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Letter to the Editor

CO(J=1–0) observations of bright carbon stars

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SUMMARY. We have surveyed a sample of bright N-type stars, with recent estimates of chemical composition, in the CO(J=1-0) line. Almost all stars were detected. The mass loss rate is well correlated with a far-IR excess measure, and the gas-to-dust mass ratio, estimated to be 350±200, seems relatively constant for this sample of stars. The mass loss rate appears to be dependent on the effective temperature, the carbon excess, and the $^{12}C/^{13}C$-ratio of the central star. In particular, the peculiar ^{13}C-rich stars have comparatively low mass loss rates. A weak dependence of gas expansion velocity of the circumstellar envelope on the carbon excess may exist.

Key words: Stars: carbon – Stars: circumstellar matter Stars: mass loss

1. INTRODUCTION

The number of highly evolved stars detected in circumstellar CO emission has recently increased substantially, mainly due to the availability of the huge data base provided by IRAS (Zuckerman and Dyck, 1986a,b and 1987; Zuckerman et al., 1986; Nguyen-Q-Rieu et al., 1987). Important statistical information on the properties of circumstellar envelopes (CSEs) and the central stars have thus been obtained (see e.g., Knapp, 1987). The observations have been concentrated towards very infrared bright and/or highly reddened, and thus heavily obscured, objects where the detection rate is high, but where little is known about the central stars. We have therefore chosen as our target list a sample of relatively well studied, bright carbon stars for which effective temperatures and CNO-abundances have been estimated (Lambert et al., 1986).

2. OBSERVATIONS

The observations were performed during 1986 and 1987 at the Onsala Space Observatory with the 20 m telescope, equipped with a SIS-receiver. The antenna FWHP and pointing errors at 115 GHz were measured to be 33" and less than 5", respectively. The back end consisted of two filterbanks, 512×1 MHz and 256×250 kHz, resulting in velocity resolutions of 2.6 and 0.65 km s^{-1}, respectively. The data are given in terms of main beam brightness temperature, $T_{mb}=T_A^*/\eta_{mb}$, where T_A^* is the chopper wheel corrected antenna temperature, and the chopper wheel calibrated main beam efficiency of the telescope, η_{mb}, was measured to be ∿0.3. The absolute intensity scale is estimated to be correct to within ±20%.

We have observed all stars with $\delta>-8^o$ from the list of Lambert et al. (1986), and detected 16 out of 21, Table 1. Some of the observed spectra are presented in fig. 1. Another four stars at more southern declinations from the list of Lambert et al. have been detected elsewhere: R Lep (Knapp and Morris, 1985; Zuckerman and Dyck, 1986a), U Hya (Zuckerman and Dyck, 1986a), R Scl (Knapp and Morris, 1985; Zuckerman and Dyck, 1986b), and V Hya (Zuckerman and Dyck, 1986b). The main beam brightness temperature, T_{mb}, the central velocity with respect to the LSR, v_c, and the gas expansion velocity of the CSE (half of the full width at zero intensity), v_e, have been obtained from a fit of a parabola (or a flat-topped parabola in some cases) to the observed spectrum.

3. RESULTS

The intent of this *Letter* is to present the observational data, and to study some simple characteristics of the CSEs that can be compared with the stellar properties. Some preliminary results were presented already by Eriksson et al. (1986).

3.1 The Sample

The list of Lambert et al. (1986) contains all non-Mira N-type carbon stars brighter than K=1^m with $\delta>-30^o$. They are mainly classified as semi-regulars. The stars in Table 1 have an average variability in the visual, $\langle|m_{V,max}-m_{V,min}|\rangle$, of only 1.8±0.7 magnitudes (Kukarkin et al., 1969). They have only moderate carbon excesses, $\langle\varepsilon_C/\varepsilon_O\rangle$=1.15±0.17, with VX And being the extreme case at $\varepsilon_C/\varepsilon_O$=1.76 (we use the notation ε_X to symbolize the abundance of a chemical element X, by number, normalized to $\log(\varepsilon_H)$=12). The effective temperatures range from 2380 K (T Lyr) to 3030 K (TX Psc) with an average of 2740±170 K. The sample includes four ^{13}C-rich stars ($^{12}C/^{13}C$∿4), Y CVn, RY Dra, T Lyr, and WZ Cas (in all figures marked with open circles). When plotted in a far-IR colour-colour diagram, fig. 2, the stars in Table 1 clearly show the characteristics of carbon stars with thin CSEs, i.e., the 12μm/25μm colour indicates a warm central object while the 25μm/60μm colour signals the presence of a cold CSE (Hacking et al., 1985).

