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Circumstellar environments – IV. Mass-loss rates for carbon stars

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Summary. We have determined the band strengths of 11.2 μm SiC features in *IRAS* spectra for a number of carbon stars whose mass-loss rates have been determined earlier from the CO $J=2\rightarrow1$ or $J=1\rightarrow0$ emission lines. The strength of the 11.2 μm SiC feature is proportional to the total mass-loss rate (as measured from CO), supporting the idea that the gas-to-dust ratio is roughly constant for carbon stars. This therefore provides an easy method of calculating mass-loss rates for carbon stars which are too distant to be detected in CO. The observed correlation probably also indicates that the ratios of carbon to silicon carbide grains in the outflows increase with age.

1 Introduction

The difficulties involved in measuring the mass-loss rates of cool, luminous stars have been expounded in an earlier paper in this series (Skinner & Whitmore 1988). Results were presented in that paper demonstrating how the 9.7 μm silicate dust feature could be used to determine mass-loss rates of oxygen-rich red giant and supergiant stars.

Such stars eject copious amounts of processed material into the interstellar medium (ISM), and are often regarded as the chief factories of interstellar dust. The dust grains that condense from the winds of oxygen-rich red giants are thought to be magnesium-rich silicates (as is expected from condensation calculations), but much of the dust observed in the ISM is thought to be graphite or amorphous carbon. Such dust grains are expected to condense from the outflows from red giants with carbon- rich atmospheres (carbon stars); these are not as common as their oxygen-rich counterparts, and represent highly evolved stars. To explain the abundance of carbonaceous dust in the ISM, carbon stars must generally have higher mass-loss rates than the oxygen-rich stars.

The frequency and evolution of carbon-stars is not well established, however, since many eject material so extravagantly that they are highly obscured optically. They are then only detected in the infrared from the thermal re-emission of radiation by the circumstellar dust. The observed carbon-rich condensates in the outflows from carbon stars generally consist of two components: amorphous carbon or graphite, which gives rise to a featureless infrared excess, and silicon carbide (SiC) which has a strong resonance feature at about 11.2 μm. Recently some debate has arisen concerning the identity of the species responsible for the 11.2 μm feature: Baron *et al.* (1987) claim the existence of an 11.7 μm feature in the spectra of many carbon stars, which they attribute to α:C–H. However the discovery of SiC in carbonaceous meteorites (Zinner, Tang & Anders 1987) tends to support the attribution of the 11.2 μm band to SiC, and we will proceed on this basis. In any case crude calculations by Puget *et al.* (1985) suggested that the unidentified infrared (UIR) features with which α:C–H is associated should be undetectable in cool circumstellar shells.

The *IRAS* survey offers an unrivalled opportunity to study carbon stars, since the unmistakable 11.2 μm feature falls in the range of the *IRAS* Low Resolution Spectrometer (LRS). First, this feature can be used to identify carbon stars in the LRS catalogue, many of which are previously unrecognized. Second, we have already shown (in Paper II) that the 9.7 μm silicate dust feature can be used to determine the mass-loss rates of oxygen-rich red giants and supergiants. SiC is thought to constitute a small fraction of the total mass of dust in carbon-rich circumstellar shells. However, if this fraction is constant, and the gas-to-dust ratio remains constant from star to star, then the SiC feature may be used as a measure of mass-loss rates for carbon-rich stars. It is the purpose of this paper to investigate this possibility.

2 Observations

Our reasons for believing CO observations to be by far the most reliable published measurements of mass-loss rates for cool, luminous stars have been fully discussed in Paper II. The mass-loss rates used in this paper derive from the same sources as those of Paper II, namely Knapp *et al.* (1982) and Knapp & Morris (1985), and from Olofsson, Eriksson & Gustafsson (1987) and Wannier & Sahai (1986). Only stars classified as carbon stars were used; we have again ignored the S-stars, on the grounds that as the abundance ratio of carbon to oxygen changes through the S sub-classes, so the gas-to-dust ratio may change. A list of the carbon stars detected in CO by Knapp *et al.* and by Olofsson *et al.* was cross-correlated with the *IRAS* LRS catalogue, and those stars flagged as having SiC emission selected; Wannier & Sahai only detected one carbon star, Y CVn. The LRS catalogue lists the quantity B(SiC) for all SiC sources, defined as

$$B(\mathrm{SiC})=10\log \mathscr{F}_\lambda(11.4\,\mu\mathrm{m})-[0.506\log \mathscr{F}_\lambda(9.8\,\mu\mathrm{m})+0.494\log \mathscr{F}_\lambda(13.3\,\mu\mathrm{m})]. \quad (1)$$

$\mathscr{F}_\lambda(\lambda)$ is the spectral flux at λ. B (SiC) thus gives the ratio of the power radiated in the SiC band to that in the underlying continuum at 11.4 μm.

