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PLANETARY NEBULAE WITH H_2 EMISSION

Margarita Rosado and Lorena Arias

Instituto de Astronomía, UNAM, México

RESUMEN

Hacemos una revisión de la emisión en hidrógeno molecular (H_2) de las nebulosas planetarias (NPs). Vemos como esta emisión se encuentra asociada a objetos de forma bipolar. Describimos los niveles de energía de la molécula de hidrógeno, los principales mecanismos para poblarlos (choques y fluorescencia) y las formas en que se puede discriminar qué mecanismo opera. Proponemos que la cinemática del H_2 también puede ser usada para discriminar el mecanismo de excitación de sus líneas de emisión. Presentamos resultados preliminares sobre el estudio de la cinemática del H_2 que estamos realizando para una muestra de cinco NPs bipolares. Este estudio nos ha permitido determinar que los choques son el principal agente en la excitación del H_2 y que las masas de los progenitores de estos objetos son mayores que las de los progenitores de NPs típicas.

ABSTRACT

We review the emission of molecular hydrogen (H_2) in planetary nebulae (PNe) and we discuss the association between this emission and the bipolar morphology of the objects. We describe the energy levels of the hydrogen molecule, the main excitation mechanisms (shocks and fluorescence) and the ways of discrimination between the different excitation mechanisms. We propose another way of identification of the excitation mechanism based on H_2 kinematical studies. We present preliminary results of the H_2 kinematics we are conducting on a sample of five bipolar PNe. By means of this study we are able of identifying shocks as the main excitation mechanism of the H_2 emission lines in these objects. We have also estimated the masses of the H_2 gas in these PNe and the result implies that the progenitor's masses of these objects are larger than those of typical PNe progenitors.

Key Words: **ISM : KINEMATICS AND DYNAMICS — ISM : MOLECULES — PLANETARY NEBULAE**

1. INTRODUCTION

Molecular gas was first detected for a planetary nebula (PN) in the young PN NGC 7027 by Treffers et al. (1976). This pioneering work reported the detection of three lines of the hydrogen molecule (H_2) in the near IR and showed that even in regions photoionized by high temperature stars the molecules could survive in the strong stellar radiation field. Twelve years later (but well before the availability of sensitive, large-format, near IR detector arrays), Zuckerman & Gatley (1988) obtained Fabry-Perot maps of the H_2 line at 2.12 μm for three extended planetary nebulae (PNe): the Dumbbell, the Ring and NGC 2346. They found extended emission of molecular gas and attributed the H_2 emission to shocks. They also advanced that H_2 emission was related to PN morphology in the sense that bipolar PNe (in particular, what they called 'bow tie') should have strong H_2 emission lines. So far, there are several surveys reporting the H_2 line emission of PNe. Kastner et al. (1996) reported the results of their search for H_2 emission in $\sim$ 60 PNe obtaining positive detections for 23 of them. Including in their statistics other objects searched for H_2, they concluded that $\sim$ 40 % presents H_2 emission. They also pointed out that most of the objects with H_2 emission are bipolar. More recently, Guerrero et al. (2000) searched for H_2 emission in a sample of 15 bipolar PNe detecting H_2 in 13 of the objects of the sample ($\sim$ 87 %) confirming Zuckerman & Gatley's idea that bipolar PNe are H_2 emitters. Surprisingly enough, no survey in the radio wavelengths has been conducted in order to study the kinematics of the CO molecule at high angular resolution and large fields of view. However, extensive surveys in the CO lines in PNe have shown that a large proportion of PNe have molecular envelopes containing a significant fraction of their masses (Huggins et al. 1996, Huggins et al. 2000, Josselin et al. 2000).

