & Hitchon (1996), oxygen-rich Miras in the LMC, in the solar neighborhood, and in globular clusters all fit the same P-L relation derived by Feast et al. (1989), it is reasonable to assume that the P-L relation obtained by Feast et al. (1989) for the 20 carbon-rich Miras in the LMC holds also for the galactic carbon-rich Miras. Even if the 10 galactic Mira variables of our sample have, on average, periods longer than those of the LMC C-Miras used to establish the P-L calibration, we do not expect large discrepancies from the values foreseen by the P-L relation. In fact the maximum period of our galactic Miras is only 30% greater than the maximum period of the LMC C-Miras and the two ranges overlap. We decided therefore, following Whitelock et al. (1994), to adopt the relation found by Feast et al. (1989) also for our sample of galactic Mira variables, deriving the average luminosity of these stars starting from their period. Except for one case, we have found that the luminosities evaluated in this way are in agreement within 17% with the mean value ($\mathrm{L_*}$ = 7050 $\mathrm{L_\odot}$) observed for the LMC carbon stars (Frogel et al. 1980). On the contrary they disagree by a factor up to 7 with the luminosity obtained for the same stars if the starting assumption is the validity of Eqs. (2-3) and (4). This is not surprising, however, since the semi-empirical formulas (2) and (3) have been obtained for bright carbon stars (Bergeat et al. 1978) and, in principle, they could not be valid for evolved carbon stars which are usually quite faint in the visible.

In the light of the previous discussion, for the 10 Miras of our sample we have adopted in this work the average luminosity derived from the P-L relation, while for all the remaining stars of the sample we have used the mean value $\mathrm{L_*}$ = 7050 $\mathrm{L_\odot}$.

The use of the mean value $\mathrm{L_*}$=7050 $\mathrm{L_\odot}$ (strictly valid for the LMC) could not appear as an appropriate choice, since carbon stars in the Galaxy and in the LMC could be two different populations. In fact, observations show that the luminosity functions for carbon stars in the Large and Small Magellanic Clouds are different (see e.g. Groenewegen & de Jong 1993) and this, according to some theoretical models (Marigo et al. 1999), should depend on the different metallicity in the two galaxies. Therefore the mean luminosity of C-Miras in the LMC could be, in principle, different from that of the same kind of stars in our Galaxy. However, the approach of using a unique luminosity for a large sample of stars is the best we can do at the moment and it can be considered a reasonable approximation (Groenewegen et al. 1992), since we are taking into account an homogeneous sample of stars of the same type and belonging to the same spectral class.

Moreover we note that our choice is supported by the satisfactory agreement between the luminosities of the 10 galactic C-Miras and the mean luminosity observed in the LMC (see above). In any case we think that the above choice should not affect dramatically our results; in fact, an indetermination of a factor of 2 on the star luminosity involves an indetermination of about 40% on the stellar distance.

Starting from L_* and the best-fit value of T_*, it is possible to evaluate, by means of Eq. (4), the star radius and, from this, the outer radius of the envelope (using the best-fit values of the ratios R_I/R_* and R_E/R_I) and eventually from Eq. (1) the distance of the star. In Table 1 we have listed the values of the distances found in this work for all the 55 sources of our sample. In the same table we report, for comparison, also the distances of the same objects evaluated by other authors with different methods.

The error in the determination of the distance is linked, in different extent, to the accuracy in the evaluation of the quantities T_*, R_I/R_*, and R_E/R_I (by means of the best-fit) and of L_* (by means of the above discussed assumptions). While the synthetic spectra are quite sensitive to variations in T_* and R_I/R_*, this is not the case for R_E/R_I. In fact, while variations of about 5% in T_* and 10% in R_I/R_* induce an appreciable variation in the calculated spectrum, the ratio R_E/R_I can be changed even by a factor 3, without producing any appreciable spectral change. Fortunately we have found that a large change of R_E/R_I does not produce a large variation of the distance. In fact a change by a factor of 10 in R_E/R_I produces a variation of only 0.5% in the stellar distance, if the other input parameters of the model are fixed.

It is worthwhile to summarize here the main features of our method which allows, in our opinion, to obtain reliable values of the distances:

- a) the flux values taken into consideration are those at 10.6 μm, a wavelength where the interstellar extinction is certainly negligible;
- b) the method does not use any kind of bolometric correction which, as well known, generally introduces large uncertainties;
- c) the starting parameters needed for the evaluation of the distances have been derived, as already noted in Paper I, using a radiative transfer model thoroughly applied to any single object.

