

ASTRONOMY

New detected CO(1-0) emission from planetary nebulae

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Abstract We report the results of CO(1-0) ($J = 1-0$) observations for 20 selected planetary nebulae (PNe), using the 13.7 m radio telescope of Purple Mountain Observatory at the Qinghai Station. Due to weak CO(1-0) emission, long integrated time observations have been carried out for most of sampled PNe. Among these PNe, nine are first detections in CO(1-0) named NGC6445, M1-59, M4-9, M2-51, M4-18, He2-459, Sh2-71, K3-31, M2-52, and one is the first possible detection named V-V1-8, a probably misclassified PN. NGC 6445, M1-59, M4-9 and M2-51 have been detected in CO(2-1) ($J = 2-1$). Although having been observed in previous CO surveys, Sh2-71 and M4-18 were not detected in CO; M2-52, K3-31, He2-459 are the first detected PNe in CO emission and V-V1-8 is given with a first completed spectrum detected in CO(1-0). Comparing these data with other previous observational ones, we discuss the relationships between CO(1-0) emission and evolution of PNe: While the nebular radii increase, the CO(1-0) line integrated intensities multiplied by distances have a decreasing trend. Also the masses of molecular envelopes (from 0.001 to 1 $M_{\odot}$) for PNe are decreased with increasing nebular radii. All the results mean the CO(1-0) emission decreases dramatically with the nebular evolution. The detectability of CO restricted by different PNe which have different dust properties and different evolutionary stages is also analyzed.

Keywords: planetary nebulae, CO emission, molecular envelope, stellar evolution.

Observations and theory have revealed that the planetary nebulae (PNe) are formed from highly evolved AGB (Asymptotic Giant Branch) stars on a very short time scale. So it is believed that many PNe may contain substantial amount of neutral and even molecular matter formed in the AGB stages. The detections of molecules will provide an important clue for us to study the evolutionary states of PNe and the mass loss from its progenitor—AGB star^[1-3]. Many molecules, such as CO, OH, H₂, CN, HCO⁺ and HCN have been detected in Proto-PN and PNe. Among these molecules CO and H₂ are the most effective probes of molecular gas in PNe^[2,4]. Since the first detection of CO emission from PNe in 1975, the extensive CO surveys in PNe have been carried out^[5,6]. Today, at least 50 PNe have been detected in CO. However, the number of CO detected in PNe is still insufficient to systematic research. Especially, because of the intrinsic CO(2-1)/(1-0) line ratio in the range 1—3^[6], the number of known CO(1-0) in PNe is still less than 40. Since the observed $J = 2-1/J = 1-0$ integrated line intensity ratio can be used to obtain the constraints on the excitation temperature, the column density, and the mass of the molecular gas^[7], increasing the number of CO(1-0) detected in PNe or improving some previous CO(1-0) data will be significant for studying the chemical and physical conditions of the neutral envelopes of PNe.

In this paper, we report the results of CO(1-0) observations with the Qinghai 13.7 m telescope in China for 20 selected PNe. In order to increase the detectability for weak CO(1-0) emission, long integrated time observations have been made for most of sampled PNe. The new observational results are analyzed and compared with other observational data. The relationships between CO(1-0) emission and evolution of planetary nebulae are also discussed by taking into account previous CO survey data and CO evolution model constructed by Sun and Kwok^[3].

1 Observations and results

1.1 Selection of sample

Twenty PNe selected to be observed are listed in table 1. In this sample, the nebular angular radius θ_r and the linear radius R cover an extent of ~ 2 order of magnitude. Since the dynamical age of a given PN can be derived from the ratio of the nebular radius and the nebular expansion velocity, the nebular radius can reflect the evolution age for PNe. Of course, the dynamical time scales are not always in good agreement with the time scales for the evolution of the PNe^[8]. In order to further emphasise the evolution properties of the selected sample, we list their infrared excess IRE^[9]. The IRE can be derived from F_{IR} (the total infrared flux emitted) and S_v (the ratio continuum flux at the optical thin wavelength λ) and written as follows:

$$\text{IRE} = \alpha \left(\frac{F_{\text{IR}}}{10^{-11} \text{erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}} \right) \left(\frac{S_v}{mJ_y} \right)^{-1} \left(\frac{\lambda}{6\text{cm}} \right)^{0.1},$$

where α is a coefficient related to the electronic density n_e of nebulae. The model result shows that under the given core mass of the central star the IRE drops down dramatically with increasing T_* (the temperature of central star, in general, the evolution direction is from lower T_* to higher T_*) when T_* is below 20 000 K and then slowly decreases with increasing T_* from 20 000 to 100 000 K^[9]. The sample listed in table 1 has a broader range in IRE, so it may represent different evolutionary states of PNe—from young PNe to evolved PNe.

Table 1 Nebular sample observed in CO(1-0)

Name	PK #	$\theta_r(^{\circ})$	D/kpc	R/pc	IRE
M2-43	27 + 4.1	1.2 ^{b)}	1.43 ^{b)}	0.008	5.2
He2-459	68 - 2.1	0.65 ^{a)}	3.35 ^{b)}	0.011	10
B1 2-1	104 + 0.1	0.8 ^{b)}	3.24 ^{b)}	0.013	3.7
K3-31	52 + 2.1	0.75 ^{a)}	3.94 ^{b)}	0.014	2.9
M1-12	235 - 3.1	0.9 ^{b)}	3.75 ^{b)}	0.016	6.6
M1-59	23 - 2.1	2.3	2.19	0.024	3.6
M1-16	226 + 5.1	1.5	5.45	0.04	4.1
M2-9	10 + 18.2	8.6	1.0	0.042	40?
M3-28	21 - 0.1	2.5	4.86	0.059	10
M4-18	146 + 7.1	1.75 ^{a)}	7.15 ^{b)}	0.061	8.6
M1-7	189 + 7.1	5.5	2.5	0.067	4.6
M2-47	39 - 2.1	4.1 ^{b)}	4.74 ^{b)}	0.094	3.4
M2-52	103 + 0.2	7.0 ^{b)}	4.41 ^{b)}	0.150	
K3-94	142 + 3.1	5.0 ^{b)}	6.51 ^{b)}	0.158	2.2
NGC6445	8 + 3.1	16.6	2.2	0.177	1.8
M2-51	103 + 0.1	19.6	1.92	0.182	
M4-9	24 + 5.1	22.1	1.78	0.191	2.5
V-V1-8	26 + 1.1	45.0 ^{b)}	0.89 ^{b)}	0.195	
Sh2-71	36-1.1	57.0 ^{a)}	1.0 ^{b)}	0.276	1.8
A6	136 + 4.1	93.0 ^{b)}	0.96 ^{b)}	0.432	2.4

a) Taken from ref. [9], b) Taken from ref. [10], “?” means uncertain value, and others are taken from ref. [6].

Some previous work has discussed the relationship between the detectability of CO emission and the type of PNe, such as the N/O abundance ratio and the morphological type. We hope to explore the detectability of CO in different PNe which have different dust properties. According to the IRAS-LRS database, V-V1-8 and M4-18 have 11.3μ SiC features^[11,12], so these PNe contain carbon-rich material in the form of solid grains classified as C-type and may be detected in CO. The M1-11, M2-43 and He2-459 show both oxygen- and carbon-rich dust features and are classified as M-type (a mixed type). In the M-type PNe, IC5117 has been detected in strong CO emission. We are interested in whether there are more M-type PNe that can be detected in CO.

1.2 Observations and results

All CO(1-0) observations were made in January, 1997 with the 13.7 m radio telescope at the Qinghai Station of Purple Mountain Observatory. The observation frequency is 115.271 GHz. The HPBW of antenna beam is $54''$ at 115 GHz. The pointing accuracy of antenna is better than $10''$ and the tracking accuracy of antenna better than $4''$. Average single-sideband system temperature is about 400 K. A 1024 channel AOS is employed with a frequency resolution of 255 kHz at 115 GHz. Since the CO(1-0) emission is very weak among PNe, the integrated time was taken to be more than 30 min for 60% sources and 60 min for Sh2-71 and M4-18 which have not been detected in previous search^[5-7].

