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MOLECULAR ENVELOPES AROUND EVOLVED STARS AND THE ORIGIN OF PLANETARY NEBULAE

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ABSTRACT

We surveyed a total of 37 late-type giant stars and IRC and CRL infrared sources in the $J = 1 \rightarrow 0$ rotational transition of carbon monoxide. Broad CO emission lines were detected toward six stars. Combination of these results with other CO observations of similar objects suggests that a majority of the red-giant stars with the largest mass-loss rates are carbon-rich (C/O > 1) or S-type (C/O $\sim$ 1). Infrared surveys tend to support this assertion. We suggest that these stars will evolve into planetary nebulae of the classical type, i.e., those having a few tenths of a solar mass and radius 0.1–0.7 pc. Most of these should, therefore, show carbon richness in the nebular matter. Planetaries originating from somewhat lower-mass stars ($M \sim 1.1\ M_\odot$), such as those found in globular clusters, in the galactic halo, or near the galactic center, have much smaller ionized masses and radii and may be oxygen-rich (O/C > 1).

Subject headings: nebulae: planetary — stars: late-type — stars: mass loss

I. INTRODUCTION

Mass loss from late-type giant stars has been recognized for at least 20 years (e.g., Deutsch 1956). Subsequent observations in the infrared showed that many stars have substantial infrared excesses, suggesting the existence of cool material surrounding these stars. Many such cool circumstellar shells are now detectable in the $J = 1 \rightarrow 0$ rotational transition of the CO molecule (e.g., Zuckerman *et al.* 1977, hereafter Paper I). At the present level of radio receiver sensitivity, this transition is likely to be observed only from stars with shell masses greater than or approximately 0.1 $M_\odot$ and mass-loss rates of at least $\sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$, i.e., comparable to mass-loss rates in planetary nebulae. Zuckerman *et al.* (1976) suggested an evolutionary sequence leading from these cool, late-type giants to planetary nebulae. Of particular significance is the abundance ratio of carbon to oxygen in the stars and their ejecta.

In the present *Letter*, we describe the results of a CO survey of IRC and CRL infrared sources, and carbon, M-type, and S-type stars. These data are discussed briefly in the context of the origin of planetary nebulae. A detailed analysis, including discussions of individual sources, is deferred to a later paper.

II. OBSERVATIONS

The equipment was the same as that described in Paper I. The definitions of the quantities listed in Tables 1 and 2 are the same as those for the corresponding tables in Paper I. The observations were carried out in 1977 April.

The objects in Table 1 have the broad CO lines that we associate with evolved stars. IRC −10236 is a carbon star (e.g., Merrill and Stein 1976*a*). The observed line is somewhat narrower than others listed in Table 1 of this *Letter* and Paper I, but a search for CO at positions 1′ north and south of IRC −10236 confirmed that the observed emission does originate from the star. IRC +60150 is classified as oxygen-rich (e.g., Merrill and Stein 1976*a*). Although this very bright infrared source has never been detected as an OH maser by Wilson (1977) despite repeated searches, SiO has been detected by Spencer *et al.* (1977). These SiO and OH results are suggestive of the microwave spectra of some S stars. W Aql is an S star which is very bright in the infrared (Wing and Yorka 1977). There is no evidence for silicate emission or absorption in the 8–13 μm spectra of CRL 2155 and 2199 (Gillett 1977). Nor is there convincing evidence of SiC emission. These 8–13 μm spectra are somewhat analogous to those of CRL 2688 and 618 (Gillette 1977), objects which, we believe, are carbon-rich (Zuckerman *et al.* 1976). In addition, CRL 2135, 2155, and 2199 have not been detected as OH masers (Silverglate *et al.* 1978; Allen *et al.* 1977; Kleinmann, Sargent, and Myers 1978).

CO lines observed toward CRL 4029, CRL 961, and Z CMa (Table 2) are strong and narrow, typical of those from interstellar molecular clouds. Further study showed the CO to be spatially extended and therefore not directly associated with the infrared objects, so they will not be considered further in this *Letter*.

We have also attempted, unsuccessfully, to confirm the CO lines we reported as "probable" in Paper I for NML Cyg and IRC +40485. For IRC +40485 there again was a suggestion of a line near −10 km s^{-1}, but with an intensity ($T_A{}^* \lesssim 0.12$ K) only half of that

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given in Paper I. We mapped the vicinity of NML Cyg and confirmed the complicated nature of the galactic CO distribution in this direction. Therefore it is not possible to isolate a contribution, if there is any, from NML Cyg.

