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MOLECULES IN NGC 6781 AND OTHER RINGLIKE PLANETARY NEBULAE

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ABSTRACT

We report the detection of extended H_2 [$S(1)$, $v = 1 \rightarrow 0$] and CO ($J = 1 \rightarrow 0$) emission from the ringlike planetary nebula NGC 6781 which, in many respects, appears to be a low surface brightness counterpart of the Ring nebula, NGC 6720. NGC 6781 is the fourth known member of a group of unusual planetary nebulae that display molecular outflows at velocities that are, apparently, considerably greater than the expansion velocity of the ionized gas. We also detected CO emission from NGC 3132 and NGC 6772, ringlike planetary nebulae with previously known H_2 emission.

Subject headings: interstellar: molecules — nebulae: planetary — nebulae: structure

I. INTRODUCTION

Following a slow start (Mufson, Lyon, and Mariani 1975; Knapp 1985), the detection of molecules from planetary nebulae (PN) is now in full swing (e.g., Huggins and Healy 1989; Zuckerman and Gatley 1988; Webster *et al.* 1988). Such measurements can reveal much about the transition of a star from red giant to PN. Also, the molecular regions promise to be unique probes of chemical processes in low-density environments (e.g., Morris *et al.* 1987; Bujarrabal *et al.* 1988; Cernicharo *et al.* 1989).

The primary purpose of the present *Letter* is to call attention to a relatively obscure PN, NGC 6781, which shares many optical morphological similarities with NGC 6720. The bright inner cores of both PN are elliptical and brightened on opposing edges and [N II] images of both are strikingly similar (Balick 1987). However, NGC 6781 has a much lower surface brightness than NGC 6720. In a survey of PN for infrared H_2 emission, Balick and Gatley (1990) discovered a large ring of H_2 emission at NGC 6781. During a subsequent survey of CO rotational emission from red giant stars (Kastner *et al.* 1990), extensive emission was discovered toward NGC 6781. Thus, it is a promising object for future detailed morphological and chemical studies. In addition to NGC 6781, we also detected CO emission from NGC 3132 and NGC 6772, two PN with previously known H_2 emission (Webster *et al.* 1988).

II. OBSERVATIONS

The H_2 image shown in Figure 1 (Plate L2) was obtained in 1987 September with the NOAO near-infrared camera at the f/14.5 Cassegrain focus of the 1.3 m telescope at Kitt Peak National Observatory. The camera contains a 58 × 62 array of InSb detectors. NGC 6781 was observed through a matched pair of interference filters whose transmission bandwidths are 1% of the central wavelength. One filter is centered close to the rest wavelength of the $v = 1 \rightarrow 0$ $S(1)$ line of H_2 at 2.122 μm, and the other is centered close to the Brγ line at 2.166 μm. The throughput of the two filters is the same to within 2% as determined by observations of standard stars. A nebular observation consists of 300 s observations through both filters. The emission expected through each filter includes the corresponding emission lines and bremsstrahlung (or other) continuum. Observations of blank sky were made in the same fashion through both filters and subtracted from the corresponding nebular observations in order to eliminate nonvariable sky or detector background. No nebular emission was detected in the exposure through the Brγ filter.

Carbon monoxide emission was measured in 1989 April with the 12 m telescope of the National Radio Astronomy Observatory,[2] also at Kitt Peak. The single-sideband receiver temperatures of the dual polarization SIS receiver were 120 K at the 115.2712 GHz frequency of the $J = 1 \rightarrow 0$ CO transition. The full half-power beamwidth of the telescope was 54″. The spectral line "backend" consisted of 256 channel filter banks. Each 1 MHz wide channel corresponds to 2.6 km s^{-1} at 115 GHz. All data shown in Figures 2 and 3 and summarized in Table 1 are an average of the orthogonal polarizations that were measured by the two SIS receivers.