Our observation shows that most of PNe observed have remnant molecular envelopes. Table 2 gives the positive observational results from 14 PNe. Nine PNe are first detections in CO(1-0). V-V1-8 is a possible first CO(1-0) observation. Some authors suggest the V-V1-8 is associated with S61^[11], and Fich and Blitz gave a CO(1-0) emission feature at 43.0 km/s^[13]. But we got two CO features (43.7 km/s and 7.6 km/s). The new CO(1-0) detections labeled by “*” can be divided into three groups: the first group named NGC6445, M1-59, M4-9 and M2-51 have been detected in CO(2-1); the second group named Sh2-71 and M4-18 have been observed in previous CO survey, but not yet detected in CO^[5-7]; the third group named M2-52, K3-31, He2-459 are the first detected PNe in CO emission, and V-V1-8 is given with a first completed spectrum of CO(1-0). The main parameters of CO(1-0) spectra including the rms noise level, antenna temperature T'_A corrected for atmospheric losses, the line of sight velocity V_0 related to LSR and the expansion velocity V_e taken to be half the full line width at zero intensity or half the velocity separation of the two main components are listed in table 2. T_A^* is the antenna temperature corrected for telescope losses, and $T_A^* = T'_A / \eta_l$, $\eta_l = 0.62$ for the Qinghai telescope. V_0/Opt and V_e/Opt show the systematic (LSR) and expansion velocities of the ionized gas, and I is the velocity integrated intensity ($= \int T_A^* dV$) of CO(1-0) spectra. Table 3 lists the PNe that were not detected in CO(1-0), the rms noise levels are also given. M_m is the derived mass of molecular envelope.

2 Analysis and discussion

2.1 New detected CO(1-0) spectra from ten PNe

Fig. 1 shows the CO(1-0) spectra newly detected in ten planetary nebulae. For the first group of sources, the spectral velocities of CO(1-0) are compared with those of CO(2-1). The CO(2-1) data are taken from refs. [5, 14]: For NGC6445, $V_0 = 20$ km/s and $V_e = 33$ km/s; for M4-9, $V_0 = -15$ km/s and $V_e = 17$ km/s; for M2-51, $V_0 = 0.0$ km/s and $V_e = 11.7$ km/s, and there is strong

Table 2 Main parameters of PNe detected in CO(1-0)

No.	Name	rms/K	T' _A /K	V ₀ /CO	V _e /CO	V ₀ /Opt	V _e /Opt	I/K·km·s ⁻¹	M _m (M _⊙)
1	* NGC6445	0.051	0.25	20	32	29		9.29	0.102
2	* M1-59	0.049	0.15	117	17	114.2	13	3.52	0.038
3	* M4-9	0.058	0.20	- 10	13.5	- 4.8		3.42	0.025
4	* M2-51	0.055	0.14	- 1.0	9.0	1.1	10.5	1.42	0.012
5	M3-28	0.155	0.45	30	13.0	36.1		7.34	0.394
						27 ± 10			
6	* M4-18	0.044	0.13	- 23.3	6.5	- 17.0	< 7.5	0.98	0.114
7	* He2-459	0.055	0.56	8.5	4.5			2.50	0.064
			0.28	2.8					
8	* Sh2-71	0.066	0.73	31.5	12.8	41.6	14	3.19	0.007
			0.25	11.1					
9	* K3-31	0.089	0.55	7.6	5.0			1.79	0.063
10	* V-V1-8	0.095	0.58	7.6	18.1			20.8	0.015
			3.78	43.7					
11	* M2-52	0.065	0.66	- 63	4.0?	- 80.1	7.5	2.68	0.118
12	M1-7	0.071	0.22	- 11.0	23			5.28	0.075
13	M1-16	0.058	0.24	50.0	26	31.9	10	8.10	0.602
14	M2-9	0.057	0.13	85.0	9.0	102.7	39	1.10	0.003