3. Discussion and conclusions

As it can be seen in Table 1 the values of the distances evaluated with our method are in substantial agreement with those found by other authors for the same carbon stars. For a quantitative summary of such comparison we can actually group the results in two categories:

- a) for the first category, including 26 stars, the comparison can be made only between the values given by two papers (i.e. this work and that by Clausen et al. 1987); the distances differ less than 20% for 23 sources, and are within 38% for the remaining 3 objects (06556+0614, 19272+4556, 20082+2811).
- b) for the second category, including 29 stars, the comparison can be made with the values given by more than two papers; for 28 sources the distances found in this work either are within the range of the previous evaluations or differ less than 25% from one extreme of the range, while it is about 33% for the remaining object (19008+0726). In all cases, however, the distances found in this paper differ from one of the two extremes of the range of the previous evaluations less than the width of the interval itself.

In addition to the stellar distances, starting from the corrected values of the star radius, we have also evaluated again for each source the mass-loss rate, finding results in agreement, within a factor of 2, with those reported in Paper I. In this way it has been possible to reconsider in the new framework the relation between the band strength of the SiC feature and the mass-loss rate of carbon stars. In Fig. 1 we report the data found with our method for all the 55 sources considered both here and in Paper I. It is worthwhile to recall that the quantity plotted in ordinate can be written as:

$$P(SiC) = B(SiC)F(12\mu m)d^2 \tag{5}$$

where the star distance d is calculated as described in the previous section, $B(SiC)$ represents the ratio of the power radiated in the SiC band to that of the underlying continuum at 11.4 μm, while F(12 μm) is the color corrected Band 1 flux. We have evaluated the last two quantities taking the data from the IRAS-LRS catalog (IRAS Science Team 1986) and from the IRAS Point Sources Catalog (Gezary et al. 1987). Since the IRAS flux at 12 μm is obtained with a broad bandpass filter, we have calculated for all sources the color correction factor in order to obtain the flux values at the effective wavelength of the filter. This factor has been derived by interpolation of the data listed in Table VI.C.6 of the IRAS catalog and Atlas Explanatory Supplement (Beichman et al. 1988).

The very clear and extremely good correlation (r=0.92) obtained in Fig. 1 confirm again the results already reported in Paper I as well as those found by SW for a lower number of sources (27 carbon stars). This means that the mass-loss rate can be linked with the band strength of the SiC band by the relation:

$$\dot{M} = 7.3 \times 10^{-19} P(SiC)^{1.5} \tag{6}$$

where $P(SiC)$ is in W m^{-2} Hz$^{-1}pc^2$, while $\dot{M}$ is in M_{sun} yr^{-1}. We note that, while the exponent of $P(SiC)$ is in perfect agreement with that obtained by SW, the coefficient of the correlation obtained in our case is a factor of 2.8 higher. The relation given in Eq. (6) is certainly more accurate than the corresponding law reported by SW and the reason is that in our case it has been obtained using a homogeneous sample of star distances; SW, instead, use values reported by different authors and obtained with various methods. Moreover, as already mentioned, the number of stars taken into consideration in our case is almost double that by SW (55 versus 28).

In conclusion we have shown how, using some best-fit parameters coming from a radiative transfer model, it is possible to evaluate the distances and the mass-loss rates of the carbon stars showing the 11.3 μm emission feature. Using such data

Table 1. Star distances in parsec

IRAS name	NAME	present work	other works
00172+4425	VX And	643	610(4) 620(7)
00248+3518	AQ And	825	870(7) 520(8)
01080+5327	HV Cas(M)	1056	1360(1) 1150(7)
01105+6241		1068	1050(6) 870(7)
01133+2530	Z Psc	662	580(4) 600(7)
01531+5900	X Cas (M)	1112	1220(7)
03229+4721		415	760(1,3) 680(2,5) 550(6) 1060 u(7)
03374+6229	U Cam	513	470(2,4) 460(6) 480(7) 330(8)
03377+5120	V 466 Per	740	640(7)
03415+4437	AC Per	1236	1150(7)
04459+6804	ST Cam	485	480(2,4) 500(7) 390(8)
04483+2826	TT Tau	652	640(7)
04573-1452	R Lep (M)	557	410(1,3) 450(2,5) 430(6,7) 270(8)
05028+0106	W Ori	346	340(2,4) 330(6) 350(7) 210(8)
05056+3856	TX Aur	1207	1110(7)
05185+3227	UV Aur	941	1050(7)
05238+3406	S Aur	731	750(6) 990u (7)
05426+2040	Y Tau	436	480(2,4) 390(6) 490(7) 300(8)
05576+3940	AZ Aur(M)	1316	1320(7)
06149+0832	GK Ori	1327	1110(7)
06192+0722	BN Mon	809	1230(7) 390(8)
06331+3829	UU Aur	294	290(2) 270(6) 300(7) 210(8)
06529+0626	CL Mon(M)	742	780(6) 940(7)
06556+0614	RV Mon	682	1000(7)
07045-0728	RY Mon	634	690(7)
07057-1150	W CMa	610	660(7)
07270-1921		1140	1430u (7)
07487-0229		1550	1510(7)
08174+0255	RY Hya	1180	1120(7)
08525+1725	X Cnc	481	460(2,4) 450(7) 430(8)
08538+2002	T Cnc	650	780(7) 420(8)
10416+6740	VY UMa	673	520(2,4) 540(7) 480(8)
12226+0102	SS Vir	550	590(7)
12427+4542	Y CVn	338	250(1,3,6) 280(4) 350(2,5) 290(7) 240(8)
12447+0425	RU Vir(M)	625	1470(3,5) 730(6) 1020u(7)
12544+6615	RY Dra	405	450(2,4) 370(6) 470(7) 270(8)
16239-1218	V Oph (M)	623	830(7) 440(8)
16374-3217	SU Sco	706	680(7)
17556+5813	T Dra (M)	675	750(1,3) 525(2,5) 830(6) 690(7)
18306+3657	T Lyr	434	490(4) 510(7) 250(8)
18410+3654	HK Lyr	988	900(7)
18562+1417	UV Aql	848	870(7)
19008+0726	(M)	422	630(6) 1370u (7)
19017-0545	V Aql	395	370(2,4) 360(6) 380(7)
19147+2149	CG Vul	731	880(7)
19184+3746	U Lyr (M)	1070	1120(7)
19272+4556	AW Cyg	1364	1000(7)
19416+3422		1325	1480(7)
19555+4407	AX Cyg	855	740(7)
20028+2030	X Sge	1040	970(7)
20082+2911		2133	1560(7)
20472+3302		1488	1250(7)
21035+5136		714	920(6) 1640u(7)
21320+3850	V 1426 Cyg	634	900(1,3) 700(2) 780(5) 610(6) 1030u (7) 250(8)
21399+3516	V 460 Cyg	449	440(2,4) 480(7)