In this work we will address several topics concerning the H_2 emission of PNe. In Sections 2 and 3 we discuss the importance of the detection of H_2 emission in PNe and the motivations we have to

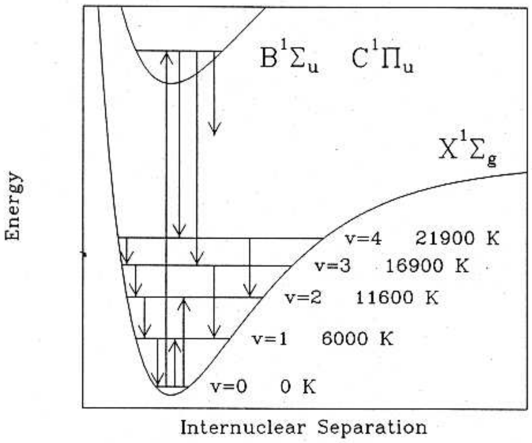

Fig. 1. Diagram showing some of the energy levels of the H_2 molecule from Stenberg (1988). Only the two lowest electronic levels and five of the fifteen vibrational levels of the ground state are displayed.

study the kinematics of the molecular hydrogen. Section 4 is devoted to the presentation of the transitions of the hydrogen molecule and its excitation mechanisms. In Section 5 we present the characteristics of the equipment we have developed to obtain the kinematics of H_2 emission lines and also of ionized gas. Section 6 contains some of the results of our observations and, in Section 7 we give the conclusions.

2. WHY THE STUDY OF H_2 EMISSION IN PLANETARY NEBULAE IS IMPORTANT?

1. First of all, the H_2 molecule is by far the most abundant molecule in the Universe and, in particular, in the molecular gas of PNe. Consequently, studies of the emission of the H_2 molecule should give us an important insight about the location, geometry, amount of mass and kinematics of the molecular gas in PNe. Other molecules, in particular the CO molecule, are currently used as tracers of the H_2 molecule in order to study the H_2 distribution and mass. This is because the H_2 molecule emits only under particular circumstances (see Section 4) while the CO is easily detectable at radio wavelengths. However, the conversion factors between CO and H_2 have been determined from objects such as molecular clouds. In objects like PNe where CNO products are released from the star and a chemical enrichment in C is present, it is uncertain that the same conversion factors apply (examples on how these conversion factors change with C abundances or dust/gas ratio can be found in Rubio, Lequeux & Boulanger 1993). Consequently, it is important to consider comprehensive data of both H_2 and CO molecules in order to study the molecular gas in PNe.

2. PNe represent the very short transition (t $\leq 10^4$ yr) between red giants and white dwarfs for stars with masses between 1 to 8 $M_\odot$. It is thought that the stars during their red giant and/or AGB phases eject their outer atmospheres composed of molecular gas. Very quickly the star evolves to the blue part of the HR diagram emerging as a hot star (the PN nucleus) inside a diffuse envelope of considerable mass that will be exposed to the intense photoionizing stellar flux. Thus, the study of the molecular H_2 give us important clues on the initial conditions of this process, the shaping and the evolution of PNe.

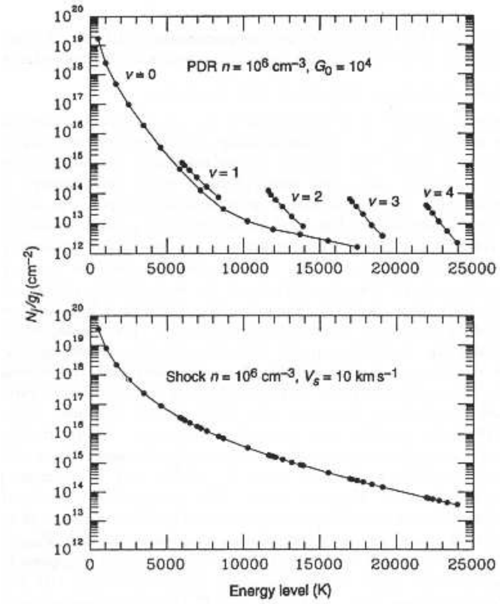

Fig. 2. "Excitation diagrams" (i.e., H_2 column densities, divided by the level of degeneracy, versus energy level (in K) for a photodissociation region and a shock (from Burton, 1992).

3. Given that H_2 and CO molecules are detected in extensive areas of PNe, it is reasonable to assume that molecular gas is an important ingredient in mass determinations of PNe. Indeed, in order to know the mass of PNe it is necessary to consider both the mass in the ionized and in the neutral gas as well as the mass of the PN nucleus. Mass determinations in PNe allow us to know the mass of the star before it evolves to form a PN and thus, an accurate knowledge of this quantity is important in the identification of the spectral types of PNe progenitors and in refining stellar evolution models.