III. DISCUSSION

The stars listed in Table 1 follow the regularities noted in Paper I. First, the detected objects are very bright at 10 and 20 μm (i.e., they are very red). Second they lie at fairly high galactic latitude (average $|b| = 13°$) and therefore are probably within ~2 kpc of the Earth (although CRL 2135, 2155, and 2199 all have large radial velocities). And third, five of the six stars are likely to be carbon-rich, if we consider the S star W Aql to be an object in which the products of a helium-burning zone have been mixed to the surface,

TABLE 1

SOURCES WITH ASSOCIATED CO EMISSION

Object	α_{1950}	δ_{1950}	T_A^* (K)	V_{LSR} (km s^{-1})	ΔV (km s^{-1})	Remarks
IRC +60150......	4h56m43s.0	+56°06′48″	0.15	+10	26	1
IRC −10236......	10 14 34.8	−14 24 31	0.17	+2	14	2
CRL 2135........	18 19 26.9	−27 08 05	0.2	+46	28	3
CRL 2155........	18 24 00.9	+23 27 01	0.2	+60	28	3,4
CRL 2199........	18 33 19.6	+ 5 33 17	0.2	+34	21	3
W Aql............	19 12 41.7	− 7 08 08	0.4	−21	25	5

REFERENCES.—(1) Position from Kukarkin *et al.* 1972 and Neugebauer and Leighton 1969; (2) position measured from Palomar Sky Survey E-plate; (3) position from Joyce *et al.* 1977; (4) identification as M2 V star (Cohen and Kuhi 1976) unlikely to be correct; (5) position from SAO catalog.

TABLE 2

SOURCES WITHOUT BROAD ASSOCIATED CO EMISSION

Object	α_{1950}	δ_{1950}	T_A^* (K)	Reference for Position
S Cas..........	1h15m57s.7	+72°20′56″	<0.15	SAO Catalog
W And.........	2 14 23.1	+44 04 30	<0.20	AGK 3
CRL 4029......	2 57 34.0	+60 17 16	†	Soifer 1977
R Lep..........	4 57 19.7	−14 52 47	<0.30	SAO Catalog
W Ori..........	5 02 48.7	+ 1 06 37	<0.20	SAO Catalog
CRL 809.......	5 40 33.3	+32 40 49	<0.20†	Kleinmann 1976
CRL 956.......	6 30 00.3	+60 58 48	≲0.10	Joyce *et al.* 1977
CRL 961.......	6 31 57.1	+ 4 15 03	†	Longmore *et al.* 1976
CRL 971.......	6 34 16.5	+ 3 28 05	<0.25‡	Joyce *et al.* 1977; Longmore *et al.* 1976
Z CMa.........	7 01 22.6	−11 28 36	†	SAO Catalog
CRL 1085......	7 09 53.7	−20 12 19	<0.25	Joyce *et al.* 1977; Longmore *et al.* 1976
CRL 1274......	8 35 44.3	−10 13 40	<0.20	Longmore *et al.* 1976
T Cnc..........	8 53 48.9	+20 02 30	<0.25	SAO Catalog
R Cam.........	14 21 17.8	+84 03 37	<0.15	SAO Catalog
CRL 1771......	15 22 35.9	−36 03 26	<0.35	Longmore *et al.* 1976
CRL 1822......	16 02 59.6	−30 41 25	<0.25	Joyce *et al.* 1977
α Sco...........	16 26 20.2	−26 19 22	<0.15	SAO Catalog
CRL 2086......	18 08 20.2	−26 30 15	<0.30	Joyce *et al.* 1977
CRL 2171......	18 27 37.2	+82 36 52	<0.15	Joyce *et al.* 1977
T Lyr..........	18 30 36.2	+36 57 39	<0.20	SAO Catalog
RY Sgr.........	19 13 16.9	−33 36 41	<0.30	SAO Catalog
CRL 2362......	19 16 08.0	+23 43 53	<0.15	Joyce *et al.* 1977
IRC −10502....	19 17 35.2	− 8 07 55	<0.15	Measured from Palomar Sky Survey E-plate
CRL 2370......	19 17 50.8	−26 20 18	<0.25	Joyce *et al.* 1977
R Cyg..........	19 35 28.7	+50 05 11	<0.20	SAO Catalog
CRL 2425......	19 36 08.7	−16 58 50	<0.20	Longmore *et al.* 1976
IRC −10529....	20 07 46.0	− 6 24 42	<0.20	Neugebauer and Leighton 1969
IRC −00499....	21 03 17.5	− 0 24 49	<0.25	Measured from Palomar Sky Survey E-plate
HR 8714........	22 52 07.6	+16 40 31	<0.25	SAO Catalog
CRL 3181......	23 54 05.5	+70 31 35	<0.30§	Joyce *et al.* 1977
WZ Cas........	23 58 41.9	+60 04 37	<0.15	SAO Catalog

† Narrow CO emission present.

