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CARBON MONOXIDE EMISSION FROM STARS IN THE *IRAS* AND *REVISED AFGL* CATALOGS. I. MASS LOSS DRIVEN BY RADIATION PRESSURE ON DUST GRAINS

B. ZUCKERMAN
University of California, Los Angeles

AND

H. M. DYCK
University of Hawaii
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ABSTRACT

We surveyed infrared bright stars in the *IRAS* and *Revised AFGL* catalogs in the $J = 2 \rightarrow 1$ rotational transition of carbon monoxide. Broad lines were detected in 39 objects not previously see in CO emission, including the unusual supergiant VY CMa, the bright giant star W Hya, and some stars first discovered in the *IRAS* survey about which very little is known. A plot of momentum in the outflowing wind, $\dot{M}V_\infty$, deduced from a simple model for the CO emission versus momentum in the stellar radiation field, L_*/c, reveals eleven objects for which $\dot{M}V_\infty$ appears to be larger than L_*/c. These objects, nine of which are carbon-rich, are distinguished by either an early-type central star or a large outflow velocity V_∞, or both.

Subject headings: infrared: sources — stars: circumstellar shells — stars: mass loss

I. INTRODUCTION

Mass loss from red giant stars is a current topic of study among astronomers (e.g., Morris and Zuckerman 1985). Most of the mass that is returned by stars to the interstellar medium is probably shed during the asymptotic giant branch (AGB) phase of stellar evolution. This mass loss can profoundly alter the fate of intermediate mass stars (1.4–8 $M_\odot$) and enriches the interstellar medium in elements such as helium, nitrogen, and carbon. (See Iben and Renzini 1983 for a general discussion of AGB evolution.)

Most of the mass is believed to be lost in the form of molecules and dust grains in, very roughly, the interstellar ratio (e.g., Sopka *et al.* 1985). Although the dust is, typically, $\gtrsim 100$ times less abundant by mass than the gas, it plays an essential role in absorbing momentum and energy from the stellar radiation field. The momentum is then transferred, via collisions, to the gas molecules. For stars with copious mass loss, much of the underlying stellar energy is radiated in the mid- and far-infrared by cool dust grains in the outflow. This has become really obvious only with the publication and analysis of the contents of the Air Force Geophysics Laboratory (AFGL) Survey and the *Revised AFGL* (RAFGL) *Infrared Sky Survey Catalog* (Price and Walker 1976; Price and Murdock 1983, and references therein). Unfortunately, even in the RAFGL catalog there still remains a significant fraction of sources, especially the 5000 series, that either are not real or for which the tabulated 11, 20, or 27 μm fluxes are much too large, or for which the source position is poorly known.

At the same time as these rocket IR data were being checked and analyzed from the ground, radio astronomers were nibbling away at the brighter and redder sources in the IR catalogs, beginning seriously in 1976 (Lo and Bechis 1976; Zuckerman *et al.* 1977) and culminating in 1983 (Knapp and Morris 1985, hereafter KM, and references therein). These observers concentrated on rotational transitions of carbon monoxide, which is, almost certainly, the best available measure of mass loss rates from AGB stars and red supergiants (e.g., Kwan and Linke 1982; Jura 1983; KM). CO surveys were hampered, however, by limited sensitivity as well as an infrared basis set that was, as mentioned above, not totally reliable in regard to flux and position.

In 1984 both the radio and infrared situations improved dramatically. The *IRAS* point source catalog was published with reliable fluxes and fairly good positions. Many of the brighter *IRAS* and RAFGL sources had appeared in the earlier *Two Micron Sky Survey* catalog (Neugebauer and Leighton 1969) and, for these, S. Kleinmann and R. Joyce (private communication) had measured accurate positions, which appeared as part of the *IRAS* catalog. In the millimeter domain, receiver temperatures at both the $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ transitions of CO (115 and 230 GHz respectively) have continued to decline and antenna performance has been enhanced at both the NRAO 12 m Kitt Peak and University of Massachusetts 14 m Quabbin observatories.

Hence, the time is ripe for a systematic CO survey of the brightest ~300 red stars in the *IRAS* point source catalog. One obvious goal of such a survey is a derivation of the total amount of mass ejected into the interstellar medium in the solar vicinity by AGB stars of various spectral types. The dust loss rate in the same set of stars may be derived from *IRAS* data using techniques similar to those described by Sopka *et al.* (1985). Thus, one can derive the dust-to-gas ratio in the outflowing envelopes around a very large sample of red giant stars. Our long-range goal is to do just that, but such a project will take considerable time. We believe that the CO data presented in the present paper and in the one that follows (Zuckerman, Dyck, and Claussen 1986, hereafter Paper II) are of sufficient interest to warrant more rapid publication. So here and in Paper II we describe CO observations of a large sample of *IRAS* and RAFGL sources. Various general remarks may already be made concerning mass loss rates and other quantities of interest. We defer detailed analysis of mass loss rates, publication of most individual spectra, and discussion of most individual stars until a later date.