4. The H_2 IR emission traces warm gas, collisionally or radiatively excited (see Section 4) and consequently, allows us to have a better insight in the physical conditions of PNe.

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3. WHY THE STUDY OF THE H_2 KINEMATICS IS IMPORTANT?

In order to answer this question we will list a series of reasons that we discuss in the remaining sections:

1. Kinematical studies of H_2 lines allow us to identify the excitation mechanism of the H_2 molecule: shocks versus fluorescence. Indeed, if shocks are present, the gas kinematics should be different from the case of a quiet and calm object.

2. The kinematics of the H_2 allows us to carry out an accurate comparison with the kinematics of the ionized gas. This point is important in the confrontation of observational data with theoretical evolutionary models of PNe (such as the 'colliding winds model'; Kwok et al. 1978, Kwok 1982).

3. H_2 kinematics allows us to have better estimates of the total mass in PNe envelopes once the exciting mechanism has been identified (see Dinerstein 1991 for a complete discussion on the effects of the H_2 excitation mechanism on mass determinations in PNe).

4. From H_2 kinematics it is possible to have kinematical ages (and thus, to determine the timescales of the events) and mass-losses of the different ejections.

5. In the case where shocks are the main excitation mechanism, H_2 kinematics of PNe is important for studying the molecular shocks themselves.

4. RADIATIVE TRANSITIONS OF THE H_2 MOLECULE AND ITS EXCITATION MECHANISMS

Figure 1 shows the energy levels of the H_2 molecule (from Stenberg 1988). As any molecule, it presents electronic levels each of which supports vibrational levels (labelled by the quantum number v) and a series of rotational levels (labelled by the quantum number j) that are associated with each vibrational level. For the H_2 molecule, the ground electronic state ($X^1\Sigma_g^+$) supports 15 vibrational levels (in Figure 1 only 5 of the 15 vibrational levels are displayed). The IR emission lines of the molecular hydrogen are due to the transitions between vibrational and rotational levels; these are called vibratio-rotational or pure-rotational transitions. The first excited vibrational level lies 6000 K above the molecular ground state. Furthermore, the energies of the rotational levels of the H_2 are widely spaced as compared with those of other interstellar molecules (such as CO). That is why H_2 emission is very difficult to detect even if H_2 is the most abundant molecule: collisional excitation is quite slow at the typical temperatures of 10 - 30 K of cold molecular clouds, where the main coolant is the CO molecule. Molecular hydrogen is homonuclear and only electric quadrupole radiative transitions are allowed between the vibratio-rotational levels. The H_2 emission line at 2.12 μm is due to the transition from the v=1 to the v=0 levels of the electronic state S (i. e., n=1) and the rotational level j=1. Thus, this transition is denoted as: S(1) 1-0. The line at 28 μm is due to the pure rotational transition S(0) 0-0.

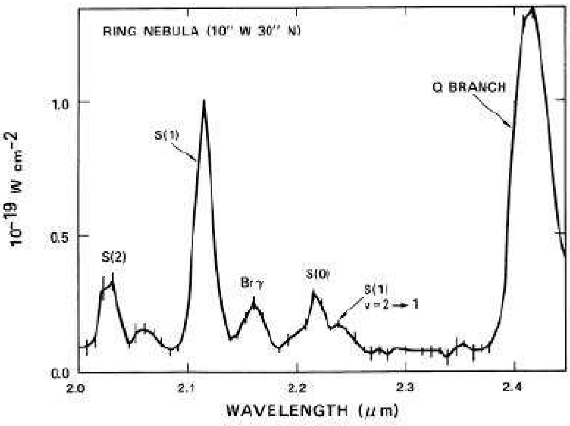

Fig. 3. Near IR spectrum (from 2 to 2.4 μm) of a PN (the Ring Nebula) displaying the most intense emission lines (from Zuckerman & Gatley, 1988).

One of the key problems concerning the near IR H_2 emission lines is the discrimination of the excitation mechanism. Indeed, energies above 6000 K are required to populate excited levels. However, it is not clear whether the energy levels are populated by radiative pumping (fluorescence) or by collisions (shocks). This constitutes at this time an open question. Usually, the way to discriminate between shocks and fluorescence is to observe lines corresponding to several energy levels and construct "excitation diagrams" (see Figure 2) to be confronted with theoretical models of shocks and fluorescence (Burton 1992). As seen in Figure 2, in the case of shocks and for the lower levels of photodissociation regions, the levels are thermalized whereas, for the higher levels of photodissociation regions the levels keep a characteristic fluorescent distribution.

