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Outflow velocities from carbon stars

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Summary. A plot of outflow velocity versus galactic latitude for a sample of 103 carbon stars clearly confirms a relationship that we claimed in a previous paper: There is a class of carbon stars that lies at small galactic latitude ($|b| \lesssim 10°$) that has large circumstellar outflow velocity ($V_\infty \gtrsim 18\,\mathrm{km\,s^{-1}}$). These must be the most massive and luminous carbon stars in the galaxy. This dependence of V_∞ on $|b|$ implies that carbon stars must originate from stars that had a fairly wide range of masses when they were on the main sequence.

We detected carbon monoxide rotational emission, $J = 2 \rightarrow 1$ or $1 \rightarrow 0$, in the circumstellar envelopes around 22 red giant stars and one planetary nebula (NGC 6302). The measured $J = 2 \rightarrow 1$ radial velocity and line width and the beam switching mode that was employed all imply that the molecular gas toward NGC 6302 is, in fact, associated with the planetary nebula. We also obtained high-quality CO profiles toward the carbon star V Hya. In addition to the standard circumstellar line, both narrow and broad kinematic components are present. In a previous paper we attributed one of the narrow components to probable CO maser emission. It now appears, rather, that this and other CO spectral features are due to unusual kinematics in the outflowing material around V Hya.

Key words: stars: mass loss – carbon stars – radio lines: molecular

1. Introduction

This is the fourth in a series of papers on mass loss from luminous red giant stars in the Infrared Astronomical Satellite (IRAS) point source catalog and the Revised Air Force Geophysics Laboratory catalog ("RAFGL", Price and Murdock, 1983). In the previous papers (Zuckerman and Dyck, 1986a; Zuckerman et al., 1986; Zuckerman and Dyck, 1986b; hereafter Papers I–III) we discussed CO and HCN rotational emission lines from approximately 130 stars. Of these, data from approximately 80 stars were presented for the first time in Papers I–III.

In Fig. 4 of Paper II we presented evidence that carbon-rich stars which have circumstellar envelopes with large outflow velocities (V_∞) are preferentially located close to the galactic plane. We inferred (1) that the envelope's ejection velocity is determined by the mass of the underlying star and rarely, if ever, by the gravitational field of a companion star and (2) that IRC + 10216 is an AGB star of only moderate luminosity and, therefore, is probably located within approximately 150 pc of the Earth. In the present paper, Sect. 3.2, we extend the data base that was available in Paper II and thereby solidify the arguments that were presented there.

In Paper III, we discussed unusual CO emission profiles observed toward the late N-type carbon star V Hya and the oxygen-rich planetary nebula NGC 6302. In the present paper, Sect. 3.1, we describe new, high-quality data that clarify the uncertain pictures that we painted of these two stars. We have also detected, for the first time, circumstellar emission from a variety of carbon- and oxygen-rich evolved stars (see Table 1).

2. Equipment and observations

We used the 12 m telescope of the U.S. National Radio Astronomy Observatory[1] equipped with a dual polarization cooled mixer receiver at 230.538 GHz and a dual polarization SIS receiver at 115.2712 GHz. The 230 GHz observations were carried out in April 1986 and April 1987; the 115 GHz observations in November 1986. In April 1986 the double sideband receiver temperatures of the two receivers were measured by the NRAO staff to be 250 and 290 K. We expect that the April 1987 temperatures were similar. At 115 GHz the NRAO staff measured the single sideband receiver temperatures to be 150 and 200 K. In April 1986 we measured the full half-power beamwidth to be 27″ in elevation at 230 GHz. At 115 GHz the NRAO staff has measured the beamwidth with the SIS receiver to be ~55″. The telescope pointing was sufficiently erratic that occasional errors may have been introduced into the 230 GHz measurements by poor pointing. The spectral line "back end" consisted of 256 channel filter banks; the width of an individual channel was either 500 kHz or 1 or 2 MHz. At 230 GHz, 1 MHz corresponds to $1.3\,\mathrm{km\,s^{-1}}$.

The April 1986 and November 1986 data were obtained by switching the telescope between a star and a reference position (typically 10′ away) at a rate of 1/60 Hz and subtracting the off-source spectra from the on-source spectra. In April 1987 a superior observing mode was employed. Using the subreflector, we chopped by 2′ at 1.25 Hz and also moved the telescope every 90 s so that the target star appeared first in one beam and then in the other. This observing technique, which is standard practice in infrared astronomy, produced very flat baselines even under

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[1] The National Radio Astronomy Observatory is operated by Associated Universities Inc. under contract with the National Science Foundation.