To obtain the power radiated in the SiC feature in absolute terms, the relative band strength B(SiC) must be multiplied by the intrinsic brightness of the star at 11.4 μm. This is obtained using the *IRAS* Band 1 flux and the published distance from Knapp *et al.*, Olofsson *et al.* or Wannier & Sahai as in Paper II:

$$P(\mathrm{SiC})=B\,(\mathrm{SiC})\,F(12\,\mu\mathrm{m})d_*^2, \quad (2)$$

$F(12\,\mu\mathrm{m})$ being the Band 1 flux, and d_* the distance.

3 Results

Of Knapp *et al.*'s 22 C-stars, 19 were present in the LRS catalogue, of which 14 were flagged as having SiC emission; one of these was Y CVn, for which we use Wannier & Sahai's mass-loss rate due to their more sophisticated analysis. A further 10 stars from Olofsson *et al.* were present in the LRS and flagged as having SiC emission. Ground-based spectra exist for a further four of Knapp *et al.*'s stars, namely V Hya, CIT 6, CRL 3068 and CRL 3099. For these latter stars an estimate of the 12 μm flux was made by comparing their spectral flux densities near 12 μm with that for α Ori, and scaling to the *IRAS* 12 μm flux for α Ori. These values of P(SiC) are therefore slightly less certain than those for the *IRAS* detected stars. CRL 3068 was noted by Jones *et al.* as having SiC absorption. This is obviously difficult to incorporate into our scheme, but we nominally set B(SiC) to be 10 for this special case. Additionally R Lep has LRS spectra, but was at the limits of detectability in CO, and so has a rather uncertain mass-loss rate. Accordingly, it falls farther from the line denoted by equation (3) than any of our other stars, and so is not included in Fig. 1. All these stars (including R Lep) are listed in Table 1, and the calculated values of P(SiC) are plotted against the published mass-loss rates in Fig. 1. A distinct correlation is obtained. The value for CRL 3068 seems to fit this correlation quite well, despite the star having SiC in absorption. We find that

$$\dot{M}=2.6\times10^{-19}[P(\mathrm{SiC})]^{1.5}, \qquad (3)$$

allowing mass-loss rates to be calculated for any carbon star in the LRS catalogue, provided its distance is known or can be estimated.

