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CARBON MONOXIDE EMISSION FROM PLANETARY NEBULAE AND THEIR POSSIBLE PRECURSORS[1]

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ABSTRACT

Carbon monoxide emission has been searched for in four planetary nebulae and four possible protoplanetary nebulae. No ^{12}CO emission was seen in the planetary nebulae, nor in M1–92, to a level of $T_A^* \sim 20$ mK. Improved ^{12}CO spectra are discussed for AFGL 618, AFGL 2688, and CIT 6. All three objects were also detected in ^{13}CO emission. This allowed lower limits to the $[^{12}\mathrm{C}]/[^{13}\mathrm{C}]$ abundance ratio to be calculated. Our observations place upper limits to the ^{12}CO emission from the planetary nebulae nearly two orders of magnitude below the level found in NGC 7027. We argue that a higher mass-loss rate in NGC 7027 is responsible for its detectable molecular cloud.

Subject headings: interstellar: molecules — nebulae: planetary

I. INTRODUCTION

The stage of evolution between red giant and fully formed planetary nebula is perhaps the most interesting through which a moderate mass star will go. At some point in the advanced evolution of a star it rapidly loses mass, cloaking itself in a dense cloud of gas and dust. Large amounts of material are lost from the star, molecules form, and shocks heat the gas shroud. Such intense activity has made protoplanetary nebulae and compact planetary nebulae the targets of numerous programs of investigation.

With the development of sensitive millimeter-wave receivers, highly evolved objects have been regularly observed for molecular emission (see the review by Zuckerman [1980]). A fairly large number of giant stars, bipolar nebulae, and other evolved stars show millimeter CO emission. However, only a single planetary nebula, NGC 7027, has been definitely detected in radio CO emission (Mufson, Lyon, and Marionni 1975; Thronson 1983).

Our goal in this project was twofold. First, we searched a number of planetary nebula for CO emission using a receiver of substantially improved sensitivity. There is still only one planetary nebula that has been detected in CO. We argue that the high mass-loss rate of NGC 7027 can account for its unique appearance. In addition, we observed ^{12}CO and ^{13}CO emission from the unusual carbon star CIT 6 and from two bipolar nebulae: AFGL 2688 (Cygnus Egg) and AFGL 618. The observations of the abundant isotope represent improvements over previously reported data. For ^{13}CO, our data are the first definite detection in CIT 6 and AFGL 2688. Comparison is made with earlier attempts at observing this isotopic species.

II. METHODS OF OBSERVATION AND ANALYSIS

The $J = 1 \rightarrow 0$ millimeter CO observations presented here were obtained during 1982, early April. We used the NRAO 11 m telescope[2] with a remote telephone data link between Laramie and Kitt Peak, and near the end of March, 1983, using the NRAO 12 m telescope. The telescope was equipped with a cooled Cassegrain receiver and a pair of 128-channel spectrometers. Resolutions of 250 kHz, 500 kHz, and 1 MHz were all employed, although the data reported here are with only the lowest resolution (2.6 km s^{-1} at the CO frequencies). The beam size was 66″, and the pointing was regularly checked to be better than 15″. The observations were made in the position-switching mode, typically placing the reference position 15′ east or west of the source. Relative temperature scales were established by using a rotating ambient absorber. Absolute calibration was accomplished by observing a number of standard sources. For resolved lines the peak T_A^* can vary with the resolution of the spectrometer used. At 1 MHz in ^{12}CO we took $T_A^* = 32.3$ K, 16.2 K, and 58 K for M17 SW, W3(OH), and Ori A, respectively. At the same resolution in ^{13}CO we adopted $T_A^* = 12.7$ K, 6.7 K, and 9.7 K for the same objects. Regular observations of these standards found them to be easily repeatable to within 10%, the value taken as the systematic uncertainty to the observations.