II. EQUIPMENT AND OBSERVATIONS

We used the 12 m telescope of the National Radio Astronomy Observatory[1] equipped with a dual polarization cooled mixer receiver. At the frequency (230.538 GHz) of the $J = 2 \rightarrow 1$ transition of CO, the double sideband temperatures of the two receivers were measured by the NRAO staff to be 280 and 380 K. We measured the full half-power beamwidth to be 29''.2 in elevation. The telescope pointing and tracking were sufficiently precise that few, if any, errors were introduced in the measurements by poor pointing. The spectral line "back end" consisted of 256 channel filter banks; the width of an individual channel was either 1 or 2 MHz. At 230.5 GHz, 1 MHz corresponds to 1.3 km s^{-1}.

The data were obtained in 1984 mid-December 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. Total integration times, including time spent at the reference position, varied between 24 and 120 minutes for all stars listed in Tables 1 and 2 that have not previously been detected in CO emission.

Our target list consisted of infrared bright sources found in the *IRAS* or RAFGL catalog or both. Specifically, with only a few exceptions, we searched for CO emission from objects in

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

TABLE 1

SOURCES WITH ASSOCIATED CO $J = 2 \rightarrow 1$ EMISSION

Object	RAFGL	α_{1950}	δ_{1950}	Position Reference	Spectral Type	T_B(K)	V_{LSR}(km/s)	V_∞(km/s)	Remarks
T Cas	57	$0^h20^m31^s.2$	55°30'56"	1	M(M)	0.26	− 7.3	5.2	Detection requires confirmation.
	190	1 14 26.3	66 58 08	2	C	0.54	−39.5	19.7	
S Cas	194	1 15 57.7	72 20 56	1	S(M)	0.33	−32.3	15.3	
BD+44°398	278	1 55 37.3	45 11 32	1	M	0.96	− 1.9	7.6	
IRAS 0215+2822		2 15 12.5	28 22 59	3	C	0.14	− 1.6	9.5	
Mira	318	2 16 49.1	− 3 12 22	4	M(M)	6.0	46.4	4.6	Previously detected.
R For	337	2 27 01.2	−26 19 13	5	C(M)	0.44	− 2.8	16.8	
IRC−30023	357	2 35 10.8	−27 11 41	5	M	0.43	− 8.4	11.6	
	5102	3 44 49.2	44 32 51	3	C	0.24	−19.8	13.3	
V Eri	542	4 02 01.6	−15 51 39	1	M(SR)	0.16	−12.3	13.0	
R Lep	667	4 57 19.7	−14 52 47	1	C(M)	0.57	15.1	9.8	Jura & Zuckerman (see text).
W Ori	683	5 02 48.7	1 06 37	1	C(SR)	0.22	− 1.0	10.2	
IRC+60154	724	5 15 08.6	63 12 51	5	M	0.30	49.4	19.9	V_∞ uncertain.
	809	5 40 33.3	32 40 49	6	C	0.65	−31.2	26.0	
UU Aur	966	6 33 06.6	38 29 16	1	C(SR)	0.66	3.6	11.5	
	971	6 34 16.5	3 28 05	7	C	0.74	1.0	9.0	V_∞ and V_{LSR} uncertain (see text).
GX Mon	1028	6 50 03.5	8 29 02	10	M(M)	1.2	− 9.1	18.7	
	1085	7 09 53.7	−20 12 18	7	C	0.2	8.0	23.8	
VY CMa	1111	7 20 54.8	−25 40 12	8	M	0.48	18.7	35.9	Supergiant (see Fig. 2).
	1235	8 08 51.2	−32 43 06	11	C	0.72	−20.9	20.7	
	5250	8 17 06.9	−21 34 47	3	C ?	0.40	− 6.4	16.1	
	5254	9 11 40.9	−24 38 54	12	C	2.0	0.2	12.8	
IW Hya	5259	9 42 56.5	−21 47 55	5	M	0.61	40.7	14.0	
IRC+10216	1381	9 45 14.8	13 30 41	9	C(M)	20.7	−25.9	14.7	Previously detected.
CIT6	1403	10 13 11.0	30 49 17	9	C(SR)	3.5	− 1.6	17.4	Previously detected.
U Hya	1427	10 35 05.0	−13 07 26	1	C(SR)	0.88	−30.3	10.7	Jura & Zuckerman (see text).
R Crt	1450	10 58 06.0	−18 03 22	1	M(SR)	0.60	10.8	11.0	
IRC−30163E	4136	11 46 08.1	−35 42 32	1	M	0.38	− 2.5	8.0	
Y CVn	1576	12 42 47.1	45 42 48	1	C(SR)	0.37	23.7	6.3	Jura & Zuckerman (see text).
SW Vir	1606	13 11 29.7	− 2 32 33	1	M(SR)	0.89	−10.6	8.6	
R Hya	1627	13 26 58.5	−23 01 25	1	M(M)	0.54	− 9.9	7.2	
W Hya	1650	13 46 12.2	−28 07 06	1	M(SR)	0.55	40.6	8.8	
X Her	5317	16 01 08.8	47 22 36	1	M(SR)	0.75	−72.7	8.8	
30g Her	1864	16 26 59.8	41 59 27	1	M(SR)	0.22	21.8	7.5	
IRC−10502	2368	19 17 35.3	−8 07 53	13	C	0.45	21.3	22.5	
V1129 Cyg	2417	19 32 08.8	27 57 30	5	C(M)	0.77	−12.1	24.4	
χ Cyg	2465	19 48 38.5	32 47 12	1	S(M)	2.3	10.2	8.0	Previously detected.
RR Aql	2479	19 55 00.3	−2 01 17	10	M(M)	0.48	28.3	7.4	
	2494	19 59 24.8	40 47 18	7	C	1.0	29.7	20.0	
IRAS 2002+3910		20 02 48.0	39 10 03	3	M ?	0.16	4.2	10.5	Narrow CO emission, also.
V Cyg	2632	20 39 41.3	47 57 45	1	C(M)	1.9	14.6	11.8	Previously detected.
	2686	20 56 59.8	27 14 59	7	C	0.37	0.8	23.5	
S Cep	2785	21 35 52.6	78 23 59	1	C(M)	0.51	−15.3	22.4	
EP Aqr	2806	21 43 56.5	−2 26 41	1	M	1.2	−33.9	8.6	
IRAS 2148+5301		21 48 59.2	53 01 23	3	C	0.42	−28.2	22.3	
IRAS 2155+6204		21 55 29.6	62 04 24	3	M	0.24	−17.3	12.6	
TW Peg	2837	22 01 43.2	28 06 20	1	M(SR)	0.24	−12.9	9.5	