The CO data were obtained using various switching modes. For NGC 6781, the spectra obtained at the central position and the positions offset to the north and south were obtained by chopping the subreflector in azimuth by 3′ at 1.25 Hz and also moving the telescope every 90 s so that the PN appeared first in one beam and then the other. For positions offset to the east and west, the telescope was switched by 10′ in azimuth between the PN and a reference position at a rate of 1/60 Hz, and the spectrum obtained at the latter position was then subtracted from the spectrum at the PN. For NGC 3132, all data were obtained by chopping the subreflector with a throw of 3′. For NGC 6772 the chop throw was in part 2′ and in part 3′.

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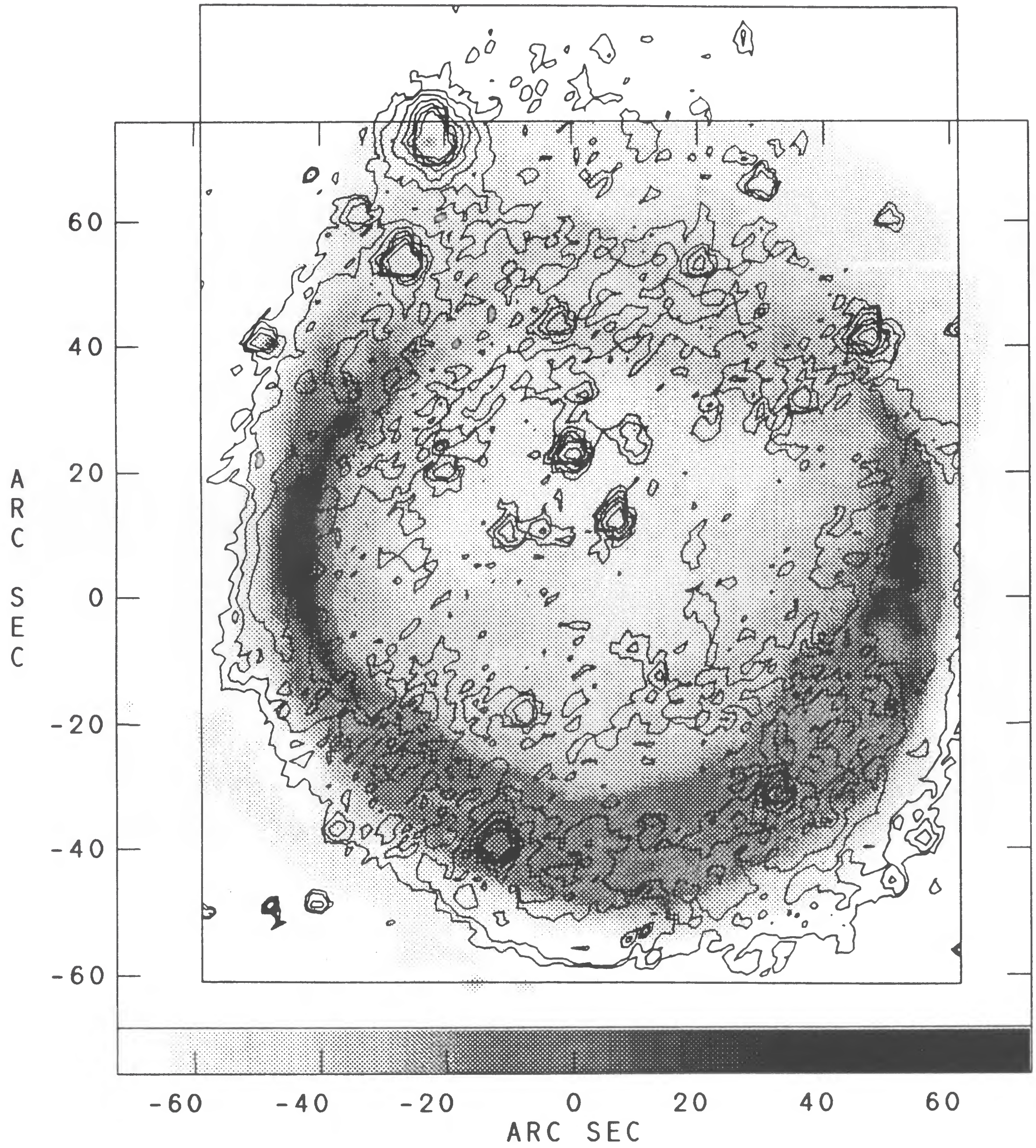