3.2 Relation between I_{CO} and S_{IR}

The integrated intensity of the CO(J=1-0) emission, $I_{CO}=\int T_{mb}dv$, for our stars has been found to correlate well with the IRAS infrared flux. As an example the data for I_{CO} and $S_{60\mu m}$ (no colour correction factors applied) are presented in fig. 3, and the best-fit line is

$$I_{CO} = 0.33\,S_{60} + 0.6\,, \qquad (r=0.84) \qquad (1)$$

where I_{CO} is given in K km s^{-1}, S in Jy, and r is the correlation coefficient. We may conclude that i) our CO calibration is rather stable, and ii) the upper limits in CO(J=1-0) for VX And (the most C-rich star), T Lyr

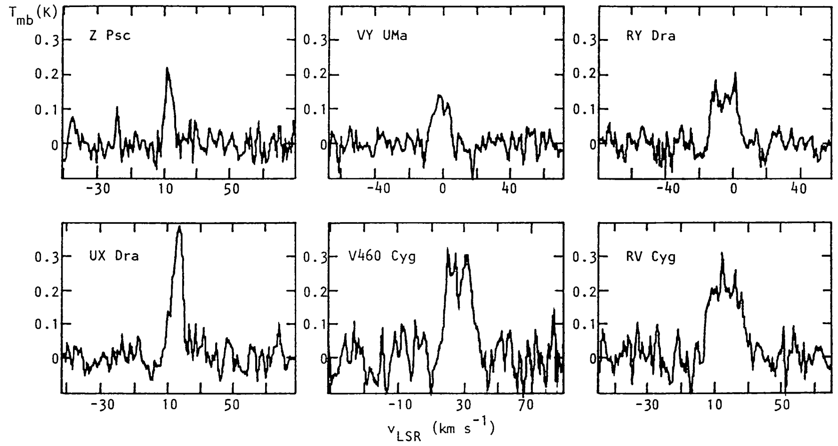

Figure 1. CO(J=1-0) spectra of some of the observed sources (velocity resolution 1.3 km s^{-1})

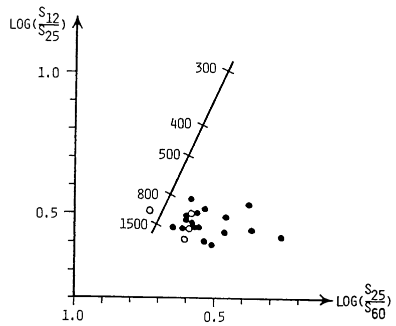

Figure 2. Far-IR colour-colour diagram for the observed sources obtained from the (not colour corrected) IRAS fluxes. In all figures the ^{13}C-rich stars are marked with open circles. A relation for blackbodies, with temperatures indicated, is also given