Table 1. CO emission toward evolved stars

Object	RAFGL	α 1950	δ 1950	Position Reference	Spectral Type	Transition	Epoch	T_B(K)	V_{LSR} (km/s)	V_∞ (km/s)	Remarks
IRC+60041	177	$1^h10^m30^s.3$	62°41′43″	3	C	2 → 1	1986	0.10	-25.1	$\gtrsim$23.3	
IRAS 0215+2822		2 15 12.5	28 22 59	2	C	1 → 0		0.058	- 2.2	8.9	J = 2 → 1 previously detected (Paper I)
Mira	318	2 16 49.1	- 3 12 23	9	M(M)	2 → 1	1987	5.6	46.5	4.3	Previously detected
V Cam	849	5 55 57.9	74 30 24	3	M(M)	2 → 1	1986	0.13	10.1	12.2	
V636 Mon	933	6 22 38.3	- 9 05 32	8	C	2 → 1	1986	0.52	12.7	25.8	
GX Mon	1028	6 50 03.5	8 29 02	5	M(M)	2 → 1	1987	1.3	- 8.6	19.3	Previously detected
CL Mon	1038	6 52 55.6	6 26 38	5	C(M)	1 → 0		0.077	27.5	23.9	
						2 → 1	86+87	0.16	27.4	27.0	
IRC-20131	1131	7 27 00.7	-19 21 34	3	C(M?)	2 → 1	1987	0.2	21.2	25.5	
X Cnc	1298	8 52 34.0	17 25 22	1	C(SR)	1 → 0		0.1	-14.7	8.8	See note (a)
IRC+10216	1381	9 45 14.8	13 30 41	4	C(M)	2 → 1	1986	20.1	-25.8	15.3	Previously detected
						1 → 0		8.3	-26.1	15.6	
						2 → 1	1987	20.9	-25.7	15.1	
CIT 6	1403	10 13 11.0	30 49 17	4	C(SR)	2 → 1	1986	4.0	- 1.4	17.4	Previously detected
						1 → 0		1.6	- 1.9	17.5	
						2 → 1	1987	4.0	- 1.1	17.3	
V Hya	1439	10 49 11.3	-20 59 05	1	C(SR)	1 → 0		0.60	-17.1	26.4	See Figure 1
						2 → 1	1987	1.4	-17.3	24.0	See note (b)
BK Vir	1554	12 27 48.1	4 41 34	1	M(SR)	2 → 1	1987	0.5	15.8	4.7	
Y UMa	1570	12 38 04.4	56 07 15	1	M(SR)	2 → 1	1987	0.5	18.8	4.7	
	1822	16 02 59.6	-30 41 25	7	M	2 → 1	1986	0.24	~ 0	~19	Fit poor
V463 Sco		17 07 59.3	-32 43 29	2	C	2 → 1	1986	0.21	20.7	25.6	
NGC 6302		17 10 21.3	-37 02 43	10	O-rich	2 → 1	1987	1.1	-39.9	22.5	See Figure 2
HD 161796	5384	17 43 40.7	50 03 47	2	F3 Ib	2 → 1	1986	0.37	-37.5	7.7	See note (c)
FX Ser	2067	18 04 04.8	- 9 41 42	3	C	2 → 1	1986	0.33	29.7	27.0	
V Aql	2314	19 01 43.9	- 5 45 38	1	C(SR)	2 → 1	1986	0.23	52.1	10.3	
	2343	19 11 25.0	0 02 18	2	K or M^d	2 → 1	1986	0.38	94.3	33.7	J = 1 → 0 previously detected (Paper III)
	2477	19 54 49.2	30 35 54	7	M?	2 → 1	1987	0.55	11.2	22.4	
V Cyg	2632	20 39 41.3	47 57 45	1	C(M)	2 → 1	1986	1.8	14.3	11.7	Previously detected
						2 → 1	1987	2.6	14.1	11.9	
	2646	20 44 02.2	- 1 05 11	11	M	2 → 1	1987	0.33	9.9	15.4	
IRAS 2100+4801		21 00 21.8	48 01 03	2	C	1 → 0		$\lesssim$0.05			
						2 → 1	1987	0.17	- 4.6	14.8	
V1549 Cyg	2704	21 03 32.6	51 36 18	3	C	2 → 1	1986	~0.4	7.1	11.4	T_B poorly determined
T Cep	2721	21 08 52.9	68 17 12	1	M(M)	2 → 1	1986	0.43	- 2.9	5.0	
UU Peg	2775	21 28 38.3	10 55 58	3	M(M)	1 → 0		0.083	29.9	13.5	
RU Cyg	2790	21 38 58.5	54 05 49	1	M(SR)	2 → 1	1987	0.25	7.2	14.2	
	2985	22 51 52.2	66 00 52	6	C	2 → 1	1986	0.10	-22.2	19.2	
IRC+40540	3116	23 32 01.3	43 16 27	8	C	2 → 1	1986	2.0	-18.4	14.8	Previously detected See note (e)
IRC+60427	3165	23 49 36.0	61 31 31	3	M	2 → 1	1986	0.17	-10.0	14.3	

References for positions in Table 1: 1) SAO catalog, 2) IRAS point source catalog, 3) Kleinmann and Joyce positions given in IRAS catalog, 4) Kleinmann and Payne-Gaposchkin (1979), 5) RAFGL catalog and Kleinmann and Joyce (see reference 3), 6) RAFGL and IRAS point source catalogs, 7) Joyce et al. (1977), 8) Claussen et al. (1987), 9) SAO catalog corrected for proper motion, 10) Rodriguez et al. (1985), 11) RAFGL catalog