FIG. 1.—Contours of H_2 emission in the $S(1)$ $v = 1 \rightarrow 0$ transition obtained through a 1% interference filter overlaid on a grayscale representation of an [N II] $\lambda6584$ image of NGC 6781. For the H_2 data, the camera pixels are square, 1".34 on a side, and the seeing was between 1".5 and 2". The contours of H_2 surface brightness are spaced by factors of 2 beginning at 1.2×10^{-15} ergs cm^{-2} s^{-1} $arcsec^{-1}$ ($\pm 20\%$). In general, the brightest H_2 emission lies adjacent to and slightly farther from the nebular center than the brightest [N II] emission. The pointlike features in the H_2 map are due to the continuum emission of stars in the field (see the optical picture in Jacoby and Kaler 1989 for details of the distribution of field stars).

The axis labels are offsets with respect to an arbitrary image center, and the unticked box shows the extent of the imaging observations in the H_2 line. As discussed by Balick and Gatley (1990), the surface brightness of thermal nebular continuum and Brγ emission lie below the detection limit of the observations. The jaggedness of the contours is an artifact of the software used to make the figure. When seen as a grayscale image, the H_2 brightness distribution of NGC 6781 is smooth, much like its optical counterpart.

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TABLE 1

OBSERVED AND DERIVED QUANTITIES FOR RINGLIKE PLANETARY NEBULAE

Planetary Nebula (1)	n_e (cm^{-3}) (2)	D (pc) (3)	[N II] Diameter[a] (4)	T_B (K) (5)	$V_{\rm CO}$ (km s^{-1}) (6)	$V_{\rm opt}$ (km s^{-1}) (7)	$(V_\infty)_{\rm CO}$ (km s^{-1}) (8)	$(V_\infty)_{\rm H\,II}$ (km s^{-1}) (9)	$M_{\rm H_2}$ ($M_\odot$) (10)	$M_{\rm H\,II}$ ($M_\odot$) (11)	Notes[b] (12)
NGC 3132	800	600	37″	0.3	−27	−28.5	9	14	0.006	0.027	1
NGC 6772	300	1200	50	0.03	39	16	18?	12	0.004	0.11	2
NGC 6781	160	800	95	~0.2	15	21.5	25	12	0.020	0.13	3, 4
1′ north	...	...	...	0.35	15	...	20	...	0.027	...	
1′ south	...	...	...	0.35	12	...	20	...	0.027	...	
1′ east	...	...	...	0.13	18	...	22	...	0.011	...	
1′ west	...	...	...	0.14	13	...	24	...	0.013	...	

[a] Separation between the peaks in surface brightness measured along the minor axis.

[b] NOTES.—(1) CO observations at positions displaced 50″ north, south, east, and west of NGC 3132 yielded negative results with $T_B \lesssim 0.08$ K. Average of these four positions yielded a possible narrow line at −26 km s^{-1} with $T_B \sim 0.08$ K. (2) The optical and CO velocities are not in good agreement. However, the error on $V_{\rm opt}$ is 25 km s^{-1} (Schneider *et al.* 1983), and the CO spectrum is very noisy. (3) CO observations at positions displaced 2′ north and 2′ south of NGC 6781 yielded negative results with $T_B \lesssim 0.08$ K. (4) The tabulated $M_{\rm H\,II}$ is the *total* ionized mass. The total mass in the molecular region, summed over the five map positions, is 0.1 $M_\odot$. Additional molecular mass is, no doubt, present at the four corner positions offset to the northeast, northwest, southeast, and southwest of the central star.