Table 1. Observational Results

Source	α_{1950}	δ_{1950}	D (pc)	T_{mb} (K)	I_{CO} (Kkms^{-1})	v_c (kms^{-1})	v_e (kms^{-1})	$\dot{M}$ ($M_\odot$yr^{-1})	Remarks
VX And	00^{h}17^{m}15^s.0	44°25'56"	610	<0.08				<1.6×10^{-7}	
Z Psc	1 13 21.0	25 30 20	580	0.18	0.96	13.3	3.5	0.4×10^{-7}	
U Cam	3 37 29.1	62 29 19	470	0.22	5.0	9.9	18.8	9.4×10^{-7}	6, a
ST Cam	4 46 01.3	68 05 02	480	0.13	2.1	-15.7	10.0	1.6×10^{-7}	
W Ori	5 02 48.7	1 06 37	340	0.21	3.7	5.2	11.8	1.9×10^{-7}	3
Y Tau	5 42 40.5	20 40 33	480	0.27	6.2	14.9	14.9	7.3×10^{-7}	6, a
TU Gem	6 07 46.8	26 01 35	630	0.19	3.4	28.4	11.4	5.3×10^{-7}	
BL Ori	6 22 36.9	14 45 04	560	0.15:					b
UU Aur	6 33 06.6	38 29 16	290	0.47	8.0	5.9	11.4	2.8×10^{-7}	3, 6
X Cnc	8 52 34.0	17 25 22	460	0.15	2.0	-15.2	12.0	2.4×10^{-7}	
VY UMa	10 41 37.1	67 40 27	520	0.12	1.4	-2.6	8.4	1.3×10^{-7}	
Y CVn	12 42 47.1	45 42 48	280	0.34	4.4	19.8	9.0	1.1×10^{-7}	2, 3
RY Dra	12 54 28.1	66 15 52	450	0.16	2.5	-5.7	10.0	1.8×10^{-7}	
T Lyr	18 30 36.2	36 57 39	490	<0.07				<0.9×10^{-7}	
S Sct	18 47 37.1	-7 57 59	520	<0.3					
V Aql	19 01 44.0	-5 45 38	370	0.26	3.5	53.9	8.2	1.4×10^{-7}	5
UX Dra	19 23 22.4	76 27 42	430	0.37	3.0	14.1	6.9	1.8×10^{-7}	
V460 Cyg	21 39 54.3	35 16 53	440	0.26	4.7	27.0	11.4	4.1×10^{-7}	
RV Cyg	21 41 12.0	37 47 17	470	0.22	4.8	16.8	14.7	5.6×10^{-7}	
TX Psc	23 43 50.1	3 12 34	280	0.29	4.7	12.9	11.8	1.5×10^{-7}	1, 4
WZ Cas	23 58 41.9	60 04 37	500	<0.07				<0.9×10^{-7}	

Also detected by (1) Eriksson et al., 1986; (2) Wannier and Sahai, 1986; (3) Zuckerman and Dyck, 1986a; (4) Zuckerman and Dyck, 1986b; (5) Zuckerman and Dyck, 1987; (6) Zuckerman et al., 1986.
[a]Blended with interstellar CO lines
[b]Tentative detection due to severe blending

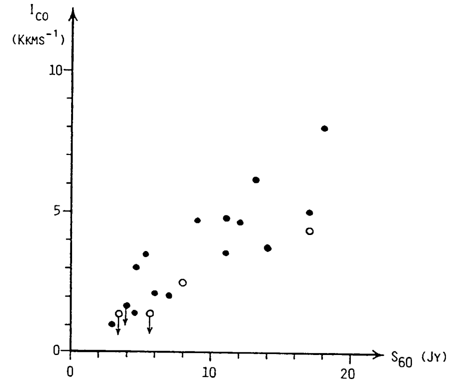

Figure 3. The integrated CO(J=1-0) intensity, I_{CO}, versus the (not colour corrected) IRAS flux at 60μm, S_{60}

(^{13}C-rich), and WZ Cas (^{13}C-rich) are not very significant in view of their IR fluxes. There is, however, a tendency that a ^{13}C-rich star for a given IR flux may have a low I_{CO} compared to a "normal" carbon star.

3.3 The Mass Loss Rate, $\dot{M}$

In order to estimate the mass loss rate we have used the relation obtained by Knapp and Morris (1985) for a CSE that is optically thick in the CO(J=1-0) line and unresolved by the telescope,