Notes to Table 1:
(a) $J=1\rightarrow0$ and $2\rightarrow1$ transitions detected independently by Olofsson et al. (1987) and Wannier, Sahai, Andersson, and Johnson (1987, private communication)
(b) V_∞ includes high-velocity wings. V_∞ for dominant component of emission is ~14 km s^{-1}, in agreement with Table 1 in Paper III. The tabulated T_B applies to the dominant emission component, not to the narrow spikes
(c) $J=1\rightarrow0$ transition detected independently by Likkel et al. (1987)
(d) Spectral classification from Sanduleak (see Likkel et al., 1987)
(e) Telescope was mispointed by ~14″ when indicated spectrum was obtained

partly cloudy conditions. Total integration times, including time spent at the reference position, varied between 24 and 270 min for all stars listed in Table 1 that have not previously been detected in CO emission.

As described in Paper I, our target list consisted of sources in the IRAS point-source catalog that had fluxes greater than 100 Jy at 12 μm or greater than 50 Jy at 25 μm. Data for all the newly detected stars are summarized in Table 1. The listed 1950 epoch positions are usually of high quality, except for a few IRAS positions. Column 6 gives the spectral type of the central star. Here C and M indicate stars that we believe to be carbon-rich (C/O > 1) or oxygen rich (C/O < 1), respectively. The letters SR and M contained in parentheses indicate semi-regular and Mira-type variable stars, respectively.