Table 3 PNe not detected in CO(1-0)

PN	rms/K	PN	rms/K	PN	rms/K
B1 2-1	0.093	M1-12	0.185	M2-43	0.156
M2-47	0.159	K3-94	0.156	A6	0.118

absorption at $v_{\text{LSR}} \sim -44 \text{ km/s}^{[5]}$; for M1-59, $V_0 = 114 \text{ km/s}$ and $V_e = (13 \pm 2) \text{ km/s}^{[14]}$. We note that there are no large differences between the two CO transitions either on central velocity or on velocity extension, or on velocity features. For instance, there is also a strong absorption in the CO(1-0) line of M2-51 at $v_{\text{LSR}} = -43 \text{ km/s}$. Of course, for most cases, the expansion velocities of CO(1-0) are smaller than those of CO(2-1). It may be reasonable for the molecular envelope of PNe.

In fig. 1, the six latter CO(1-0) spectra are from the second and the third groups. Because five PNe of them are located in the galactic plane and toward the inner galaxy, the considerable contamination is from line-of-sight molecular clouds, which makes it difficult to confirm the presence of CO emission associated with the PNe. However, the line profile of CO and the system velocity of ionized gas from PNe will help us to deal with this problem. We already got the system velocities taken from optical spectra data: $(-17.0 \pm 12.0) \text{ km/s}$, $(-80.1 \pm 25) \text{ km/s}$ and $(41.6 \pm 3) \text{ km/s}$ for M4-18, M2-52 and Sh2-71, respectively, which are not too far away from the velocity of CO emissions. Besides, in the cases of M4-18 and Sh2-71, the expansion velocities of CO envelopes agree well with the expansion velocities from ionized gas (see table 1). In the case of M2-52, the nebulae expansion velocity is larger than that of CO, so it is likely that we only detected one spectral peak from the remnant CO envelope. Finally, He2-459 has double-peak profile just as some CO profile that appeared in PNe.

In these newly detected CO/PNe, M4-8 is a young, low-excitation, C-rich PN with one of the coolest known central stars with a temperature of $\sim 20\,000 \text{ K}$, and the reddening toward M4-18 is extremely high, so it is believed that M4-18 probably contains substantial amount of dust