REFERENCES.—(1) SAO catalog. (2) Gehrz and Hackwell 1976. (3) *IRAS* point source catalog. (4) SAO catalog corrected for proper motion. (5) Kleinmann and Joyce positions given in *IRAS* catalog. (6) Lebofsky *et al.* 1978. (7) Joyce *et al.* 1977. (8) Bowers *et al.* 1983. (9) Kleinmann and Payne-Gaposchkin 1979. (10) RAFGL catalog and Kleinmann and Joyce (see ref. 5). (11) RAFGL and *IRAS* point source catalogs. (12) See § II in the text. (13) RAFGL catalog; Zuckerman *et al.* 1978; Kleinmann and Joyce (see ref. 5).

TABLE 2

SOURCES WITHOUT BROAD ASSOCIATED CO $J = 2 \rightarrow 1$ EMISSION

Object	RAFGL	α_{1950}	δ_{1950}	Reference	Spectral Type	T_B (K)	Remarks
Red Rectangle ...	915	$6^h17^m37^s.0$	−10°36′52″	1	B0–A9	<0.16	Bipolar reflection nebula
R CrB	4219	15 46 30.7	+28 18 32	2	C	<0.10	Peculiar carbon-rich spectrum
α Her	1947	17 12 21.9	+14 26 45	2	M	<0.26	Supergiant
CH Cyg	2383	19 23 14.2	+50 08 31	2	M(SR)	<0.10	Symbiotic star
BC Cyg...........	2560	20 19 46.7	+37 22 22	3	M(LC)	<0.16[a]	Supergiant
MWC 349........	2603	20 30 56.8	+40 29 20	4	M	<0.20[a]	Double radio source
R Aqr.............	3136	23 41 14.2	−15 33 43	2	M(M)	<0.16	Symbiotic star
PZ Cas	3138	23 41 38.8	+61 30 43	3	M(SR)	<0.20	Supergiant

[a] Narrow CO emission present.

REFERENCES.—(1) Lo and Bechis 1976. (2) SAO catalog. (3) Kleinmann and Joyce positions given in *IRAS* catalog. (4) Grasdalen *et al.* 1983; Dreher and Welch 1983.

the *IRAS* point source catalog that had fluxes greater than 100 Jy at 12 μm or greater than 50 Jy at 25 μm. We attempted to discriminate against objects that were clearly young stars embedded in molecular clouds by a variety of techniques that included examination of (1) relative fluxes in the four *IRAS* wavebands, (2) source associations in the *IRAS* and RAFGL catalogs, (3) *IRAS* low-resolution spectrometer (LRS) designations, and (4) Galactic latitudes. For stars of known spectral type, we found that the LRS designations were usually, although not invariably, correct. Therefore, searching for CO in objects for which we had only an LRS identification to go by was sometimes an adventure.