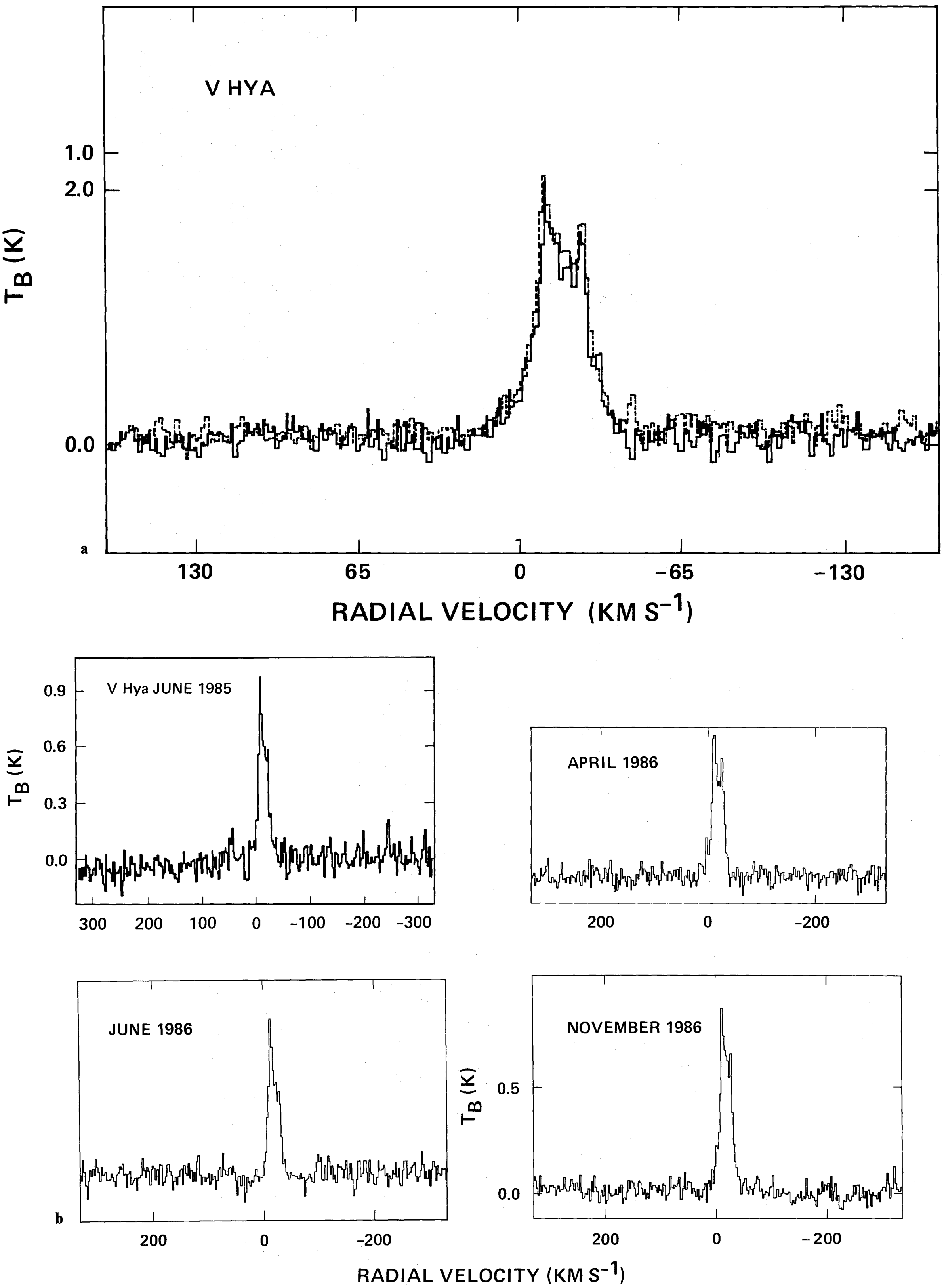

Fig. 1 a and b. CO emission spectra toward V Hya. The ordinate is brightness temperature as defined in the text. In **a** the label 1.0 K applies to the $J = 1 \rightarrow 0$ transition (dashed line) and the label 2.0 K to the $J = 2 \rightarrow 1$ transition (solid line). The abscissa is radial velocity with respect to the local standard of rest. **a** displays spectra of the $2 \rightarrow 1$ and $1 \rightarrow 0$ transitions overlayed on each other. These spectra were obtained with 1.3 km s^{-1} resolution in April 1987 and November 1986, respectively, and, to within the noise, appear to be virtually identical. **b** displays $1 \rightarrow 0$ data obtained with 2.6 km s^{-1} resolution at four different epochs. All data were obtained with the 12-m telescope except the April 1986 spectrum, which was obtained with the 30-m IRAM telescope (Rieu, Zuckerman, and Truong-Bach, 1986, unpublished). Data from June 1986 were very kindly given to us by Mr. W. Latter. The position switching was in azimuth by the following amounts: June 1985, $+5'$; April 1986, $+3'$; June 1986, $+15'$; November 1986, $-10'$; April 1987, $\pm 2'$. Typically, the observations were obtained fairly symmetrically before and after the transit of V Hya

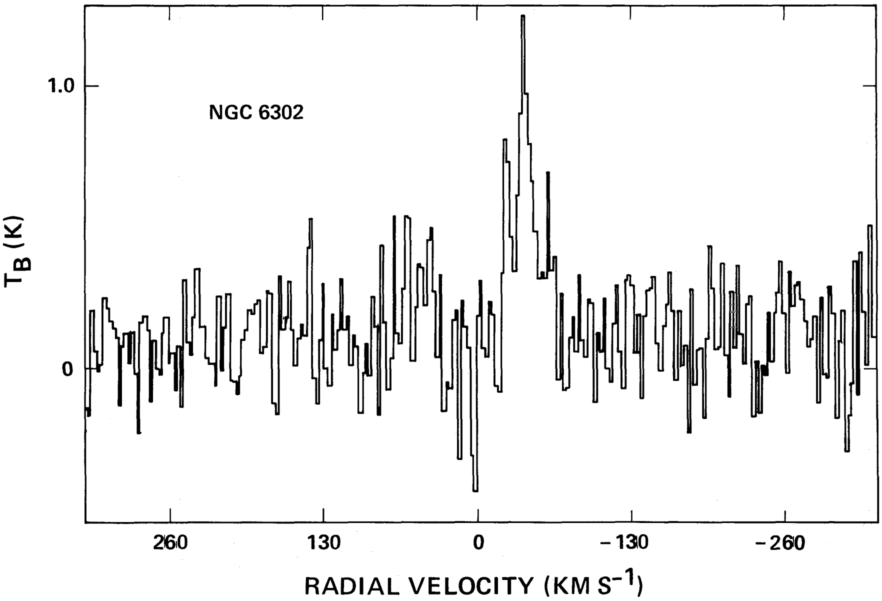

Fig. 2. CO $J=2\rightarrow 1$ emission spectrum toward NGC 6302. Ordinate and abscissa are the same as in Fig. 1

The column headed "Epoch" indicates whether the tabulated $J=2\rightarrow 1$ data were obtained in April 1986 or April 1987. The column headed T_B gives the peak brightness temperature averaged over the main-beam of the telescope and corrected for all telescope and atmospheric losses; that is, T_B is the Rayleigh-Jeans equivalent brightness temperature that would be measured by a perfect antenna above the Earth's atmosphere. To obtain T_B, we divided the CO temperatures that were actually measured by a factor of 0.48 at 230 GHz and a factor of 0.82 at 115 GHz which is appropriate for sources such as circumstellar envelopes that are comparable to or somewhat smaller than the main beam (P.R. Jewell, 1988, personal communication). We estimate that typical errors in T_B are approximately 20% for the stronger sources (dominated by systematic errors) and perhaps twice as large for weaker sources with poor signal-to-noise ratios. For the stars in common in Table 1 of the present paper and Papers I and III, the agreement in T_B is generally good.

The columns headed V_{LSR} and V_∞ give the central velocity of the CO profile with respect to the local standard of rest and the terminal outflow velocity, respectively. V_∞ is basically one-half the width of the profile at zero power. Both V_{LSR} and V_∞ were determined, in almost all cases, by fitting profiles of the form given in Eq. (7) in Morris (1985). Most of the line shapes resemble parabolas or rectangles. We estimate that errors in V_{LSR} are typically 1 km s^{-1} and, in V_∞, 2 km s^{-1} (but occasionally, perhaps, a good deal larger).