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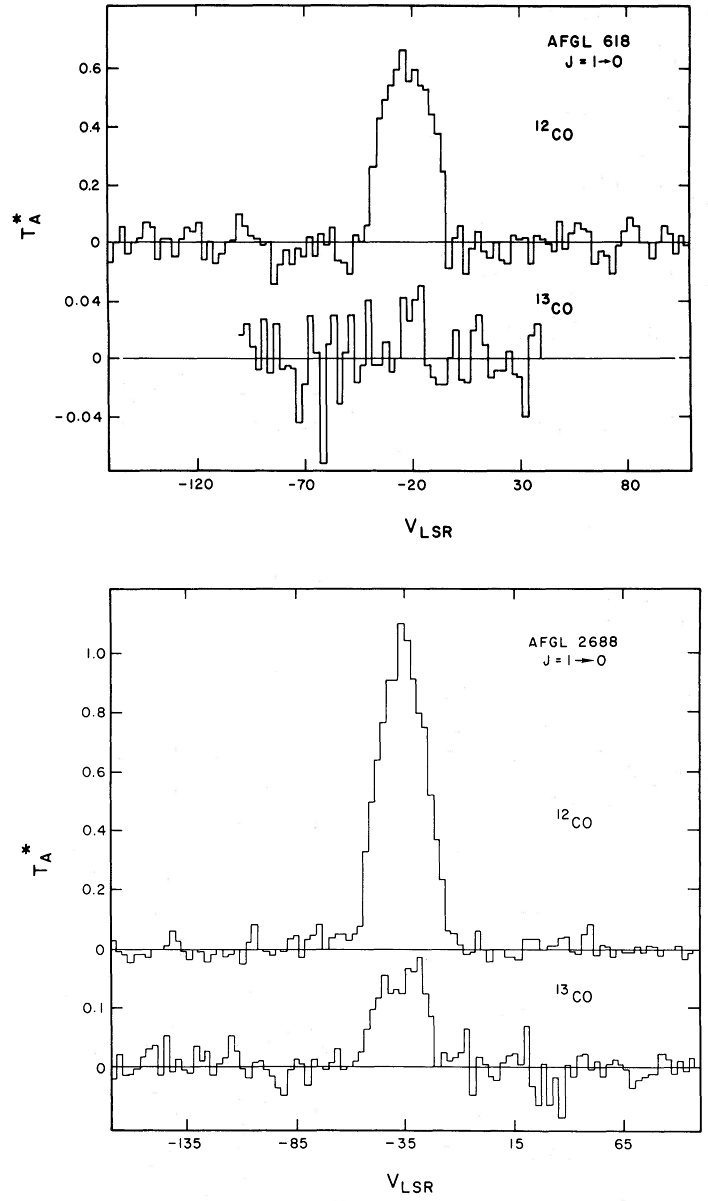

FIG. 1.—The $J = 1 \rightarrow 0$ CO spectra of detected sources. The vertical scale is in kelvins and the horizontal is in km s^{-1}. The source positions and adopted LSR velocity are in Table 1.

The detected emission lines are presented in Figures 1*a*–1*c*. The observed and derived parameters are listed in Table 1. Interpretation of the columns is the topic of the following section; the techniques used in their derivation are discussed here. The first four columns give the name of the object, its R.A. and Decl., and its adopted radial velocity.

The observed line strengths, columns (5) and (6), require *a priori* knowledge of the line width for a suitable estimate of the uncertainty. Individual objects are discussed in more detail in § III. If a line was not clearly present, $\int T_A^* dv$ was found either by assuming a total line width of 30 km s^{-1}, or in the case of ^{13}CO, by integrating over the ^{12}CO line width if it was observed. The choice of a particular line width, 30 km s^{-1}, was made on the basis of similar line widths found in a variety of evolved objects (see, e.g., Knapp, Kuiper, and Zuckerman 1979; Knapp *et al.* 1982; Thronson 1983;