In this paper and in Paper II we describe observations of some sources found only in the *IRAS* catalog (or also in the 5000 series of the RAFGL catalog) for which only LRS identifications (or no identifications) are available. Comparison of *IRAS* catalog fluxes with 5000 series sources in the RAFGL suggests that many of the latter are not real, at least not at the flux levels that are tabulated in the RAFGL. On the other hand, we found relatively few *IRAS* sources at the flux levels indicated in the previous paragraph that are not included in the RAFGL. Table 1 includes four *IRAS* sources that are not associated with an RAFGL source. None of these is particularly bright at 12 or 25 μm.

The data are summarized in Tables 1 and 2. The 1950 epoch positions listed in the two tables are usually of high quality except for a few *IRAS* positions. The position given for AFGL 5254 is a tentative mix of the *IRAS* position, a position determined from a three-point CO map at the 12 m telescope, and a position measured at Mauna Kea Observatory in the mid-infrared. The sixth column in each table is the spectral type of the central star. Here C, M, and S indicate stars that are believed to be carbon-rich (C/O > 1), oxygen-rich (C/O < 1), or neither (C/O ∼ 1) respectively. The letters SR and M in parentheses indicate semiregular and Mira-type variable stars respectively. For six of the stars we have only an *IRAS* LRS classification of the C/O ratio. In each such case we examined the LRS spectrum. For five of the stars we agree with the *IRAS* designation of C/O. For AFGL 5250, however, based on both the LRS spectrum and the relative *IRAS* fluxes at 12, 25, and 60 μm (Zuckerman and Dyck 1986), we disagree with the LRS classification and classify this star as probably carbon-rich. *IRAS* 2002+3910 was not classified by the LRS. Based on its 12, 25, and 60 μm fluxes, it is probably oxygen-rich (Zuckerman and Dyck 1986).

The seventh column in each table is T_B, the peak brightness temperature in the line, averaged over the main beam and corrected for all telescope and atmospheric losses. That is, T_B is the Rayleigh-Jeans (R-J) equivalent brightness temperature that would be measured by a perfect antenna above Earth's atmosphere. For a source that fills the main beam of the telescope, T_B would equal the true R-J equivalent brightness temperature. For smaller sources, the true R-J brightness temperature would be larger by a factor equal to the solid angle subtended by the main beam divided by the solid angle subtended by the source. In KM, T_B is called T_A^*. We estimate that errors in T_B for the stronger sources are probably ∼20% (dominated by systematic errors) and perhaps twice as large for the weaker sources with poor signal-to-noise ratios.

In Table 1 the central velocity V_{lsr} of the CO profile with respect to the local standard of rest and the terminal outflow velocity V_∞ is given in the eighth and ninth columns respectively. The quantity V_∞ is basically one-half the width of the profile at zero power. Both V_{lsr} and V_∞ were determined by fitting profiles of the form given either in equation (2) in KM or equation (7) in Morris (1985) to the data. The actual fitting routine that was used was part of a program entitled COMB that was kindly supplied by Dr. P. Wannier. It was clear from visual inspection of the fits that they were usually quite good. Most of the line shapes resemble parabolas or rectangles, although some of the narrower ones can be fitted rather well by Gaussians. We estimate that the errors in V_{lsr} are typically 0.5 km s^{-1} and, in V_∞, 1 km s^{-1} (but occasionally, perhaps, a good deal larger for V_∞). For AFGL 971, the stellar line, which is quite strong, is blended with an even stronger interstellar CO line so that V_{lsr} and V_∞ are both a bit uncertain. We postpone discussion of line shapes until a later paper.

In only two cases, EP Aqr and AFGL 190, did we obtain spectra near but off the target star to insure that the putative stellar line is really of circumstellar origin and not interstellar. However, most of the objects listed in Table 1 are located fairly far from the Galactic plane, where interstellar CO emission is usually weak, and the large line widths and rather flat-topped shapes both suggest, quite strongly, that the observed lines are indeed due to circumstellar gas.

Three stars listed in Table 1, R Lep, U Hya, and Y CVn, were detected in 1984 June by Jura and Zuckerman (1984). U Hya had not previously been detected by radio astronomers. KM list tentative (uncertain) detections of the $J = 1 \rightarrow 0$ CO line in R Lep and Y CVn. For the latter star, our measurements of V_{lsr} and V_∞ are in substantial agreement with KM. For R Lep our value for V_∞ (9.8 km s^{-1}) is much smaller than the KM value (20.5 km s^{-1}). Because of our much better signal-to-noise ratio, 9.8 km s^{-1} is to be preferred.