In a few cases we obtained spectra near but not on the target star to insure that the observed line really was associated with the star and was not interstellar. In the case of AFGL 2704, the circumstellar profile was seriously contaminated by interstellar CO emission and, as indicated in Table 1, T_B was very poorly determined.

3. Discussion

In this section we first discuss two of the interesting stars listed in Table 1 and then we consider outflow velocities, V_∞, from carbon stars.

3.1. Individual evolved stars

V Hya: In Paper III we reported the presence of an unusual narrow emission feature in the $J=1\rightarrow 0$ spectrum of this N-type carbon star. Because of its narrowness and its apparent absence in a similar spectrum obtained nine years earlier, we suggested that the feature was probably due to CO maser emission. In Fig. 1 we present new data on both the $J=1\rightarrow 0$ and $J=2\rightarrow 1$ spectra of V Hya obtained at various times between June 1985 and April 1987. Most striking are the high-quality spectra obtained with 1.3 km s^{-1} resolution that are displayed in Fig. 1a. To within the noise, the $J=1\rightarrow 0$ and $2\rightarrow 1$ spectra are virtually identical. They both show two narrow emission features that sit atop the much broader, more typical looking, primary CO emission feature from the star. However, even this broad feature is very unusual for a late-type carbon star in that it possesses weak, but unmistakable, high-velocity wings. To the best of our knowledge, the only evolved stars to show similar high-velocity wings are all of much earlier spectral type than is V Hya (NGC 7027, e.g., Masson et al., 1985; AFGL 2688, e.g., Heiligman et al., 1986; Kawabe et al., 1987; Sopka et al., 1988; AFGL 618, e.g., Sopka et al., 1988).

The virtually identical $J=1\rightarrow 0$ and $2\rightarrow 1$ profiles displayed in Fig. 1a indicate that the entire profile is due to optically thin, approximately thermal, emission at both transitions. The maser emission that we suspected in Paper III is surely not the correct explanation of the narrow emission features. Two recent studies (Tsuji et al., 1988; Kahane et al., 1988) of the spatial distribution of the CO emission show that it is quite extended, relative to most evolved stars, and shows very interesting kinematic structure. Unusual dynamics, discussed in the papers by Tsuji et al. and by Kahane et al., are evidently responsible for the narrowness of the two features.

But what of the apparent "time variation" that we claimed between 1976 and 1985 in Fig. 5 of Paper III? Tsuji et al. also believe that their CO data probably display time variations on a scale of $\lesssim 1$ year between April 1985 and March 1987. However, the various spectra shown in Fig. 1 of the present paper show no evidence for any time variation between June 1985 and April 1987. Therefore, we attribute the apparent time variation in the earlier