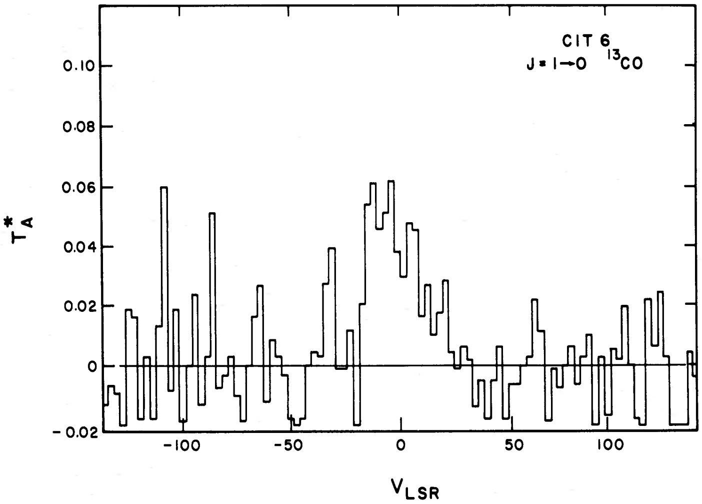

FIG. 1.—*Continued*

this work). A number of the objects in Table 1 suggest lines detected at about the 2 σ level. Because of baseline difficulties inherent in the 11 m telescope, we consider as real only those detections that approach 3 σ; i.e., ^{12}CO and ^{13}CO in AFGL 618, CIT 6, and AFGL 2688.

Column (7) presents the isotopic abundance ratio, $[^{12}\mathrm{CO}]/[^{13}\mathrm{CO}]$. If the two different molecular species are similarly excited, this ratio will be $[^{12}\mathrm{CO}]/[^{13}\mathrm{CO}] \geq \int \nu^{-2} T_A^*(^{12}\mathrm{CO})\,dv / \int \nu^{-2} T_A^*(^{13}\mathrm{CO})\,dv$. The limit comes from the possibility that the ^{12}CO emission is optically thick. Knapp *et al.* (1982) investigated this for all our detected sources using the 230 GHz $J = 2 \rightarrow 1$ line. Theirs was a fairly difficult observation, with a calibration uncertainty perhaps as high as 40%. They conclude, on the basis of available observations, that all the detected sources that we discuss here have optically thick $J = 1 \rightarrow 0$ emission. As those are the only observations of the important $J = 2 \rightarrow 1$ transition available, we shall adopt the Knapp *et al.* conclusion. This allows a calculation of the CO excitation temperature, shown in column (8). An improved value to the isotopic ratio can be found by fitting a line transfer model to the observations of each object. This was attempted by Morris (1980) for the case of spherically symmetric flows in highly evolved stars. Unfortunately, his results cannot be unambiguously applied to the bipolar nebulae that we consider. Nevertheless, if we apply his results, the resultant isotopic ratios for the protoplanetary nebulae all are in the range 30–40.

The source sizes (column [9]), necessary to determine the telescope's forward beam coupling coefficient, were taken from Knapp, Kuiper, and Zuckerman (1979) and Knapp *et al.* (1982). The ^{13}CO column density was calculated assuming thermodynamic equilibrium, giving the usual equation for simple geometries (see, e.g., Elmegreen and Elmegreen 1978):

$$N(^{13}\mathrm{CO}) = \frac{2.3 \times 10^{14} \tau(^{13}\mathrm{CO})\,\Delta v\,(T_{\mathrm{ex}} + 0.9)}{1 - \exp(-5.29/T_{\mathrm{ex}})} .$$

The line width, Δv, is in units of km s^{-1} and the ^{13}CO optical depth was estimated via

$$\tau(^{13}\mathrm{CO}) = -\ln\left[1 - \int T_A^*(^{13}\mathrm{CO})\,dv \Big/ \int T_A^*(^{12}\mathrm{CO})\,dv\right].$$

These equations assume that the ^{12}CO $J = 1 \rightarrow 0$ line is optically thick, an assumption that the Knapp *et al.* data appear to confirm.