III. DISCUSSION

We consider a few general relationships among the evolved objects that have been searched for CO emission in either the $J = 1 \rightarrow 0$ or $J = 2 \rightarrow 1$ transition. Our primary aim here is to investigate the relationship, if any, between the momentum in the outflowing wind, $\dot{M}V_\infty$, and the momentum in the stellar radiation field, L_*/c. These momenta will be equal when, for example, $\dot{M} = 10^{-5}$ $M_\odot$ yr^{-1}, $V_\infty = 20$ km s^{-1}, and $L_* = 10^4$ $L_\odot$. As Jura (1983) has emphasized, it is important to compare, as carefully as possible, these two momenta to evaluate the hypothesis that radiation pressure on dust grains propels the winds that emanate from red giant stars. Jura (1983) and Morris (1985) argue that CO data up to and including those obtained in the KM survey comply, with very few, if any, exceptions, to $\dot{M}V_\infty \lesssim L_*/c$, consistent with radiation pressure–driven outflow.

The sample of stars with detected CO available to the above two researchers was ~ 50. The current total is ~ 130, due primarily to newly detected stars listed in Tables 1 in the present paper, in Paper II, and in Zuckerman and Dyck (1986). In Figure 1 we plot ~ 80 stars with CO emission for which we also know F, the total stellar flux received at Earth. The quantity F is equal to L_*/D^2, where D is the distance between Earth and the star in question. We calculated F from single random-epoch IR fluxes given in the literature. Generally, the plotted values of F are accurate to about a factor of 2 for variable stars and better than a factor of 2 for nonvariable stars.

The ordinate, $T_B V_\infty^3$, is proportional to $\dot{M}V_\infty/D^2$ since, according to models discussed by KM, $\dot{M}$ is proportional to $T_B V_\infty^2 D^2$ for stars that are not too close to Earth. The proportionality constant is a function of the detailed model of a specific stellar envelope and a quantity f, which is the CO/H_2 abundance ratio in the envelope (see KM for details). KM assume that for O-rich, C-rich, and S-type stars, f is in the ratio 3:8:6.

The CO data for the 80 stars were obtained from a variety of sources, primarily from this paper, Paper II, and KM. Data for IRC +10420, OH 231.8+4.2, and NML Cyg were taken from Zuckerman *et al.* (1985); for AFGL 67 from B. Zuckerman and P. Palmer (1978, unpublished); and for OH 231.8+4.2 from Jewell (1985). For V Hya and R Scl we used data from Zuckerman *et al.* (1977), since they had better signal-to-noise ratios than those of KM. Because the data were obtained with a variety of telescopes and include both $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ observations, it was necessary to adjust the measured values of T_B to a given scale which we choose to be that which would be measured with the 14 m telescope (Paper II) at CO $J = 1 \rightarrow 0$. We estimate that this scaling procedure should be accurate to a factor of 2 or better except, conceivably, in a few pathological cases. Errors in V_∞^3 could also be as large as a factor of 2 for the weakest sources with the poorest signal-to-noise ratio. The various symbols used to plot the 80 stars are described on the figure itself.

Were all giant stars alike in the sense that, for example, $\dot{M}V_\infty = L_*/c$, then oxygen-rich stars would all lie along a