$$\dot{M} = \frac{T_{mb} v_e^2 D^2}{0.8\times10^{16} f^{0.85}} , \qquad (2)$$

where $\dot{M}$ is the mass loss rate in $M_\odot yr^{-1}$, v_e is the gas expansion velocity of the CSE in km s^{-1}, D is the stellar distance in pc, and f=(CO)/(H_2). Eq.(4) of Knapp and Morris has been scaled by a factor of five to account for the larger Onsala telescope. For a point source the factor should be nine but we may partly resolve the sources. If line dissociation determines the size of the CO emitting region we may use Eq.(14) of Morris and Jura (1983), in the rewritten version of Knapp and Morris, to calculate a photodissociation radius of $\sim 2\times10^{17}$ cm for our mass loss range. This corresponds to ∿35", a full beam width, at a distance of 400 pc. We have also corrected for a cosmic He abundance. D is estimated assuming that M_K=-8 (Glass, 1979). Using f=8×10^{-4} (Knapp and Morris, 1985; Zuckerman and Dyck, 1986a) we obtain the mass loss rate estimates given in Table 1. The rather low mass loss rates, a few × 10^{-7} $M_\odot$ yr^{-1}, are not totally unexpected considering the low variability of the stars – it has been argued that it is the pulsational activity that raises enough material to a sufficiently high level in the stellar atmosphere for radiation pressure on grains to act as an effective mass loss mechanism (Jones et al., 1981; Jura, 1986).

3.4 Relation between $\dot{M}$ and the Far-infrared Properties of the CSE

It is of importance to calibrate a relation between the mass loss rate (as estimated from the CO observations) and a measure of the far-IR excess, as given by the IRAS data. Since in our case the CSEs are relatively thin (so that the photospheric flux may dominate for λ<25 μm), we have adopted the following definition of an IR excess measure, IR_e,

$$IR_e = \frac{S_{25}+S_{60}}{S_{2.2}} . \qquad (3)$$

We define the corrected IR excess , ΔIR_e, as

$$\Delta IR_e = IR_e - IR_{e,star} \qquad (4)$$

where $IR_{e,star}$ has been calculated from the estimated effective temperature for each star (Lambert et al.,

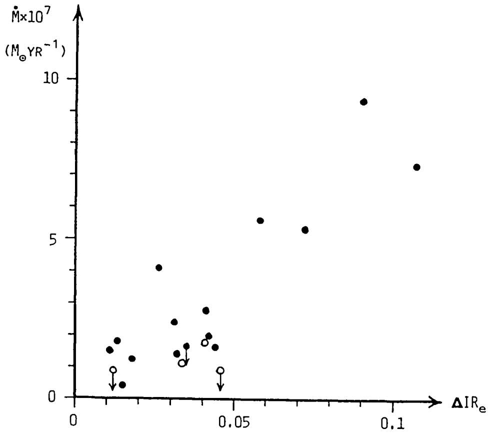

Figure 4. The mass loss rate, $\dot{M}$, versus the IR excess measure, ΔIR_e (defined in the text)

1986), and where we have used the (not colour corrected) IRAS fluxes. The low variability of the stars should make this quantity relatively reliable despite the fact that the infrared data have been obtained at different epochs. The following relation results from a comparison between $\dot{M}$ and ΔIR_e (also shown in fig. 4),

$$\dot{M} = (80\ \Delta IR_e - 0.3) \times 10^{-7}\ , \qquad (r=0.86) \qquad (5)$$

where $\dot{M}$ is given in $M_\odot\ yr^{-1}$.

3.5 The Gas-to-dust Ratio

An implication of relation (5) is that the gas-to-dust ratio seems to be fairly constant for the observed CSEs. This is further strengthened by the fact that the mass loss rate is well correlated with the relative strength of the SiC feature at ∿11.5 μm , as taken from the IRAS LRS spectra.

We have made a rough estimate of the gas-to-dust ratio using the simple model of Sopka et al. (1985) in the rewritten version of Jura (1986) (Eqs.(2) and (3)). The results are subject to substantial uncertainties as discussed by Jura. The IRAS flux at 60 μm has been corrected for the photospheric contribution (estimated from the 2.2 μm flux and the effective temperature given in Lambert et al., 1986), and a colour correction has been applied (estimated from the 25/60 μm colour temperature). The drift velocity of the dust relative to the gas is obtained from Eq.(6) in Sopka et al.. The integrated flux of the central star is calculated from the 2.2 μm flux and the effective temperature given in Lambert et al. (1986). We have found a fairly constant gas-to-dust mass ratio, $\dot{M}_g/\dot{M}_d$, with an average of 350±200. This value is higher than the lowest possible value (i.e.,all the carbon exist in the form of dust) by a factor of two, but is considerably lower than the value one would obtain if only the carbon excess relative to oxygen was used in grains. The oldest and most C-rich stars tend to have lower $\dot{M}_g/\dot{M}_d$.