A lower limit to the total mass may be found from the ^{13}CO abundance after a number of uncertain assumptions are made, which are briefly discussed here. First, a $[^{12}\mathrm{C}]/[^{13}\mathrm{C}]$ ratio of 30 is assumed for the objects. This is the value expected for protoplanetary evolution that begins during the red giant phase (Lambert and Ries 1981) and is probably not more than about a factor of 2 away from values appropriate for other stages of post–main-sequence evolution. Since the detections are all of carbon-rich objects, we adopt $[\mathrm{CO}]/[\mathrm{H}] \approx [\mathrm{O}]/[\mathrm{H}] \approx 2 \times 10^{-4}$, a value characteristic of the ionized material in carbon-rich planetary nebulae (see, e.g., Kaler 1981). Even so, these values may vary widely from object to object. Because of the uncertain distances to these objects, the masses have been normalized to a distance of 1 kpc. These masses should be strong lower limits to the true neutral hydrogen mass as significant amounts of carbon and oxygen are possibly tied up in grains, in atomic form, or in other molecules. If this is the case, the true [CO]/[H] ratio would be lower than that which we have adopted.

TABLE 1
SOURCE PARAMETERS

OBJECT (1)	R.A. (1950) (2)	DECL. (1950) (3)	$V_{\rm LSR}$(km s^{-1}) (4)	$\int T_A^* dv$(K-km s^{-1})[a] ^{12}CO (5)	$\int T_A^* dv$(K-km s^{-1})[a] ^{13}CO (6)	$\frac{[^{12}\text{CO}]}{[^{13}\text{CO}]}$[b] (7)	$T_{\rm ex}$ (8)	SOURCE RADIUS (arcmin) (9)	$N(^{13}$CO) (cm^{-2}) (10)	$M_{\rm H2}$ $(D/\text{kpc})^2 M_\odot$ (11)
Possible Protoplanetary Nebulae										
AFGL 618	$4^{\rm h}39^{\rm m}33\overset{\rm s}{.}8$	36°01′15″	−20	15.1±0.3	0.46±0.20[c]	30:	5.7	0.4	$3\pm1\times10^{15}$	0.1
CIT 6	10 13 12.0	30 49 24	0	13.1±0.11	1.30±0.11	10.4±0.9	5.4	0.4	$8\pm1\times10^{15}$	0.4
M1–92	19 34 18.4	29 26 05	0	−0.09±0.35						
AFGL 2688	21 00 20.0	36 29 44	−35	25.5±0.4	4.1±0.25	5.7±0.3	7.8	0.4	$30\pm2\times10^{15}$	1.5
Planetary Nebulae										
IC 418	$5^{\rm h}25^{\rm m}09\overset{\rm s}{.}5$	−12°44′15″	42	0.34±0.21	0.24±0.1					
IC 4593	16 09 23.4	12 12 00	45	−0.48±0.20						
NGC 6210	16 42 23.7	23 53 29	−35	0.61±0.37						
BD +30°3639 ...	19 32 47.5	30 24 21	−14	−0.08±0.23						
NGC 7027[d]	21 05 09.4	42 02 03	24	38.2	0.97±0.16	36±6	13.4	0.4	$6\pm1\times10^{15}$	0.05

[a] Uncertainties are 1 σ, internal only; systematic uncertainties are expected to be ±10%.

[b] Isotopic ratio calculated from observations, as described in text.

[c] Uncertainty is probably lower; see § III*a*.

[d] NGC 7027 data from Thronson (1983).

Although the implications and applicability of these assumptions will be discussed in more detail for each source in the next section, some general comments are appropriate here. It might seem unusual that the derived parameters in Table 1—T_{ex}, $N(^{13}CO)$, M_H—all have quite similar values for the four objects with CO detections. This is not merely coincidence for at least three reasons. First, there is of course expected to be a certain similarity among the four: evolutionary stage, initial mass, total luminosity, etc. This would tend toward similar characteristics in the surrounding cloud. Second, of necessity we had to adopt some source parameters—[O]/[H], $[^{12}C]/[^{13}C]$, and distance—that were the same for all, thus reducing object-to-object variation. Finally, there was a selection effect in the objects detected in this program. Simply stated, based on past experience the sources had to have $T_A^*(^{13}CO) \sim 50$ mK. Twice this value and they would have already been observed in detail. Half this value and our program probably would have considered them a nondetection. Since many of the calculated parameters derive directly from $T_A^*(^{13}CO)$, they will not show a very large variation.