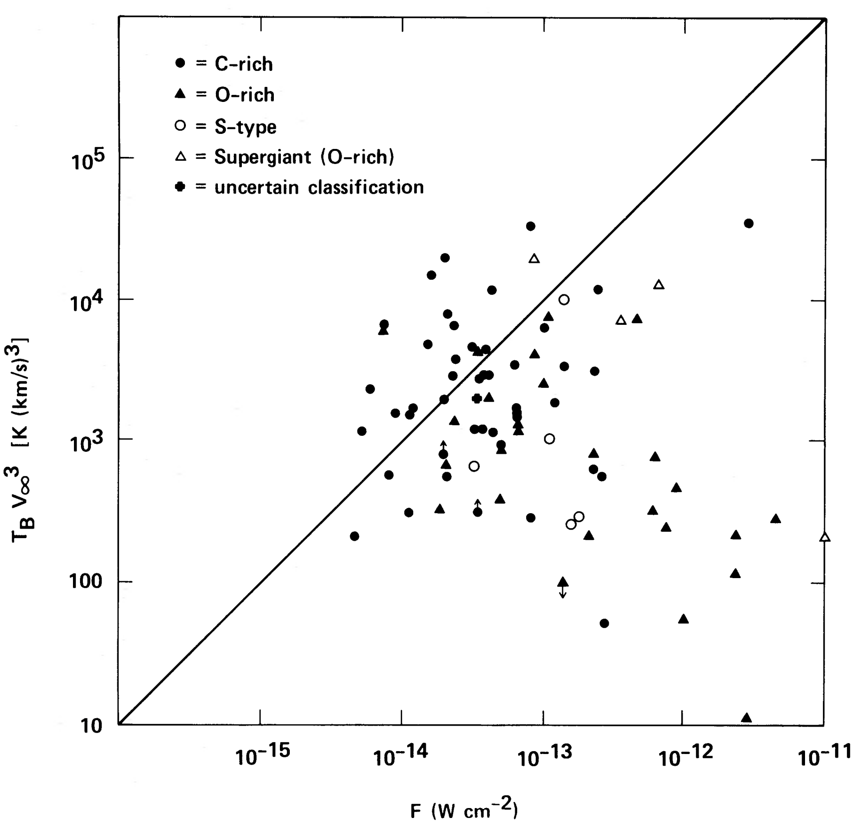

FIG. 1.—Plot of momentum in the stellar wind $T_B V_\infty^3$ vs. total infrared flux received at Earth from the star F. The diagonal line across the center of the figure represents the locus of points for which $\dot{M}V_\infty = L_*/c$ for carbon- and S-type stars. The one star that is plotted which has uncertain classification, in our opinion, is IRC +60144. This star is classified as oxygen-rich in the RAFGL (where it is mislabeled as DO 28489 instead of DO 28389), but the *IRAS* LRS spectrum apparently shows a clear SiC feature at 11 μm, indicating a carbon star.

diagonal line with slope equal to unity, and all carbon-rich stars would lie along a parallel line displaced upward by a factor of 8/3 in the case of the KM choices for *f*. Clearly, no such simple relationship holds among the stars that are plotted! To check that the figure is really telling us something about mass loss and is not simply a scatter diagram, we compared the relative locations of the actual plotted points for 11 stars with the relative locations that they would have had in the plot had we used mass loss rates, distances, and luminosities derived from the detailed models of KM, Kwan and Linke (1982), Jura (1983, 1984*a*), and Huggins (1985). We considered the following stars, all analyzed in one or more of these papers: α Ori; CIT 6; AFGL 2688, 865, and 3068; IRC +10216, +10011, and +40540; Mira; and NML Tau. Also, for VY CMa, we used data shown in Figure 2 and scaled the analysis of KM for other stars that are located at comparable distances from Earth (~1500 pc) to derive a mass loss rate of $\sim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$. This compares favorably with that derived by Bowers, Johnston, and Spencer (1983) and by Sopka *et al.* (1985) from OH and submillimeter data respectively.

When the relative values of *f* preferred by KM (see above) or by us (see below) are used, the relative placement of the 11 model points agrees well (about a factor of 2) with the relative placement of the actual points shown in Figure 1. (For IRC +10216, the point in the upper right-hand corner, it was necessary to consider the substantial resolution of the envelope by the 46″ 14 m beam. Accounting for all the flux in the CO map obtained by Morris, Stark, and Jura 1985 would raise the plotted point by perhaps a factor of 5. For α Ori, *f* may be considerably smaller than for the other oxygen-rich stars in the sample; Huggins 1985.) Since this set of 11 stars covers a wide range of intrinsic luminosities and *F* values and includes both C-rich and O-rich objects, we believe that the relative placement of the other stars in Figure 1 must be approximately correct in spite of the absence of detailed models of the CO emission from many of them.

To estimate the factor $f(=[CO]/[H_2])$, we use recent values for the abundances of C and O in the Sun and in planetary nebulae (Zuckerman and Aller 1986; Dinerstein, Lester, and Werner 1985). In oxygen-rich stars, *f* is determined by the C/H ratio, and in carbon stars by the O/H ratio. For the Sun we take $C/H = 4.57 \times 10^{-4}$ and $O/H = 8.12 \times 10^{-4}$, so that $[C/O]_{\odot} = 0.56$. For planetary nebulae (PNs) we use $O/H \lesssim [O/H]_{\odot}$. For oxygen-rich PNs we assume $C/O = 0.46 \pm 0.19$ (one standard deviation of the mean), which is determined from 16 PNs. Of these 16 O-rich PNs, at most one or two have measured C/O ratios a factor of 2 or more below the mean for the sample, which agrees well with the findings of McWilliam and Lambert (1984): for a sample of 193 MO to M5 giants, none has a carbon abundance more than a factor of 2 below the mean value for its spectral type. Hence, if all the oxygen were fully associated into CO in C-rich stars and all the carbon into CO in O-rich stars, the values of *f* would be, on the average, approximately a factor of 2 larger in the C-rich stars. Since the CO may not be fully associated, we suggest that appropriate values to use for *f* are 5×10^{-4} for oxygen-rich stars and 10^{-3} for carbon-rich and S-type stars. (For S stars we assume that the carbon abundance has been enhanced so that it equals the oxygen abundance.)