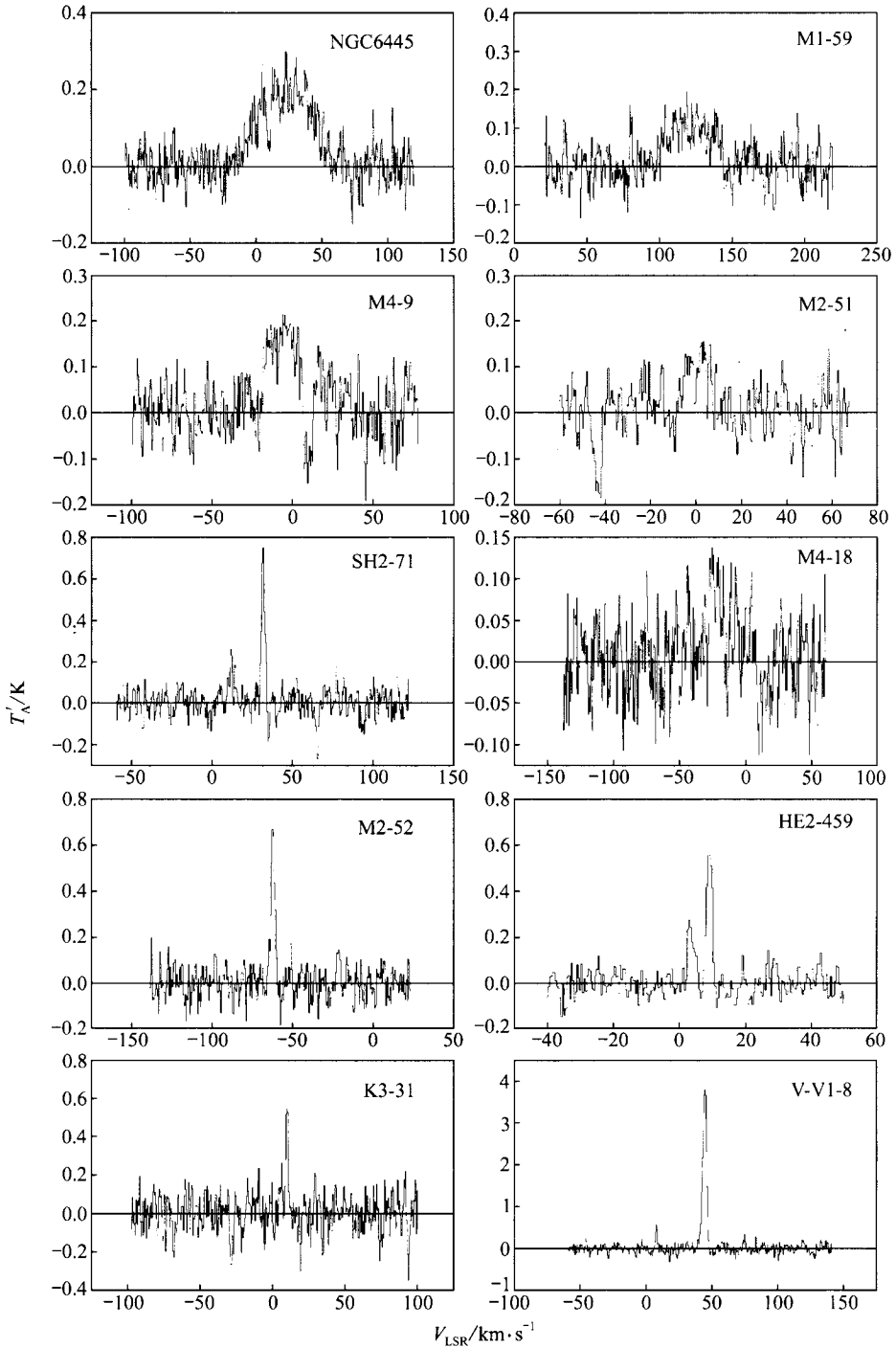


Fig. 1. The CO(1-0) spectra newly detected in ten planetary nebulae.

and molecular matter. Although the signal-to-noise ratio for M4-18 is very low, we still can confirm the presence of CO(1-0) emission based on its line profile, radial velocity and expansion velocity. He2-459 and K3-31 are two of the most compact and young PNe in detected CO/PNe.

The 18 μm silicate feature is prominent in the LRS spectrum of He2-459, although the 10 μm silicate feature is relatively weak, and the ground-based 8—13 μm spectrum of He2-459 has already been fitted with 8.6 and 11.3 μm (SiC) features^[12]. The detection of CO emission in He2-459 will help us to understand the properties of dust envelope of mixed type. Sh2-71 is an extended PN and one of the largest ionized nebulae in our newly detected CO/PNe. Recently, the high resolution spectroscopy and infrared photometry in the Sh2-71 indicated that there is a tilted, expanding disk ($V_D \approx 19.6$ km/s), surrounding a high excitation central star associated with bipolar outflow velocities $V \sim \pm 500$ km/s. Sh2-71 also has a large N/O ratio ($\sim 6.8_{-3.1}^{+3.9}$). As we know, the CO emissions are often detected in these kind of PNe with high N/O ratios or bipolar morphologies. The CO(1-0) emission we detected in Sh2-71 has two completely separated features, which is reasonable for the resolved optical thin CO 1-0 emission^[3]. V-V1-8 is another extended PN. Strong CO(1-0) emission ($T_A^* \sim 6.1$ K) has been detected in the direction of V-V1-8 at 43.7 km/s and there is a weaker CO(1-0) emission ($T_A^* \sim 0.9$ K) at 7.6 km/s. According to the strength of CO(1-0) at 43.7 km/s, we suggest that V-V1-8 is a probably HII region or say it is a misclassified PN. Many people also consider this source a misclassified PN based on its far infrared color and strong radio emission.