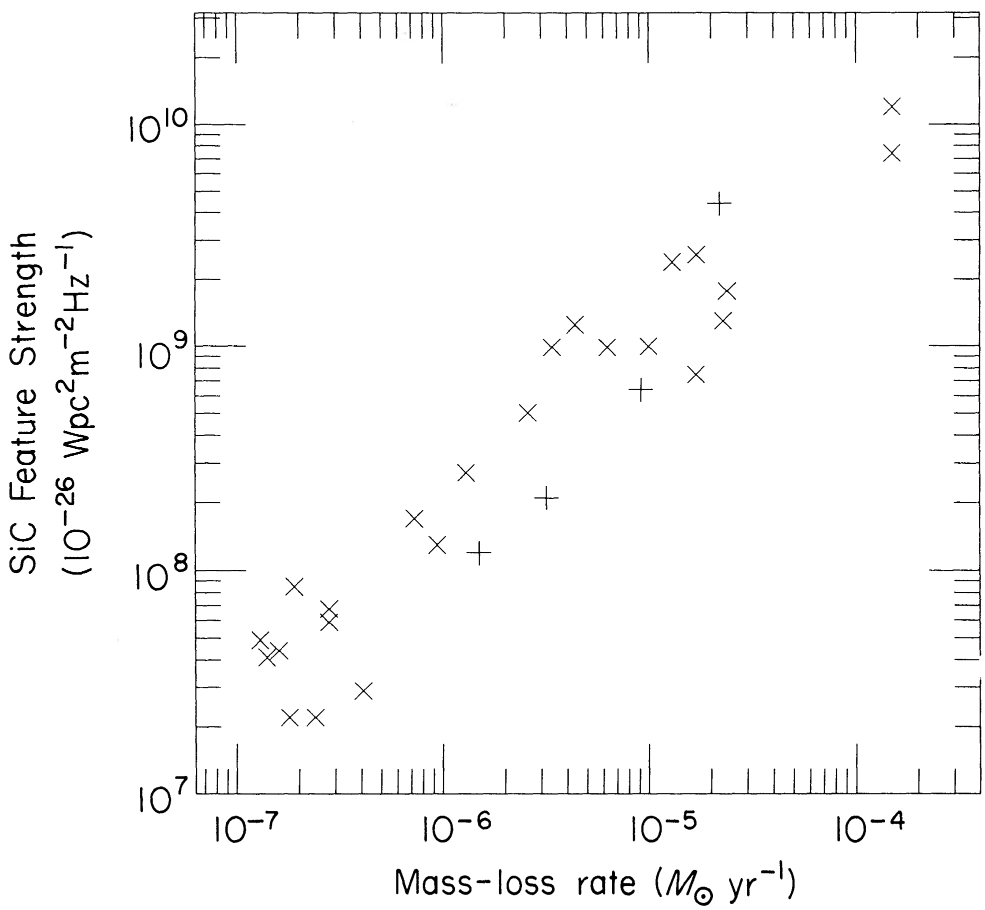

Figure 1. Band strength of the SiC dust feature plotted against published (CO) mass-loss rate. $\times$ = *IRAS* observations; + = ground-based infrared observations.

Table 1.

IRAS name	Star	Spectral type	*B*(SiC)	Mass-loss rate $M_\odot$ yr^{-1}	Distance (pc)	Source
03186+7016	CRL 482	C	2	1.7×10^{-5}	1600	2,3
03229+4721	IRC 50096	N	4	6.3×10^{-6}	680	2,3
03373+6229	U Cam	C6,4	5	9.4×10^{-7}	470	7,3
04307+6210	IRC+60144	C	5	2.3×10^{-5}	1000	2,3
04456+6804	ST Cam	C6,4	2	1.6×10^{-7}	480	7,3
04573−1452	R Lep	N6e	5	$<2.1\times10^{-6}$	450	2,3
05025+0106	W Ori	C5,3	4	1.9×10^{-7}	340	7,3
05426+2040	Y Tau	C7,4	5	7.3×10^{-7}	480	7,3
06331+3829	UU Aur	C5,3	3	2.8×10^{-7}	290	7,3
08523+1725	VY UMa	C6,3	2	1.3×10^{-7}	520	7,3
09452+1330	IRC+10216	C9,5	3	1.5×10^{-4}	290	1,3
10131+3049	CIT 6	C4	1	3.2×10^{-6}	190	1,4
10413+6740	X Cnc	C5,4	2	2.4×10^{-7}	460	7,3
10491−2059	V Hya	C6,3e	3	9.2×10^{-6}	400	1,4
12427+4542	Y CVn	C5,4	2	2.8×10^{-7}	350	8,3
12542+6615	RY Dra	C4,4	1	1.8×10^{-7}	450	7,3
17556+5813	T Dra	N0e (C8e)	5	1.3×10^{-6}	525	2,3
18194−2708	CRL 2135	C	3	1.5×10^{-4}	1900	1,3
18240+2326	CRL 2155	C	2	1.7×10^{-5}	1330	2,3
18333+0533	CRL 2199	C	2	1.3×10^{-5}	2000	2,3
18397+1738	IRC+20370	C7,3e	3	1.0×10^{-5}	790	1,3
19014+0545	V Aql	C6,4	2	1.4×10^{-7}	370	7,3
20396+4757	V Cyg	C7,4e	4	3.4×10^{-6}	610	2,3
21032−0024	IRC+00499	Ne, C6,3	5	4.4×10^{-6}	900	2,3
21320+3850	IRC+40485	C	4	2.6×10^{-6}	700	2,3
21395+3516	V460 Cyg	C6,3	2	4.1×10^{-7}	440	7,3
23166+1655	CRL 3068	C	10	2.2×10^{-5}	570	1,5
23257+1038	CRL 3099	C	1	1.5×10^{-6}	500	2,6
23320+4316	IRC+40540	C8,3.4	2	2.4×10^{-5}	960	2,3

Sources used in Table 1: [1] Knapp *et al.* 1982; [2] Knapp & Morris 1985; [3] *IRAS* LRS catalogues; [4] Hackwell 1972; [5] Jones *et al.* 1978; [6] Gehrz, Hackwell & Briotta 1978; [7] Olofsson *et al.* 1987; [8] Wannier & Sahai 1986.