‡ Data contaminated by galactic CO in both the on-source and reference spectra.

§ Data contaminated by galactic CO in the reference spectrum.

so that it is more nearly like a carbon star than an M-type giant. Elaboration of the third point requires additional spectroscopic study of the three relevant CRL sources.

The results of Paper I and the present *Letter* suggest that, if CO line intensity is proportional to rate of mass loss, then carbon-rich stars dominate among those stars that have very large mass-loss rates. In a previous paper we suggested that such stars are evolving into planetary nebulae (Zuckerman *et al.* 1976). Of the ~20 evolved stars with detectable CO discussed in Paper I and the present *Letter*, ~80% have $C/O \gtrsim 1$. (We consider some possible selection effects in the following paragraphs.) Carbon-rich stars constitute a similar fraction (~67%) of the CRL objects studied in the infrared by Merrill and Stein (1976*b*), although there may be significant selection effects involved here. An infrared study likely to be free of selection effects was carried out by Strecker and Ney (1974), who examined ~230 sources in the IRC catalog that were first classified by Vogt (1973). Whereas Vogt found that the fraction of carbon-rich stars in this sample was comparable to the percentage (5%–10%) of carbon stars in the general red-giant population, Strecker and Ney found that 20% of the 30 stars with large infrared excesses are carbon-rich. Thus both the infrared and radio data suggest that at the largest mass-loss rates, probably comparable to mass-loss rates in planetary nebulae, carbon-rich stars are heavily represented.

Various criteria were used to choose the stars that were surveyed in Paper I and the present *Letter*. We tended to examine stars that lie out of the galactic plane, have C/O (when known) greater than unity, and have large 11 μm and/or 20 μm fluxes. The first two criteria will bias the results toward the regularities noted above. The last criterion could introduce a bias in the C/O ratio for detected objects if the 11 μm and 20 μm properties of the circumstellar dust are very different for oxygen- and carbon-rich stars. Most oxygen-rich stars display 10 μm silicate emission, although those with the thickest envelopes show 10 μm absorption (Merrill and Stein 1976*a*, *b*). Therefore it is conceivable that ground-based confirmation of CRL sources, if carried out at 10 μm, might miss some of the reddest oxygen-rich stars. Such stars would be relatively faint at 11 μm but very prominent at 4 μm and/or 20 μm. Since there are few, if any, such objects in the CRL catalog that remain to be confirmed, we doubt that their addition will significantly change our results. Confirmation programs currently under way at 5 μm should definitely settle this point (Gillett 1977).

In spite of these possible biases, there are at least three things which, when taken together, leave us feeling sanguine that the prevalence of carbon-rich and S-type stars among the CO detections is not simply a selection effect. First, many of the CRL sources observed by us and by Lo and Bechis (1976) had unknown C/O ratios at the time of the CO observations. Of 13 CRL sources associated with carbon-rich, evolved stars, seven have been detected in CO, whereas of nine CRL sources searched for CO and now known to be oxygen-rich, evolved stars, none have shown CO radio emission. Second, the normalization of $T_A{}^*$ carried out in Figure 1 of Paper I makes it reasonably certain that oxygen-rich red giants without large infrared excesses are not losing mass at rates greater than or approximately 10^{-5} $M_\odot$. And third, surveys concentrating on oxygen-rich, late-type giants by Gilmore and Bowers (1977) and by Lo and Bechis (1977) have yielded insufficient CO detections to offset the preponderance of carbon-rich detections in our work.