With these choices for *f*, if one is to use Figure 1 to read off relative values for $\dot{M}V_{\infty}$, then it is necessary to (mentally) raise all the ▲'s by a factor of 2 relative to the ●'s and the ○'s. For α Ori, Huggins (1985) has argued that not only is C/H smaller than solar by a factor of ~2 but, in addition, CO is under-associated by a factor of ~10, so that *f* approximates 5×10^{-5}. For the other three supergiants in Figure 1, VY CMa, NML Cyg, and IRC +10420, we do not know *f*. Therefore, it is possible that these three plotted △'s need to be

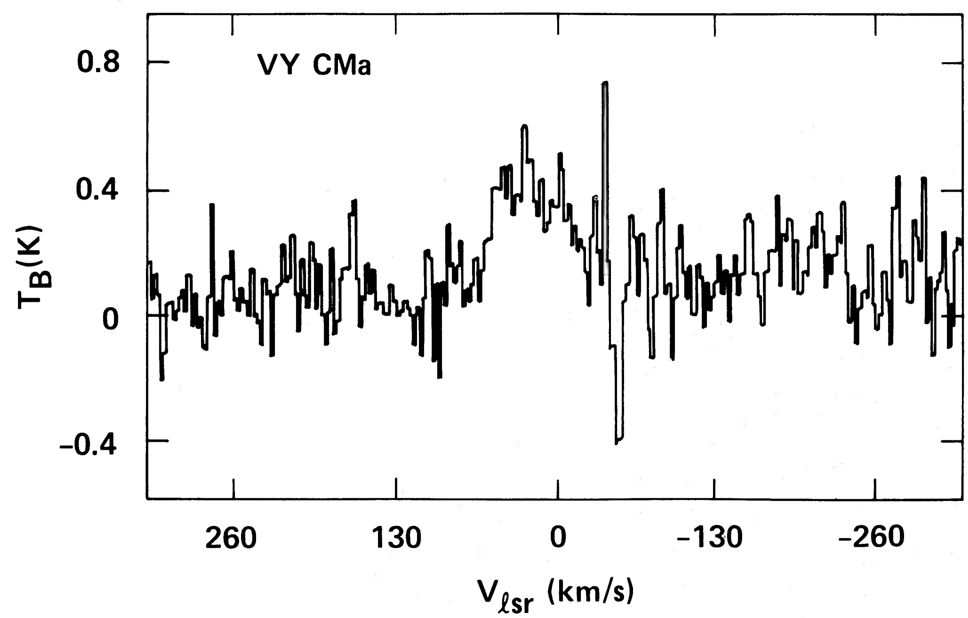

FIG. 2.—Spectrum of CO emission in VY CMa. The ordinate is brightness temperature as defined in the text. The abscissa is radial velocity with respect to the local standard of rest. These data were obtained with the 2 MHz filter bank. With the 1 MHz filter bank, we obtained an equivalent quantity of independent data (not shown here) in the orthogonal sense ot polarization. The line parameters given in Table 1 for VY CMa are an average of the two data sets. The narrow, upward spike seen near 40 km s^{-1} is probably a bad channel in the 2 MHz filter bank, since it is not present in the 1 MHz data. The adjacent downward spike is either bad channels or CO in the reference position.

raised, relative to the ●'s, by more than a factor of 2 when one compares mass loss rates.

Based on the model analyses of the 11 stars mentioned above, we estimate that, for an S-type or carbon star, the diagonal line drawn across Figure 1 represents $\dot{M}V_\infty = L_*/c$ to within a factor of 2. Oxygen-rich stars must be raised by appropriate factors, as discussed above, for comparison with the line.

With the above as background, we can draw the following conclusions from Figure 1:

1. The stars with the largest values of $\dot{M}V_\infty/(L_*/c)$ are, with very few exceptions, carbon-rich.

2. Many bright (close) M-type AGB stars (Mira-type and semiregular variables) are losing mass at a rate much lower than L_*/cV_∞.

3. Four of the stars with the largest apparent ratio of $\dot{M}V_\infty/(L_*/c)$ are early-type: NGC 7027 (O-type), AFGL 618 (O9.5–BO), IRC +10420 (F8 I), and AFGL 2688 (F5). For NGC 7027 and AFGL 618, it is possible that the large ratios are due to an order of magnitude decrease in the luminosity of the central star subsequent to the time that the CO envelopes were ejected, presumably by radiation pressure, from their carbon-rich red giant progenitors (Jura 1984*b*; Spergel, Giuliani, and Knapp 1983). For AFGL 2688 and IRC +10420, which are of later type, such an explanation, although conceivable, seems less plausible. If the luminosity of IRC +10420 has declined recently by a factor of ~ 5, then its previous luminosity would have been huge, $\sim 10^6\ L_\odot$, even at the closest distance (3.4 kpc) estimated in the literature (Mutel *et al.* 1979). Zuckerman *et al.* (1985) discuss this star in greater detail. If AFGL 2688 was four times more luminous when it was a red AGB star, then it must be closer to Earth than 1 kpc.