4 Discussion

Uncertainties in the distances to these stars obviously account for some scatter in the data. Additionally there are differences in the mass-loss rates measured using the $J=2\rightarrow1$ and $J=1\rightarrow0$ transitions for individual stars in the papers by Knapp *et al.* (1982) and Knapp & Morris (1985), indicating a significant uncertainty in published mass-loss rates. Despite this we must conclude that the SiC feature represents a reliable measurement of the mass-loss rates for carbon stars.

This leaves us with the suggestion that any nearby star with SiC emission should be detectable in CO. Unfortunately the 'standard' works on CO in red giants still tend to be those of Knapp *et al.* (1982) which were based on surveys of stars known to be relatively bright optically or in the near-infrared, with rather poor detection limits. Hence stars like R Lep, which is relatively bright among the stars in the LRS, were at the threshold of detection in CO, and S Aur and FX Ser were too faint. More recent CO surveys, such as that by Olofsson *et al.*, would certainly have detected these two stars unambiguously.

The reasonable correlation found here appears surprising at first sight, since SiC is not generally regarded to be an abundant atmospheric constituent (or even always present) in the outflows from high mass-loss rate C-stars. However, this work suggests the following scenario. It seems that the infrared excesses of low mass-loss rate stars like Y CVn can be explained almost entirely by SiC dust (Goebel *et al.* 1980). In the case of high mass-loss rate objects like IRC+10216, the entire infrared continuum is dominated by the featureless emission from amorphous carbon grains (and SiC around 11.5 μm). In fact many similar C-rich mass-loss stars in the LRS catalogue, which are not flagged as having SiC emission, do appear to have weak SiC features, which have almost been swamped by the optically thick carbon grain emission (Little-Marenin, private communication).

We suggest that the ratio of SiC to carbon dust decreases with increasing mass-loss rate, so that in many high mass-loss rate objects the SiC feature becomes lost due to dynamic range problems. This is borne out by the non-linear dependence of P(SiC) on $\dot{M}$, which is to be compared with Knapp's results (1985) that the gas-to-dust ratio is constant for C-stars (this was based on models of the emission from carbon dust grains). Many of the highest mass-loss rate carbon-rich objects, such as IRC+10 216 or CRL 2135, are suspected to be protoplanetary nebulae (PPN). It seems likely that the mass-loss rates increase with age for carbon stars, culminating in the very high mass-loss PPN and subsequent PN stages. A further change with age may be a continuing increase in the surface abundance of carbon relative to other elements. Most of the silicon in the atmospheres becomes bound up in SiC molecules (and grains in the outflows), leaving an excess of carbon to form the observed carbon grains. An increase of both carbon abundance and mass-loss rate with age would lead to an increase in C to SiC ratio with increasing age, and hence mass-loss rate (as implied by our results), provided that the silicon abundance does not also change with age. In other words, the younger carbon stars will tend to have lower mass-loss rates and infrared spectra dominated by SiC, whilst their older cousins have higher mass-loss rates and continua dominated by circumstellar carbon grain emission.

Metallicities of carbon stars are generally poorly known, but Lambert *et al.* (1986) found no evidence for enhancement of metals in a sample of 30 carbon stars. The fate of carbon stars is to end as planetary nebulae (PN), and metallicities are more readily available for PN, owing to the rich variety of emission lines present in their spectra. In general Mg, Fe and Si are all found to be depleted in the ionized shells of PN, in a manner consistent with their incorporation into dust grains such as Fe, SiC, C and silicates (Shields 1983 and Barlow 1983, for example), and even MgS in some cases (Goebel & Mosely 1985). There is again no suggestion of Si enhancement in carbon-rich nebulae, which seems to preclude such an effect in their carbon star progenitors. Thus our suggestion that the SiC/C abundance ratio decreases with age is consistent with all the available observations.

A consequence of this suggestion, if it is borne out by further observations, is that the contrast of the SiC feature against the continuum (B(SiC)) is not a good indicator of mass-loss rate. Only its strength can be used; however the SiC feature used in this way does provide a useful means of estimation of carbon star mass-loss rates, which will be much more widely applicable than either CO mm-wave emission lines (only nearby or very high mass-loss rate stars are detectable by this means) or the emission from carbon grains which requires large computer models.

5 Conclusions

We have shown that the power radiated in the 11.2 μm SiC feature by C-stars may be used to determine their mass-loss rates, provided their distances are known. The results suggest that the ratio of SiC to carbon dust grains decreases with increasing mass-loss rate.

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