We noted (Zuckerman *et al.* 1976) that it is desirable to compare the average mass of a planetary nebula with the lower limit to the mass of a carbon star to decide whether most planetaries might be carbon-rich—an entirely plausible possibility, on the basis of the above discussion. The typical preplanetary main-sequence star is believed to have a mass ~1.5 $M_\odot$ (Miller 1974) or perhaps even somewhat less (Ford 1977). The lower limit to the mass of a carbon star is difficult to determine observationally, but may be around 1.5 $M_\odot$ (Eggen 1972; Barbaro and Dallaporta 1972). Theoretically it is, at present, difficult to produce a carbon-star of mass $\lesssim 2$ $M_\odot$. Models of low-mass stars do not allow convection to mix carbon-rich material from the interior to the surface (Rose 1977). (Admittedly, convection in stars is not well understood.) One way around this difficulty would occur if many of the very red carbon stars we are discussing have already lost most of their oxygen-rich envelopes (e.g., Reimers 1975; Wood and Cahn 1977) and thus do not require much mixing to invert the C-to-O ratio. Helium shell flashes, capable of producing a large C-to-O ratio, are computed to occur even for stars of mass as low as 0.5 $M_\odot$ (Sackmann 1977).

Comparison of the time scale for the mixing of carbon-rich material into the stellar envelope (possibly due to the onset of helium shell flashes) with the time scale for loss of an oxygen-rich envelope as a function of stellar mass might explain why some oxygen-rich stars (e.g., IRC +10011, NML Tau, and IRC +60150) are currently losing mass very rapidly. If a large core luminosity and hence, presumably, mass-loss rate are established before the outer layers have escaped, then an object like IRC +10011 might be produced. It is unclear whether such objects will evolve into carbon stars before they evolve into planetary nebulae.

It is commonly assumed that all optically thin planetary nebulae contain similar masses, M, of ionized gas (~ few tenths of a solar mass). These "classical" planetaries characteristically have radii between 0.1 and 0.7 pc. The latter dimension is set by the observational constraint that when the surface brightness, S, falls below some value, say, $S_{\min}$, the nebula is undetectable against the background. This is a useful criterion because S is a very strong function of the radius, R, of the planetary nebula: $S \propto M^2/R^5$.

It has been known for many years (e.g., Osterbrock 1964) that the planetary nebulae observed in the globular cluster M15 and near the galactic center typically have radii near 0.1 pc, while those with larger radii (e.g., those near the Sun) are very scarce in the halo and near the galactic center. Osterbrock suggested three possible explanations for this effect. His preferred explanation—that the brighter stellar background in M15 and near the galactic center discriminates against detection of low-surface-brightness objects—seems unlikely to us because of the very strong R dependence of S. This same R dependence also argues against interstellar extinction as an explanation of the observed scarcity of large planetaries.

A more likely explanation for the above effect is that planetary nebulae in the halo and near the galactic center have systematically much lower masses than local disk planetaries. For a given $S_{\min}$, $R_{\max} \propto M^{2/5}$, implying that local disk planetaries are $\sim$100 times more massive than the one in M15 and those near the galactic center. We suggest that the latter planetaries originate from relatively low-mass stars ($M \sim 1.1\ M_{\odot}$) and may well be oxygen-rich. Wood and Cahn (1977) suggest that the distribution of planetary nebulae masses is bimodal, with peaks near 0.01 and 0.8 $M_{\odot}$. If this is true, it fits naturally with our idea that most of the high-mass planetaries, originating from higher-mass ($M \geq 1.5\ M_{\odot}$) stars, will be carbon-rich, while the low-mass planetaries, originating from less massive stars, may be mostly oxygen-rich.

Some support for the preceding suggestions may be obtained from studies of K648, the planetary nebula in M15. Peimbert (1973) and Minkowski (1965) suggest that K648 is a very low-mass planetary (Peimbert derives 0.018 $M_{\odot}$). More recently, Peterson (1977) has detected a planetary nebula that might be associated with the globular cluster NGC 6401. According to Peterson, this planetary is "subluminous" and may be similar to the one in M15.

IV. SUMMARY

A total of about 200 late-type giant stars and planetary nebulae have now been surveyed for CO $J = 1 \rightarrow 0$ emission. (Paper I and the present *Letter* account for $\sim$50% of the total.) About 30 objects have yielded CO emission lines. These are mainly very red stars, very bright at 10 μm and 20 μm, with mass-loss rates ($\sim 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$) comparable to mass-loss rates in classical disk planetaries. It appears likely that most of these stars will soon evolve into planetary nebulae. Since a majority of these stars are carbon-rich (C/O > 1) or S-type (C/O $\sim$ 1), we suggest that most disk planetaries have C/O $\gtrsim$ 1 in their nebular ejecta.

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