Properties of the observed PN are summarized in Table 1. Representative electron densities, n_e, are listed in column (2). For NGC 6772 and NGC 6781 values for n_e were estimated from Hα surface brightnesses measured by Balick (1987). Distances, D, to the nebulae were obtained from the literature. Column (5) lists brightness temperature for the $J = 1 \rightarrow 0$ CO transition 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 Earth's atmosphere. Columns (6) and (7) give systemic velocities of the molecular and ionized gas respectively, the former from our CO measurements and the latter from the literature. Columns (8) and (9) give expansion velocities for the molecular and ionized gas, the former from our CO data. Calculations of the total mass of gas, including helium, in the molecular regions (col. [10]) are described in § III*b*. Column (11) is a rough estimate of the ionized masses, again including helium, based on n_e, D, and the angular sizes of the PN.

III. DISCUSSION

a) *Morphology*

In NGC 6781 the diameter of the ring of H_2, defined as the separation between the two peaks in surface brightness, is about 105″, slightly larger than the 95″ diameter of the [N II] ring as measured by Balick (1987). This is similar to the situation in the ringlike PN, NGC 6720, NGC 3132, and NGC 6772 (Zuckerman and Gatley 1988; Greenhouse, Haywood, and Thronson 1988; Webster *et al.* 1988). As discussed in these papers, this is not unexpected if the H_2 excitation is by shocks near the edge of the ionized gas. It is, however, less obvious that CO emission or thermal emission from dust grains in the remnant molecular envelope of the red giant phase should cut off so sharply at this edge. From deconvolving *IRAS* scans of NGC 6781, Hawkins and Zuckerman (1989) found that the full width at half-maximum of the 25, 60, and 100 μm emission is less than or about 100″, i.e., the dominant dust grain emission is from the ionized region. Our CO mapping results show

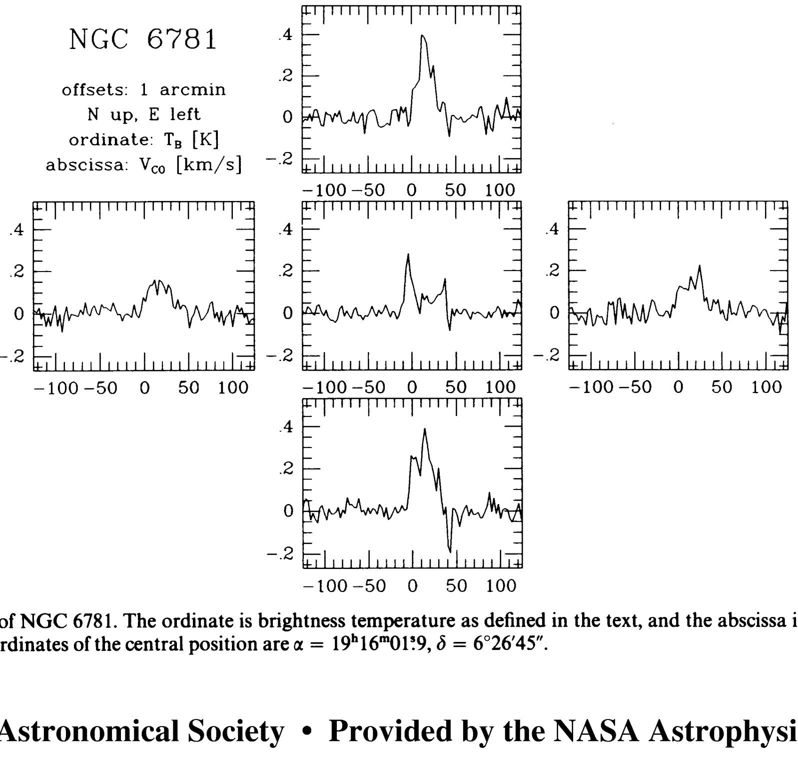

FIG. 2.—$J = 1 \rightarrow 0$ CO spectra of NGC 6781. The ordinate is brightness temperature as defined in the text, and the abscissa is radial velocity with respect to the local standard of rest. The 1950 coordinates of the central position are $\alpha = 19^{\rm h}16^{\rm m}01^{\rm s}.9$, $\delta = 6°26'45''$.