Our observational result of CO(1-0) from M3-28, M1-7, M1-16 and M2-9 also presented in table 2 confirms the previous data of other people.

2.2 CO emission from PNe and nebular evolution

2.2.1 Distribution of CO(1-0) line integrated intensity with nebular radius.

As we know, molecular CO emission is a very common property in AGB stars. However, only a small part of PNe is detected in CO emission, especially in CO(1-0) which is much lower than CO(3-2) and CO(2-1). So to better relate the CO(1-0) line strength to nebular evolution is very important to explore the detectability of CO(1-0) in PNe. Fig. 2 shows the distribution of integrated CO(1-0) line intensity I_{CO} with nebular radius. The $I_{\text{CO}}(\text{K} \cdot \text{km} \cdot \text{s}^{-1}) = \int T_{\text{MB}} dV$, $T_{\text{MB}} = T_A^* / \eta_{\text{MB}}$, $\eta_{\text{MB}} (= 0.4)$ is the main-beam efficiency of the Qinghai telescope. The circle symbols in fig. 2 are taken from this paper except for V-V1-8 because it is a possible misclassified PN. The triangle symbols are taken from the CO(1-0) data observed by Huggins et al.^[6] They are NGC6781, NGC6853, BD30° 3639, IC5117, NGC7008, VV47, M1-17, M1-13 and NGC2440.

Because the data distribution shown in fig. 2 is very disperse, the decreasing trend on the line intensity is difficult to see when the nebular radius increases. As mentioned before the observed line intensity is related to the source distance and the mass loss rate of progenitor star^[3]. However, the distances of galactic PNe are well known to be problematic^[15]. In order to decrease the effects of distance D , the distribution of $I_{\text{CO}} \cdot D$ with nebular radius R is plotted in fig. 3. For the three smallest PN ($\theta_r < 1''$), He2-459, K3-31 and IC5117, we put a very simple correction factor to deal with the effect of beam dilution. Comparing fig. 2 with fig. 3, we can note that the spread of data points is decreased. There is an obvious correlation between $I_{\text{CO}} \cdot D$ with nebular radius R .

2.2.2 Mass of molecular envelope and nebular evolution.

The estimation of mass of molecular envelope for planetary nebulae is another significant problem. It can give us an important clue to

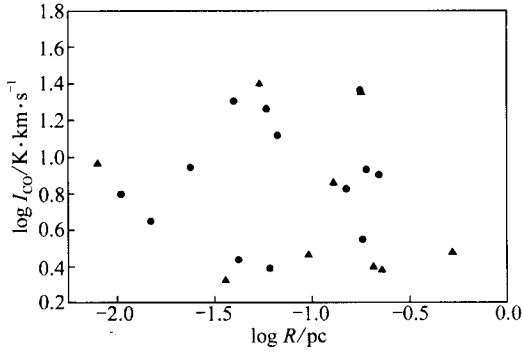


Fig. 2. The CO(1-0) integrated line intensity vs. nebular radius for the PN samples. The circle symbols are detected in CO(1-0) listed in table 2. The triangles are taken from the CO(1-0) data observed by ref. [6].