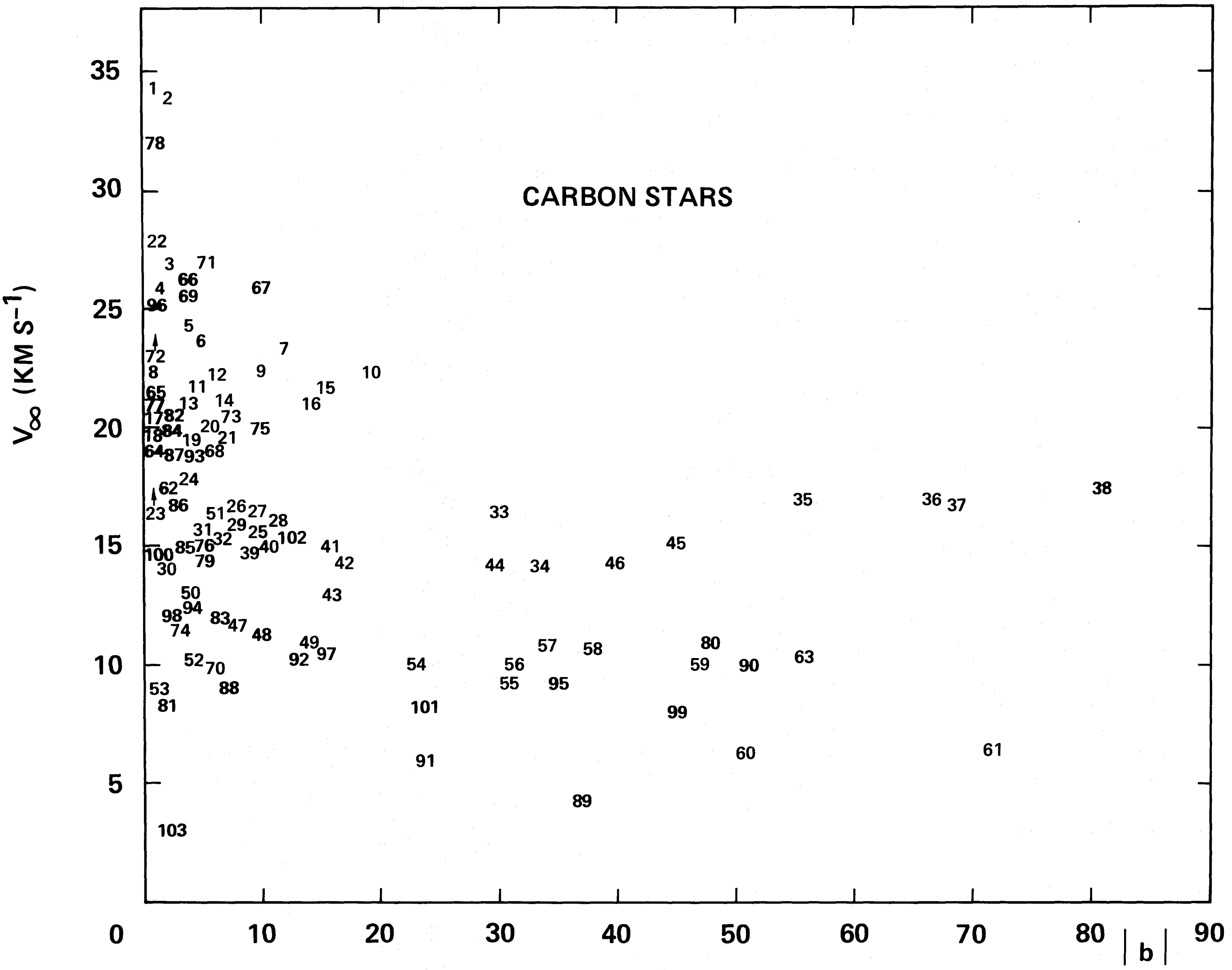

Fig. 3. Plot of circumstellar outflow velocity (V_∞) versus the absolute value of the galactic latitude $|b|$ of the carbon star in question. DG Cep (Star 103) has a very small V_∞ and is fairly close to the galactic plane. It would, therefore, be prudent to regard the association of the CO with the star as tentative until a map of the emission is obtained. The DG Cep data are from Wannier, Sahai, Andersson and Johnson (1987, private communication) who did not map

Key to Fig. 3:

1) AFGL 2233
2) AFGL 2901
3) AFGL 2154
4) AFGL 809
5) AFGL 2417
6) AFGL 1085
7) AFGL 2686
8) IRAS 2148+5301
9) AFGL 2368
10) S Cep
11) AFGL 2259
12) U Cam
13) AFGL 3011
14) AFGL 618
15) PQ Cep
16) AFGL 954
17) AFGL 1235
18) IRAS 0453+4427
19) AFGL 190
20) AFGL 2494
21) AFGL 2688
22) IRC+10401
23) S Aur
24) NGC 7027
25) IRC+60144
26) IRC+50096
27) AFGL 1922
28) AFGL 482
29) AFGL 5250
30) AFGL 341
31) AFGL 2135
32) AFGL 865
33) RV Aqr
34) V Hya
35) CIT 6
36) RU Vir
37) R For
38) R Scl
39) IRC+40485
40) IRC+20370
41) AFGL 2155
42) IRC+40540
43) AFGL 5254
44) T Dra
45) IRC+10216
46) AFGL 3068
47) AFGL 5102
48) AFGL 935
49) UU Aur
50) V Cyg
51) AFGL 67
52) Y Tau
53) AFGL 971
54) W Ori
55) IRAS 0215+2822
56) R Lep
57) IRC−10236
58) U Hya
59) AFGL 3099
60) V CrB
61) Y CVn
62) IRAS 0807−3615
63) TX Psc
64) AFGL 2333
65) AFGL 2513
66) CL Mon
67) V636 Mon
68) AFGL 2985
69) V463 Sco
70) V Aql
71) FX Ser
72) AFGL 177
73) IRAS 2326+6854
74) AFGL 2704
75) IRAS 0510+2055
76) IRAS 0513+4712
77) IRAS 0608+1909
78) IRAS 0721−1246
79) IRAS 0758−1933
80) IRAS 1130−1020
81) IRAS 1721−3916
82) IRAS 2043+3825
83) IRAS 2053+5554
84) IRAS 2122+5114
85) IRAS 2137+4540
86) IRAS 2144+4950
87) IRAS 2230+5950
88) IRAS 2327+5336
89) Z Psc
90) RY Dra
91) UX Dra
92) V460 Cyg
93) IRAS 1758−1744
94) IRAS 1934+1209
95) X Cnc
96) IRC−20131
97) ST Cam
98) TU Gem
99) VY UMa
100) RY Mon
101) Y Hya
102) RV Cyg
103) DG Cep

(June 1976) spectrum to a combination of two causes: a modest pointing error and mediocre signal-to-noise in 1976. The high spatial resolution observations of Tsuji et al. and Kahane et al. show that the narrow blue ($-25.7\,\mathrm{km\,s^{-1}}$) and red ($-10.7\,\mathrm{km\,s^{-1}}$) features originate from regions that are spatially separated in an east-west direction. If in 1976 the old NRAO 11-m telescope was pointed $\gtrsim 10''$ to the west of V Hya when the data displayed in Paper III were obtained, then the $-10.7\,\mathrm{km\,s^{-1}}$ spike would have been depressed substantially relative to the $-25.7\,\mathrm{km\,s^{-1}}$ spike and the June 1976 spectrum would be the expected product. Such a possibility seemed remote to us while writing Paper III, because CO emission from almost all evolved stars appears point-like or nearly so when observed with a $60''$ beam.