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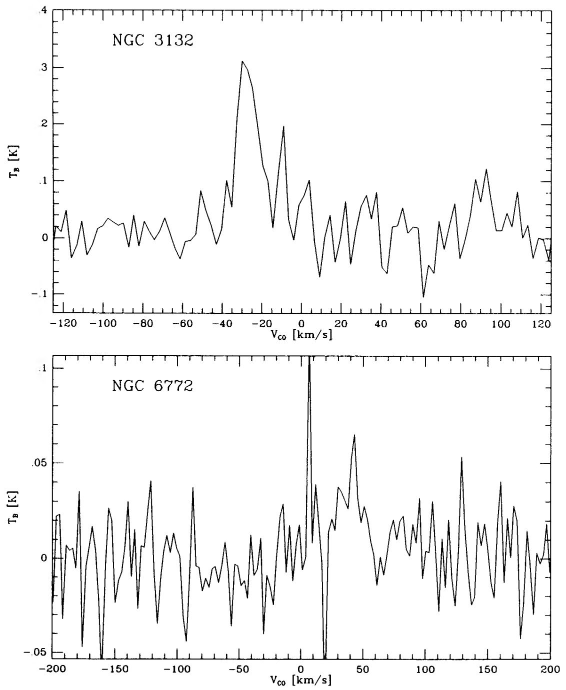

FIG. 3.—$J = 1 \rightarrow 0$ CO spectra of NGC 3132 and NGC 6772. Abscissa and ordinate as in Fig. 2. The 1950 coordinates are NGC 3132, $\alpha = 10^h04^m55^s.1$, $\delta = -40°11'29''$; NGC 6772, $\alpha = 19^h11^m59^s.8$, $\delta = -2°47'42''$.

strong emission out to the ring of H_2 emission but little beyond it at positions 2′ north and south of the central star (see Table 1). Similarly, NGC 3132 yielded a positive CO detection only at the central position, consistent with an optical size slightly smaller than our 54″ beam (see Table 1). Although the CO emission from NGC 6772 was too weak to map given our limited observing time, in light of the above regularities it is unlikely to be extended much beyond the size of the optical nebula.

The brightening of both the [N II] and H_2 emission along the minor axes of both NGC 6781 (Fig. 1) and NGC 6720 (Zuckerman and Gatley 1988; Greenhouse, Haywood, and Thronson 1988) is quite evident. On the other hand, the CO emission from both nebulae seems to be brightest along the major axis (see Table 1, Fig. 2, and Bachiller *et al.* 1989). If this regularity proves to be true for other ringlike PN, then it may be an important clue to the dynamics and evolution of this class of objects.

b) *Outflow Velocities*

Observations and currently fashionable models of the evolution of PN suggest that the expansion velocity of the ionized component, $(V_\infty)_{\rm H\,II}$, should be comparable to or somewhat larger than the outflow velocity $(V_\infty)_{\rm CO}$ of the remnant molecular envelope. Although such comparisons can be tricky, due in part to the presence of multiple components in $(V_\infty)_{\rm H\,II}$, for the typical PN studied by Huggins and Healy (1989) at least one component of $(V_\infty)_{\rm H\,II}$ is comparable to or greater than $(V_\infty)_{\rm CO}$. This is also the case for NGC 3132 in our Table 1. However, Huggins and Healy note that for M1-7, M1-16, and NGC 6563, $(V_\infty)_{\rm CO}$ appears to be at least twice as large as $(V_\infty)_{\rm H\,II}$. NGC 6781 appears to be the fourth member of this curious group.