4. One group of late-type carbon stars has large outflow velocities and, apparently, relatively large values of $\dot{M}V_\infty/(L_*/c)$. These six stars, all detected in the present CO survey and in that described in Paper II, include: AFGL 2233 ($V_\infty = 34.5$ km s^{-1}), AFGL 2901 ($V_\infty = 34.2$ km s^{-1}), AFGL 2154 ($V_\infty = 27$ km s^{-1}), AFGL 809 ($V_\infty = 26$ km s^{-1}), AFGL 2417 ($V_\infty = 24.4$ km s^{-1}), and AFGL 190 ($V_\infty = 19.7$ km s^{-1}). Excepting AFGL 190, the other five stars listed here have the largest outflow velocities of the carbon-rich stars plotted in Figure 2 of Paper II. The ratio $\dot{M}V_\infty/(L_*/c)$ for AFGL 809 is as large as that for the four early-type stars discussed in (3) above. Carbon stars with large V_∞ are discussed in more detail in Paper II.

5. For OH 231.8+4.2, which is neither a carbon star nor of early spectral type, $\dot{M}V_\infty$ is apparently one order of magnitude larger than L_*/c. This result was already apparent from data given in Table 3 of Sopka *et al.* (1985). (In Fig. 1, OH 231.8+4.2 is the one ▲ that lies well above the diagonal line.)

6. Supergiant stars are not easily seen in CO emission. In addition to NML Cyg, VY CMa, IRC +10420, and α Ori, which are plotted in Figure 1 and which were all quite difficult to detect, α Her, BC Cyg, and PZ Cas (Table 2), μ Cep (KM; Jura and Zuckerman 1984), and VX Sgr (Wannier and Sahai 1985) are not yet detected, although all are very bright in the infrared.

7. CH Cyg and R Aqr are both bright in the IR but not detected in CO emission (Table 2). R Aqr is plotted as the only upper limit in Figure 1. So symbiotic stars are apparently rather weak CO sources.

IV. SUMMARY

We have detected CO $J = 2 \rightarrow 1$ emission from a variety of infrared-bright evolved stars. For most objects, our observations and those of others are consistent with radiation pressure–driven mass loss, for which one expects that the momentum in the wind, $\dot{M}V_\infty$, is less than or equal to the momentum in the radiation field L_*/c. Some possible exceptions to this expectation are discussed at the end of § III. In each such case, $\dot{M}V_\infty$, when estimated from a very simple model of CO microwave emission, is apparently 3–12 times larger than L_*/c.

For ratios at the lower end of this range, there is no strong reason to suspect that radiation pressure cannot drive the mass outflow, since for very optically deep envelopes, $\dot{M}V_\infty$ can be a few times larger than L_*/c, and errors of observation and in the model analysis could also account for a factor of 3.

For stars for which $\dot{M}V_\infty$ is ~ 10 times larger than L_*/c, an additional explanation is probably required. For early-type objects that have almost become planetary nebulae, rapid downward evolution of the luminosity of the central star may suffice. For supergiants such as IRC +10420 and late-type carbon stars with large V_∞, our simple analysis of the CO emission may be inadequate since it is implicitly based on a "standard model" (e.g., Kwan and Linke 1982) of a star like IRC +10216 which has substantially smaller V_∞. Clearly, a more detailed investigation of models with large V_∞ (~ 30 km s^{-1}) would be of interest.

The perplexing late-type object OH 231.8+4.2 has, apparently, a high loss rate of both gas and dust grains (Sopka *et al.* 1985) and cannot be easily explained away by any of the above ideas. It remains a prime candidate for mass ejection by a mechanism other than radiation pressure.

In conclusion, a small ($\lesssim 10\%$) but not insignificant percentage of evolved, infrared-bright stars may be losing mass at a rate greater than that expected from radiation pressure on dust grains. Careful observations and detailed analysis of individual objects will be required before this question can be regarded as settled.

Note Added in manuscript 1985 December 16—In 1985 November we detected HCN emission from both AFGL 5250 and IRC +60144. The $J = 1 \rightarrow 0$ HCN lines were sufficiently intense that both stars are, almost certainly, carbon-rich. These HCN data and others will be discussed in Zuckerman and Dyck (1986).

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B. ZUCKERMAN: Astronomy Department, University of California, Los Angeles, CA 90024

H. M. DYCK: Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822