NGC 6302: In Paper III we reported the detection of CO $J=1\rightarrow 0$ emission toward this unusual nitrogen- and oxygen-rich planetary nebula. Because the CO emission occurred at a peculiar velocity with respect to NGC 6302 and because, at that time, CO had been unambiguously detected from only two other bona fide planetaries, we were not certain that the observed $1\rightarrow 0$ line was, in fact, associated with NGC 6302. In Fig. 2 we present new data on the $J=2\rightarrow 1$ transition. We believe that this CO emission is almost certainly associated with NGC 6302 for the following reasons: 1) The smaller telescope beam at 230 GHz compared to the beam at 115 GHz will discriminate better against interstellar CO emission. In addition, the chopping mode that was employed in April 1987 (see Sect. 2), will also discriminate against galactic CO if its gradient is small; 2) The radial velocity of the $2\rightarrow 1$ line is in good agreement with the various OH and HI emission profiles seen in this direction and which are quite likely associated with NGC 6302 (Payne et al., 1988); and 3) The line width and shape are characteristic of circumstellar, not interstellar, gas.

3.2. *Circumstellar outflow velocities from carbon stars*

Figure 3 is a plot of V_∞ versus the absolute value of the galactic latitude $|b|$ of the star in question. This plot is an improvement on Fig. 4 in Paper II because Fig. 3 displays only carbon stars, including improved values of V_∞ for some as well as others that were recently detected and were not plotted at all in Paper II. In that paper we pointed out that carbon stars with large V_∞ are located preferentially at small $|b|$. This is strikingly clear from Fig. 3. The break between large and small V_∞ seems to occur at $V_\infty \sim 18\,\mathrm{km\,s^{-1}}$. For 63 stars with $V_\infty \leqq 18\,\mathrm{km\,s^{-1}}$ we calculate that the mean of $|b|$ is equal to 21.8 ± 20.9 and for 39 stars with $V_\infty \geqq 19\,\mathrm{km\,s^{-1}}$, the mean $|b|$ is 4.9 ± 4.6, where the dispersions represent one standard deviation of the mean. (Star 23 is not included in the statistics.)

If radiation pressure on dust grains drives the mass outflow from these stars, then V_∞ would be proportional to the grain condensation temperature, T_C, to the stellar luminosity, L_*, to the one-fourth power and to the square root of the opacity per gram k_ν (Jura, 1984). Since we are discussing only carbon stars, we assume that the grains are basically alike and that, therefore, T_C is the same for all stars in Fig. 3. We suspect that all the stars are on the asymptotic giant branch (AGB). In that case, differences in L_* could account for only a factor of approximately 2 in V_∞. Since the measured spread in V_∞ is a factor of approximately 7, the implication is that k_ν also plays a role in determining V_∞. Two stars, 60 and 103 (V CrB and DG Cep), with small V_∞, have large space velocities and are likely to be Population II stars. Perhaps the other stars with small V_∞ are also Population II. These stars may have low metallicities and, therefore, relatively small dust-to-gas ratios (and hence k_ν) in their circumstellar envelopes. At the other extreme, some of the relatively massive stars with large V_∞ (and small $|b|$) may efficiently mix large amounts of carbon to their surfaces. If the dust grains are composed primarily of a form of pure carbon (e.g., Zuckerman, 1980; Sopka et al., 1985), then the dust-to-gas ratios (and k_ν) could be quite large. More quantitatively, explanation of the data plotted in Fig. 3 would require a dust-to-gas ratio in Stars 1 and 2 that is approximately ten times larger than in Stars 60, 61, 91, 89, and 103.

We suspect that AGB carbon stars with $V_\infty \gtrsim 19\,\mathrm{km\,s^{-1}}$ had initial main-sequence masses $M_\mathrm{ms} \gtrsim 3\,M_\odot$, those with $9 \lesssim V_\infty \lesssim 18\,\mathrm{km\,s^{-1}}$ had $1 \lesssim M_\mathrm{ms} \lesssim 3\,M_\odot$, and those with $V_\infty \lesssim 9\,\mathrm{km\,s^{-1}}$ had $M_\mathrm{ms} \sim 1\,M_\odot$. Knapp (1983) arrived at a similar conclusion for a different sample of AGB stars, as did Baud and Habing (1983, Sect. 5) for OH/IR stars. In particular, as we emphasized in Paper II, IRC+10216 (Star 45) is, almost certainly, a star that had only a modest main-sequence mass and, therefore, is located considerably closer to the Earth than 290 pc.