III. DISCUSSION

a) *Detected Sources*

This section discusses the sources with detected CO emission more fully. Since much of the discussion applies equally to all objects, the first, AFGL 618, will have the most elaborate analysis.

i) *AFGL 618*

This object is a bipolar nebula, studied in detail by Westbrook *et al.* (1975), Schmidt and Cohen (1981), and Thronson (1981), with the first millimeter-wave CO detection reported by Lo and Bechis (1976). Additional CO observations of this object include the $J = 2 \rightarrow 1$ line reported by Knapp *et al.* (1982). Our ^{12}CO spectrum in Figure 1*a* is about 50% stronger than that reported by Lo and Bechis. This difference cannot be explained entirely as observational uncertainties. It is therefore possible that the $J = 1 \rightarrow 0$ ^{12}CO emission from the object has become somewhat stronger over the last several years. If real, this may be related to the apparent brightening of the object in the radio continuum (Kwok and Feldman 1981) and in the near-infrared H_2 lines (Beck and Beckwith, private communication).

Figure 1*a* also shows a possible detection of $J = 1 \rightarrow 0$ ^{13}CO emission from AFGL 618: a feature appears in the spectrum at the appropriate radial velocity. The marginal detection of emission in this object points out the difficulties in our analysis of weak signals. As with the other sources with a ^{12}CO detection, the ^{13}CO line strength reported in Table 1 here was found by integrating over the width of the former, and much stronger, line. However, the ^{13}CO line in Figure 1*a*, if real, appears only ~ 10 km s^{-1} wide. Integrating it over the 34 km s^{-1} width of the ^{12}CO line does not change the calculated line strength much, but almost *doubles* the formal uncertainty. *If* the ^{13}CO line is in fact only 10 km s^{-1} wide, its strength is 0.43 ± 0.12 K-km s^{-1}. Because ^{13}CO is probably optically thin in emission, it would be no surprise if these lines had a different width than those of the more abundant isotopic species. Such a determination awaits higher signal-to-noise data than those presented here.

The isotopic abundance ratio found for AFGL 618 is $[^{12}CO]/[^{13}CO] \geq 30 \pm 8$, where the uncertainty here was calculated assuming a narrow, 10 km s^{-1} wide ^{13}CO line. It would be important to improve upon this value as it bears directly upon the evolutionary stage of the precursor. Morris (1981) describes a model where mass loss from an asynchronous close binary system, with one member on the red giant branch, creates the characteristic double-lobed geometry. Mass loss on the red giant branch should usually be characterized by $[^{12}C]/[^{13}C] = 15$–25 (Dearborn, Tinsley, and Schramm 1978; Lambert and Ries 1981), although a small number of giant stars are seen to have ratios that are outside this range. AFGL 618 has an isotopic ratio in agreement with the expected upper part of the range, and would therefore seem to be a satisfactory candidate for Morris's model. However, as with the other two objects discussed here, the observed isotopic ratio is a lower limit. In addition, the bipolar nebulae—AFGL 618 and AFGL 2688—are apparently carbon rich and therefore may have evolved significantly *beyond* the red giant stage. This alone would seem to preclude simple application of Morris's model of evolution during the red giant stage: at this point most stars are oxygen rich rather than carbon rich.

The final column in Table 1 is a lower limit to the neutral gas mass, presumably also a limit to the total mass lost from the star. It is unfortunate that a number of uncertain parameters had to be adopted for this calculation. Indeed, it seems reasonable to expect the correct value of M_H to be perhaps a factor of 10 higher, primarily because only a fraction of the oxygen or carbon should be in CO. A total mass in the neutral region of $\sim 1\ M_\odot$ may be expected not only on the basis of the calculations presented here, but also on the mass-loss rate and lifetime of the object as derived by Knapp *et al.* (1982). Of course, more than a few solar masses cannot be lost by a star that evolves to a planetary nebula.