3.6 Is $\dot{M}$ dependent on T_{eff}, Carbon excess, and $^{12}C/^{13}C$-ratio ?

Very little is known about the relation between the properties of the CSE and the characteristics of the central star. Our sample provides a unique possibility to perform some initial tests. Fig. 5 shows plots of the mass loss rate as a function of the effective temperature, the carbon excess (defined as $\log(\varepsilon_C-\varepsilon_O)$), and the $^{12}C/^{13}C$-ratio of the central star. There are no clear trends. However, it appears that $\dot{M}$ decreases with increasing T_{eff}, but for a given T_{eff} the mass loss rate may take on any value below a certain limit. A simple explanation to the first fact may be that the hotter the star the larger the dust condensation radius, and the less effective the grain condensation and hence the radiation pressure on the grains.

There is also an indication that the higher the carbon excess the higher the possible mass loss rate, although a high carbon excess is by no means a sufficient condition for a high mass loss rate. The reason for an $\dot{M}$-dependence on carbon excess could be that a high carbon excess may lead to a more efficient condensation of grains. Since there is a correlation between effective temperature and carbon excess according to Lambert et al. (1986), figs 5a and b are somewhat redundant.

Fig. 5c presents a plot of the mass loss rate as a function of the $^{12}C/^{13}C$-ratio. It appears that $\dot{M}$ increases with increasing $^{12}C/^{13}C$-ratio, but also in this case we find that for a given $^{12}C/^{13}C$-ratio the mass loss rate may take any value below a certain limit.

We tentatively conclude that there is a tendency for $\dot{M}$ to increase with decreasing T_{eff}, with increasing carbon excess, and with increasing $^{12}C/^{13}C$-ratio (a dependence of f, which enters into our mass loss calculation, on any of these quantities will alter this conclusion). The known errors in the determination of photospheric parameters and in I_{CO} do not account for the scatter in the relation between $\dot{M}$ and these parameters. Thus something else, possibly the pulsational activity (Jura, 1986), or a molecular cooling instability (Muchmore et al., 1987), is more decisive for the rate at which the star loses mass. Finally we note that a low T_{eff}, a high carbon excess, and a high $^{12}C/^{13}C$-ratio probably reflect a later stage at the asymptotic giant

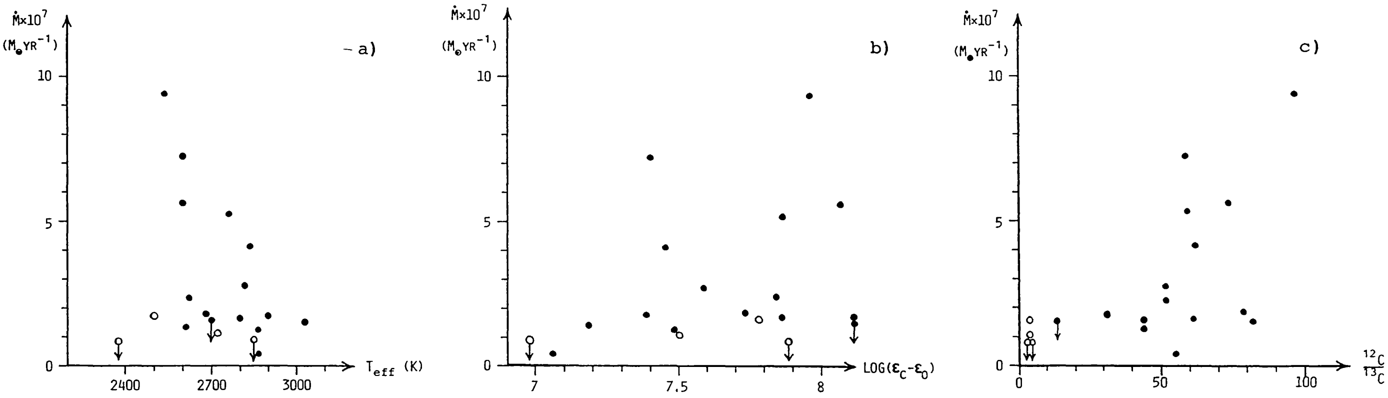

Figure 5. The mass loss rate, $\dot{M}$, versus a) the effective temperature, T_{eff}, b) the carbon excess, $\log(\varepsilon_C-\varepsilon_O)$, and c) the $^{12}C/^{13}C$-ratio of the central star.

branch, and thus the mass loss rate appears to increase with time.