Examination of references listed in Sabbadin (1984) and Sabbadin, Strafella, and Bianchini (1986) reveals that both long slits and circular apertures have been employed in measurement of $(V_\infty)_{\rm H\,II}$ for the four PN. Since it appears rather unlikely that unfortunate choices of slit position angles and nebula geometries have conspired to make $(V_\infty)_{\rm H\,II}$ appear much smaller than $(V_\infty)_{\rm CO}$, more detailed optical velocity measurements would now be desirable. We can discern no obvious size or morphological similarities among the four PN. If the uncertain distances, *D*, in Table 3 of Huggins and Healy (1989) and in Table 1 are approximately correct, then M1-7 and M1-16 are rather small PN whereas NGC 6781 is fairly large.

c) *Masses*

Although H_2 is widely observed from PN, it is generally recognized that it is not a useful quantitative probe of the total molecular mass because of the special conditions that are required to excite it. CO, although much more useful, is still far from ideal for reasons outlined below. We note in passing that the relative surface brightness of *S*(1) and optical emission is significantly different in NGC 6781 and NGC 6720. The peak Hα surface brightness of NGC 6720 is an order of magnitude brighter than that of NGC 6781, whereas their peak *S*(1) brightnesses are comparable. This could be due in part to the relatively large density in NGC 6720 so that the upper level of the *S*(1) transition is often collisionally deexcited.

The most comprehensive attempt to derive molecular masses in PN is due to Huggins and Healy (1989) who surveyed the $J = 2 \rightarrow 1$ transition of CO with the NRAO 12 m telescope. They used this transition in preference to the $J = 1 \rightarrow 0$ which is expected to be much weaker in the case of optically thin emission. For NGC 6720 Bachiller *et al.* (1989) find that the brightness temperature of the $2 \rightarrow 1$ line is, typically, 5 times larger than that of the $1 \rightarrow 0$ line. If this ratio is also appropriate for NGC 6781 and NGC 3132, then their CO emission would rank among the brighter of the 20 or so PN listed in Table 2 of Huggins and Healy.

As discussed in detail by Huggins and Healy, conversion of measurements of CO emission to total molecular mass associated with a PN is subject to many uncertainties. These include, for example, the CO rotational excitation temperature, the abundance ratio [CO]/[H_2], and the distance to the PN. Fortunately, when one calculates the important ratio, [total molecular mass]/[total ionized mass], the distance uncertainty largely disappears. The density in most of the volume containing molecular gas is not likely to be larger than the density of the ionized gas (Zuckerman and Gatley 1988). At the low densities that characterize the latter (Table 1), CO will be subthermally excited above the $J = 2$ level. Therefore, we assume an excitation temperature of 15 K in the partition function. This is unlikely to be in error by more than a factor of 2 unless the molecular density is either much lower or much greater than the ionized density. The latter might be the case if most of the CO emission originates in clumps of warm, shocked gas near the outer edge of the ionized zone. We also assume that $[{\rm CO}]/[{\rm H_2}] = 3.3 \times 10^{-4}$ (see discussions in Zuckerman and Dyck 1986 and Huggins and Healy 1989), and a helium abundance of 0.1 by number. The [CO]/[H_2] ratio is quite uncertain because we do not know [C]/[O] for the PN listed in Table 1 and because CO can be photodissociated more easily than H_2. Because most of the beam is filled with CO, the measured low brightness temperature ensures that the $1 \rightarrow 0$ emission is optically thin.

With the above assumptions we calculate the total gas mass in the molecular regions, and these are listed in column (10) of

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Table 1. Much of the mass in NGC 6781 and NGC 3132 is still molecular. The ratio of molecular to ionized mass in NGC 6781 is comparable to that of its "twin" NGC 6720 where this ratio is of order unity (Bachiller *et al.* 1989).

IV. CONCLUSIONS

NGC 6781 and NGC 3132 are ringlike planetary nebulae that contain substantial molecular components. Observations at high spatial resolution of CO, and perhaps other molecules, of the type carried out for the Ring nebula by Bachiller *et al.* (1989) should be quite revealing. Hopefully, combination of velocity-resolved maps in both ionized and molecular species for multiple examples of ringlike PN will clarify the longstanding problem of their true three-dimensional structure.

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