The total mass deduced from the molecular observations is in rough agreement with that found from the far-infrared observations of Kleinmann *et al.* (1978). The gas mass may be found from these data via

$$M_H \sim \frac{fa\rho L_{FIR}}{3\sigma Q T_d^4},$$

where f is the gas-to-dust mass ratio (~ 100), a is the grain radius (0.05 μm), ρ is its specific density (2 g cm^{-3}), $L_{\rm FIR}$ is the object's total luminosity, σ is the Stefan-Boltzmann constant, Q is the grain's absorption efficiency at the peak of infrared emission ($Q \approx 5 \times 10^{-4}$ at 30 μm), and T_d is the dust temperature taken from Kleinmann *et al.* The dust parameters are those adopted by Jones and Merrill (1976) for graphite dust around evolved stars and are a major source of uncertainty in this calculation. For AFGL 618, $M_{\rm H} \sim 2\ M_\odot\ (D/{\rm kpc})^2$, where D is the distance to the object in kiloparsecs. We note that this mass is consistent with a mass-loss rate of $\sim 10^{-4}\ M_\odot$ yr^{-1} for 10^4 years, typical for these types of objects (Knapp *et al.* 1982). Draine (1981) suggested that at about 30 μm, $Q/a = 800$ cm^{-1}, about a factor of 8 larger than proposed by Jones and Merrill. Adopting this value would lower the derived mass by a similar factor, bringing it into good agreement with the results in Table 1.

ii) *AFGL 2688 (Cygnus Egg)*

AFGL 2688 has been studied for a number of years as the prototypical bipolar nebula (Ney *et al.* 1975; Crampton, Cowley, and Humphreys 1975; Zuckerman *et al.* 1976; Thronson 1982). Lo and Bechis (1976) reported the first $J = 1 \rightarrow 0$ ^{12}CO and ^{13}CO spectra, and Knapp *et al.* (1982) detected the $J = 2 \rightarrow 1$ line. Our results are presented in Figure 1*b*. The spectra are in good agreement with those presented by Lo and Bechis, although of substantially higher quality. Beichman *et al.* (1983) also present a recent ^{13}CO spectrum, taken with the Owens Valley Radio Observatory telescope. It is in generally good agreement with the spectrum presented here, when corrected for the different aperture efficiencies of the OVRO and NRAO telescopes.

Much of the discussion of AFGL 618 in the previous section applies to AFGL 2688, although less strongly. The limit to the isotopic abundance in this object is $[^{12}{\rm CO}]/[^{13}{\rm CO}] \geq 5.7 \pm 0.3$. This agrees with values expected for rapid mass loss at the beginning of, during, or subsequent to the red giant stage.

The calculated mass limit for the hydrogen cloud is likewise in the range expected for an evolved, low-to moderate-mass star. Finally, this mass estimated from the CO observations is in reasonable agreement with that found from the far-infrared observations of Kleinmann *et al.* (1978), as was the case with AFGL 618.

iii) *CIT 6 (AFGL 1043, IRC + 30°219)*

Like the other detected sources, CIT 6 is a well-known, highly evolved carbon-rich object. It has been fairly extensively studied using radio molecular emission. Millimeter-wave ^{12}CO was first reported by Wilson, Schwartz, and Epstein (1973). Mufson and Liszt (1975) reported a detection of ^{13}CO at a level not observed later by Knapp, Kuiper, and Zuckerman (1979). The latter authors searched for, but failed to find, a mechanism that might explain an intrinsic ^{12}CO and ^{13}CO variation (see also Morris 1980). As with AFGL 2688, we do not believe CIT 6 is an intrinsic CO variable, although additional observations are necessary to firmly establish this.

The observations of ^{12}CO and ^{13}CO presented here are in good agreement with those of Knapp, Kuiper, and Zuckerman. Our ^{12}CO results were only slightly superior in signal-to-noise ratio to those of Knapp *et al.* and agree to roughly the combined 1 σ level of the two observations. We therefore do not present this spectrum. The ^{13}CO spectrum (Fig. 1*c*) is consistent with that in Knapp *et al.* but is a substantial improvement in quality. The previous authors did not claim that they definitely detected ^{13}CO, but comparison with their marginal feature and that of Figure 1*c* shows the same general characteristics: (1) at $V_{\rm LSR} \approx -15$ km s^{-1}, a sharp rise in emission to a peak $T_A^* \approx 50$ mK; (2) a slow decrease in T_A^* toward the higher velocities, reaching the zero-intensity level at about $V_{\rm LSR} = 25$ km s^{-1}.