The fact that the ^{13}C-rich stars appear to lie at the low end of the mass loss range, irrespective of their location in the T_{eff}, $\log(\varepsilon_C-\varepsilon_O)$-plane, is probably significant.

3.7 Is v_e dependent on Carbon excess ?

In a simple model for a dust-driven CSE (e.g., ignoring the drag force between the gas and the dust) the expansion velocity is given by (Jura, 1984),

$$v_e = \text{const} \times \chi^{0.5} L^{0.25} \sim \text{const} \times \chi^{0.5} \quad , \qquad (6)$$

where χ is the dust opacity per unit mass, and L is the stellar luminosity. In fig. 6 we have plotted the expansion velocity versus the carbon excess. A fit to the data yields,

$$v_e = 0.026\,(\varepsilon_C-\varepsilon_O)^{0.35} \quad , \qquad (r=0.61) \qquad (7)$$

where v_e is given in km s^{-1}. Eqs (6) and (7) give the following relation between the dust opacity and the carbon excess,

$$\chi = \text{const} \times (\varepsilon_C-\varepsilon_O)^{0.7} \quad . \qquad (8)$$

If one assumes that the volume of a dust grain scales linearly with the carbon excess and that the number of grains stays constant, then the geometrical cross section of the grains scales as $(\varepsilon_C-\varepsilon_O)^{0.67}$. If, on the other hand, the volume of a grain stays constant while the number of grains increases linearly with the carbon excess, then the cross section of the grains scale as $(\varepsilon_C-\varepsilon_O)$. In both cases this is close to our observationally derived value. However, relation (7) rests on fairly loose grounds since a single star, Z Psc, gives a strong weight to the result. Part of the scatter in fig. 6 may be due to the fact that severe blending with interstellar CO lines makes the determination of v_e uncertain in some cases.

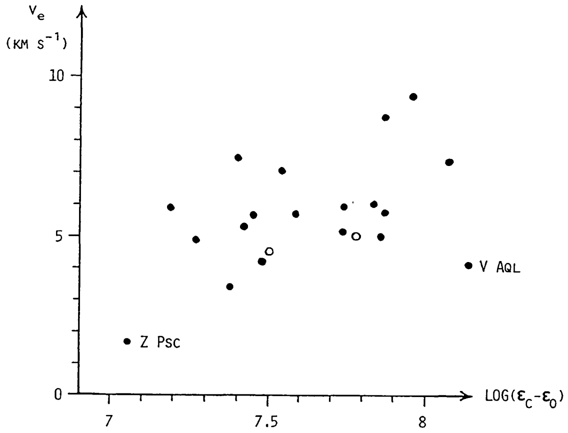

Figure 6. A plot of the expansion velocity of the CSE, v_e, versus the carbon excess, $\log(\varepsilon_C-\varepsilon_O)$. Included in this plot are also data for R Lep and U Hya (Zuckerman and Dyck, 1986a), and for R Scl and V Hya (Zuckerman and Dyck, 1986b)

4. CONCLUSIONS

An important conclusion of the present paper is that most bright N-stars have circumstellar envelopes. The mass loss rate does not depend entirely on known photospheric parameters, such as effective temperature or carbon excess, although there is a general tendency for the more evolved stars (low T_{eff}, high $\varepsilon_C/\varepsilon_O$, and high $^{12}C/^{13}C$-ratio) to have larger mass loss. In particular, the ^{13}C-rich stars show low mass loss rates.

The present sample of stars should be extended further and the already discovered circumstellar envelopes should be studied with other techniques. It seems reasonable to assume that the understanding of stellar mass loss could benefit considerably if such studies were made for statistically well controlled samples of stars with homogeneous estimates of photospheric characteristics.

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