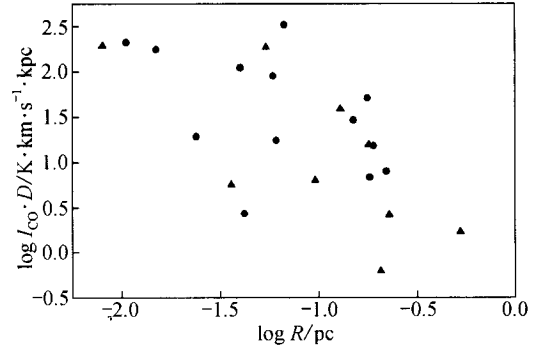


Fig. 3. CO(1-0) integrated line intensity times distance vs. nebular radius for the PN samples. The others are the same as in fig. 2.

find out the link between AGB and PN stages. Similar to the CO line intensity, the mass of molecular envelope of PN is related to the nebular radius, mass loss rate of AGB stages and the ultra-violet radiation from the central star and the inter-stellar medium^[3,5,6]. In this paper we try to estimate the molecular envelope mass using CO(1-0) data. Based on a basic assumption that the CO(2-1) line emission is optically thin, an expression $M_m = 3.0 \times 10^{-7} I_{CO} D^2 f^{-1} C$ can estimate the mass of molecular envelope with CO(2-1) integrated intensity^[5]. Since in the case of planetary nebulae, the optical depth of CO(1-0) emission is always smaller than one of CO(2-1)^[3], and the optical thin assumption is easy to be satisfied for CO(1-0), so we can estimate the M_m with CO(1-0). On the average, the (1-0) line intensity is smaller than (2-1) line intensity a factor of ~ 2 . Also we set $f(\text{CO}/\text{H}_2) = 3.3 \times 10^{-4}$, $C = 1$. The derived M_m are listed in table 2. Fig. 4 shows the distribution of molecular mass with nebular radius. Same as fig. 3, the effects of beam dilution have been corrected for those three smallest PNe. In fig. 4, in spite of the uncertainties in estimating M_m , it is still true that there is a large amount of neutral and molecular material from $0.001 M_\odot$ to $1 M_\odot$ in PN system. Fig. 4 also indicates that the mass of molecular envelope is decreased with nebular radius increasing. If the dynamic time scale is in agreement to the evolution time scale for PNe, CO(1-0) emission decreases sharply with nebular evolution because the remnant AGB envelope disperses quickly. Moreover, all these results restrict the detectability of CO(1-0) in PNe.

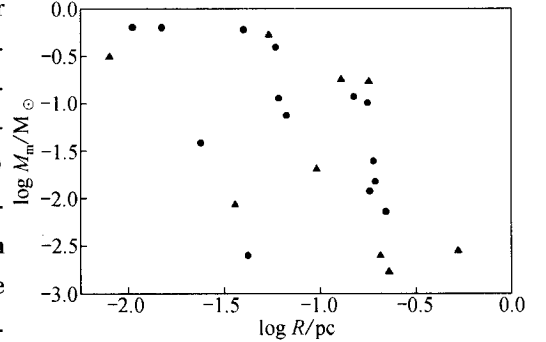


Fig. 4. The envelope molecular mass vs. the nebular radius. The circle symbols are PNe detected CO(1-0) listed in table 2. the triangles are taken from CO(2-1) data presented by refs. [6, 7] for IC5117.

3 Conclusions

1) We present the CO(1-0) observations with the Qinghai 13.7 m telescope of China for 20 se-

lected PNe, nine ones are first detection on CO(1-0), and one is the first possible detection. So they significantly improve the available data on the CO(1-0) emission in PNe.

2) Our observations show that most of PNe observed have remnant molecular envelope. The main parameters of 14 PNe detected in CO(1-0) and the rms noise levels for not detected sources in CO(1-0) are presented.

3) We have analyzed the new observational results and compared them with other observational data in detail.

4) $I_{\text{CO}} \cdot D$ (the CO(1-0) line integrated intensities multiplied by distances) and the mass of molecular envelope (from 0.001 to 1 $M_{\odot}$) for PNe are decreased with nebular radius increasing. This means CO(1-0) emission decreases dramatically with nebular evolution.

5) The detectability of CO(1-0) in different PNe can be restricted by different dust properties and different evolutionary stages in PNe.

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