Whatever the exact range of carbon star initial main-sequence masses implied by Fig. 3, it is clear that this range must be fairly large. In particular, it must be larger than the range 1.2 to 1.6 $M_\odot$ that is preferred by Claussen et al. (1987) and the 3 to 5 $M_\odot$ range preferred by Thronson et al. (1987). Arguments given by Zuckerman (1987) imply that (1) the Claussen et al. range encompasses the bulk of carbon stars and (2) the Thronson et al. sample of carbon stars cannot be as massive as they claim, even though the masses of some carbon stars do, no doubt, lie in this range.

4. Conclusion

We have detected CO rotational emission from 22 infrared bright giant stars bringing the total number detected in this survey program (Papers I–III) to just over 100. A roughly equal number of stars has been detected *in toto* in CO emission in other survey programs. We have gathered together the carbon-rich subset of the total sample (Fig. 3) which clearly corroborates the association of large outflow velocity and small galactic latitude that we pointed out in Paper II. The dependence of V_∞ on galactic latitude implies that carbon stars must originate from stars that had a fairly wide range of masses when they were on the main sequence.

High-quality CO $J=1\rightarrow 0$ and $2\rightarrow 1$ spectra of the carbon star V Hya show a variety of unusual kinematic features (Fig. 1). Models of this emission, based on data with better spatial resolution than those reported here, are presented in Kahane et al. (1988) and Tsuji et al. (1988).

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References

Baud, B., Habing, H.J.: 1983, *Astron. Astrophys.* **127**, 73
Claussen, M.J., Kleinmann, S.G., Joyce, R.R., Jura, M.: 1987, *Astrophys. J. Suppl.* **65**, 385

Heiligman, G.M. et al.: 1986, *Astrophys. J.* **308**, 306

Joyce, R.R., Capps, R.W., Gillett, F.C., Grasdalen, G., Kleinmann, S.G., Sargent, D.G.: 1977, *Astrophys. J.* (*Letters*) **213**, L125

Jura, M.: 1984, *Astrophys. J.* **282**, 200

Kahane, C., Maizels, C., Jura, M.: 1988, *Astrophys. J.* **328**, L25

Kawabe, R. et al.: 1987, *Astrophys. J.* **314**, 322

Kleinmann, S.G., Payne-Gaposchkin, C.: 1979, *Earth and Extraterrestrial Sciences* **3**, 161

Knapp, G.R.: 1983, in *The Nearby Stars and the Stellar Luminosity Function*, *IAU Coll.* **76**, eds. A.G. Davis Philip, A.R. Upgren, Davis, Schenectady, p. 113

Likkel, L., Omont, A., Morris, M., Forveille, T.: 1987, *Astron. Astrophys.* **173**, L11

Masson, C.R. et al.: 1985, *Astrophys. J.* **292**, 464

Morris, M.: 1985, in *Mass Loss From Red Giants*, eds. M.Morris, B.Zuckerman, Reidel, Dordrecht, p.129

Olofsson, H., Eriksson, K., Gustafsson, B.: 1987, *Astron. Astrophys.* **183**, L13

Payne, H.E., Phillips, J.A., Terzian, Y.: 1988, *Astrophys. J.* **326**, 368

Price, S.D., Murdock, T.L.: 1983, *The Revised AFGL Infrared Sky Survey Catalog*, AFGL-TR-83-0161

Rodriguez, L.F., et al.: 1985, *Monthly Notices Roy. Astron. Soc.* **215**, 353

Sopka, R.J., Olofsson, H., Johansson, L.E.B., N.-Q.-Rieu, Zuckerman, B.: 1988, *Astron. Astrophys.* (in press)

Sopka, R.J., Hildebrand, R., Jaffe, D.T., Gatley, I., Roellig, T., Werner, M., Jura, M., Zuckerman, B.: 1985, *Astrophys. J.* **294**, 242

Thronson, H.A., Latter, W.B., Black, J.H., Bally, J., Hacking, P.: 1987, *Astrophys. J.* **322**, 770

Tsuji, T., Unno, W., Kaifu, N., Izumiura, H., Ukita, N., Cho, S., Koyama, K.: 1988, *Astrophys. J.* **327**, L23

Zuckerman, B.: 1980 *Ann. Rev. Astron. Astrophys.* **18**, 263

Zuckerman, B.: 1987, in *Fifth Cambridge Workshop on Cool Stars, Stellar Atmospheres, and the Sun*, eds. R. Stencel, J. Linsky, Springer, Berlin, Heidelberg, New York

Zuckerman, B., Dyck, H.M.: 1986a, *Astrophys. J.* **304**, 394 (Paper I)

Zuckerman, B., Dyck, H.M.: 1986b, *Astrophys. J.* **311**, 345 (Paper III)

Zuckerman, B., Dyck, H.M., Claussen, M.J.: 1986, *Astrophys. J.* **304**, 401 (Paper II)