Notes: M indicates a Mira variable; u denotes an upper limit
References: (1) Knapp (1985); (2) Skinner & Withmore (1988); (3) Jura (1986); (4) Olofsson et al. (1987); (5) Knapp & Morris (1985); (6) Groenewegen et al. (1992); (7) Clausen et al. (1987); (8) Bergeat et al. (1978)

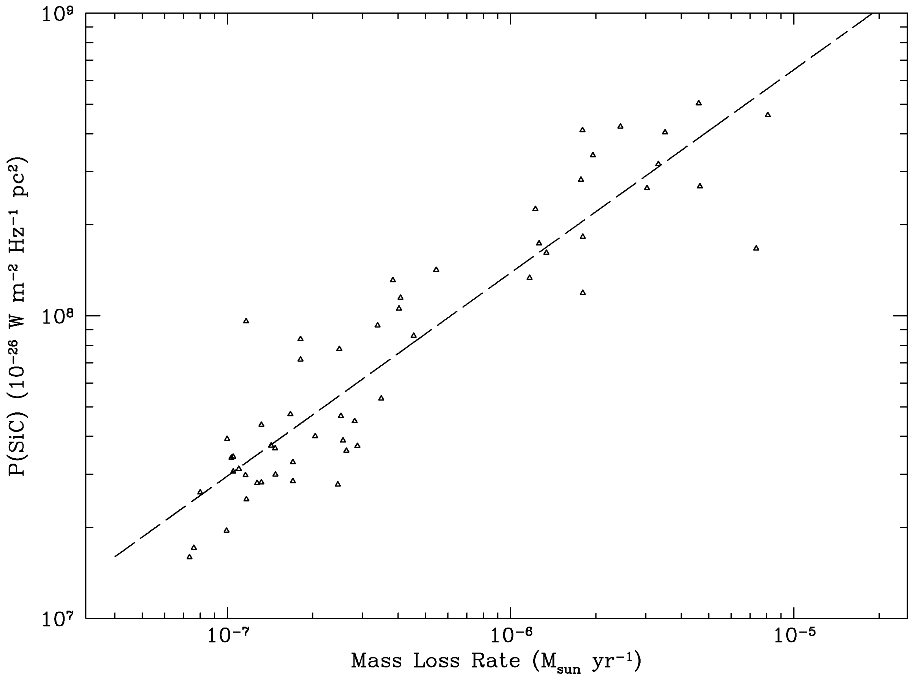

Fig. 1. Band strength of the SiC feature, P(SiC), plotted against the mass–loss rate for the 55 sources of our sample. The straight dashed line represents the log-log plot of the best–fit correlation given by Eq. (6)

for all the 55 stars of our sample, we have shown that the correlation between the absolute band strength of the SiC feature and the mass-loss rates not only confirms what already found by SW with an independent method, but it is statistically strengthened by the increased number of stars taken into consideration. This correlation provide an easy method to derive the distance and/or the mass-loss rate of other carbon stars not included in our sample.

We plan in the near future to apply the results obtained here and in Paper I to the ISO spectra of many other carbon stars. This will allow us to provide the scientific community of a set of physical parameters which will be useful for the study of dust formation processes, the evolutionary sequence and the galactic distribution of the same type of objects.

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