Most of the derived parameters (in Table 1) are in general agreement with the values found for the other sources. An exception is the $[^{12}{\rm CO}]/[^{13}{\rm CO}]$ ratio, 10.4 ± 0.9, although since this is a lower limit the true value may be in good agreement with that for the other two objects.

b) Undetected Sources and CO *Emission from Planetary Nebulae*

Five objects were unsuccessfully searched for CO emission: the planetary nebulae IC 418, IC 4593, NGC 6210, and BD +30°3639, and the bipolar nebula M1–92 (Minkowski's Footprint). Of the planetary nebulae, IC 418 was included as it had the most persuasive of the marginal CO detections reported by Mufson, Lyon, and Marionni (1975). Knapp *et al.* also reported a marginal detection, in the $J = 2 \rightarrow 1$ line. The 1 σ value in Table 1 is about a factor of 8 below the reported line strength in Mufson, Lyon, and Marionni.

Two other planetary nebulae—BD +30°3639 and NGC 6210—were observed in the far-infrared by Moseley (1980). The former, in particular, is one of the brightest at infrared wavelengths and has occasionally been compared to NGC 7027. As Table 1 shows, the 2 σ limit to ^{12}CO line emission from BD +30°3639 is about two orders of magnitude below the emission from NGC 7027.

The possible protoplanetary and bipolar nebula, M1–92, was unsuccessfully searched for a molecular cloud. Lo and Bechis (1976) also failed to detect this object, but at a level about a factor of 2 greater than that presented here.

Our observations do not, therefore, alter the fact that NGC 7027 remains the only planetary nebula in which

CO has been definitely detected. It has been suggested that its molecular cloud is just the happenstance conjunction of a random interstellar cloud and the planetary nebula. This we believe to be unlikely for two reasons: the V_{LSR} of the CO lines is identical to that of the radio recombination lines, and the ^{12}CO line shape is characteristic of mass loss from a central star (Thronson 1983).

We believe that the most likely explanation lies in the very high mass-loss rate for NGC 7027, among the highest known for evolved objects (see, e.g., Knapp *et al.* 1982). The main effect of a high mass-loss rate is to significantly increase the survivability of a molecular cloud by protecting the gas from photodissociation. This can happen in at least two ways: dust absorption of UV photons and CO self-absorption. So far as dust is concerned, NGC 7027 is known to show more visual extinction than most planetaries, with $A_v = 2-3$ mag (Kaler 1976). Since extinction by dust enters exponentially into the photodestruction rate, a small change in the amount of dust can result in a major change in the cloud's lifetime.

As pointed out by J. Black (private communication), CO self-shielding by line absorption may be much more effective than the dust, especially for carbon-rich objects. Although detailed models are necessary to fully investigate this possibility, one important effect of molecular self-shielding may be the altering of isotope ratios (this has been discussed recently by Bally and Langer [1982] for star-forming regions). Under appropriate conditions, the abundant isotope (^{12}CO) is more effectively protected than the less abundant (^{13}CO). Of course such a mechanism could affect any isotope ratio derived from the radio molecular observations. If self-shielding is important in these objects, the isotope ratios derived here would tend to be too high.

IV. SUMMARY

A number of planetary nebulae and protoplanetary nebulae have been searched for $J = 1 \rightarrow 0$ CO emission. The protoplanetaries generally show very weak ^{13}CO emission, and the resultant [^{12}CO]/[^{13}CO] values are consistent with post-main-sequence evolution. No ^{12}CO was found in four planetary nebulae, and we argue that the high mass-loss rate in NGC 7027 explains its relatively strong millimeter-wave emission.

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