In the case of the faint emission of the H_2 lines in PNe, only spectra integrated over the whole extension of the nebula have been obtained but their implications could be misleading due to a series of reasons. An easier, but not safe enough, way is to consider the ratio between the lines S(1) 2-1 (at 2.24μm) and S(1) 1-0 (at 2.12μm). When this ratio is much smaller than 0.5, there is an indication of

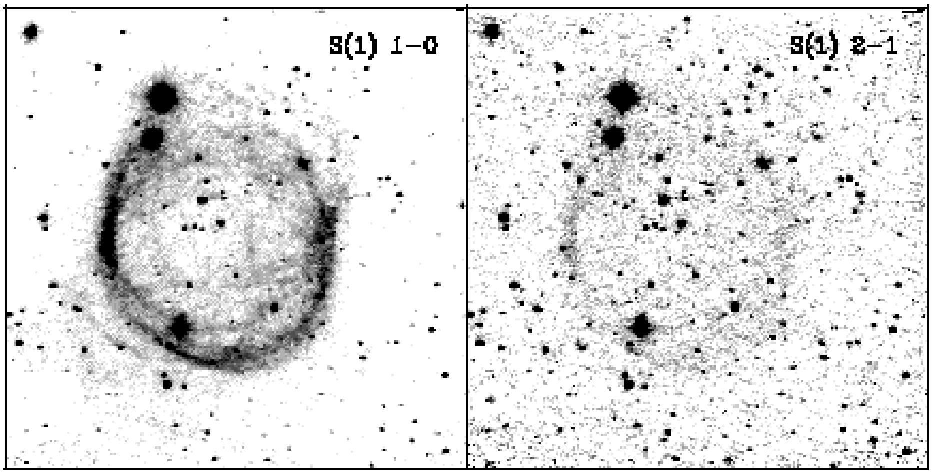

Fig. 4. Images at 2.12 and 2.24 μm corresponding to the lines of the S(1) 1-0 and S(1) 2-1 emission lines of the H_2 for the PN NGC 6781.

shock excitation. Figure 3 displays a spectrum of a PN showing the lines at 2.12 and 2.24 μm of the H_2. We have conceived an independent way of discrimination using the kinematics of the H_2 line at 2.12 μm. If we are able to measure expansion velocities in the molecular gas larger than the sound speed of the medium, then we can show that the molecular gas is shocked.

5. INSTRUMENTS AND OBSERVATIONS

All the observations were carried out with the 2.1m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, B.C. (México). We have developed two instruments which use scanning Fabry-Perot (FP) interferometers in order to obtain the radial velocity profiles at every point within the whole extent of a nebula, both for the ionized and the molecular gas. To study the molecular gas we are developing PUMILA, which use a scanning FP interferometer optimized in the near IR (see Rosado et al. 1999, Arias et al. 2001). It has been used to obtain velocity-cubes of the line at 2.12 μm of the molecular hydrogen. To study the emission lines of the ionized gas we have developed the UNAM scanning FP interferometer PUMA (Rosado et al. 1995), which allows to obtain velocity-cubes at Hα, [NII](λ 6583 Å), [SII](λ 6717 and 6731 Å) and [OIII](λ 5007 Å). The sampling spectral resolutions of the FP interferometers are about: 10 and 20 km s^{-1} for the IR and visible, respectively.

Scanning FP interferometers are ideal for this kind of work on extended objects because observations with these instruments give line profiles at each pixel over the complete field of view of the instrument. This allows to construct the radial velocity field of the object and to detect the existence of different velocity components and their velocity broadening, which are important characteristics for measuring expansion velocities and detecting possible shock excitation.

Fig. 5. RGB images at Hα (green), [NII] (red) and [OIII] (blue) of one of the PNe in the sample (NGC 6781).

6. RESULTS

As part of her PhD thesis, Lorena Arias is studying the interrelation between ionized and molecular gas in PNe focusing mainly on the kinematics of the line at 2.12 μm of the H_2, for the molecular gas, and on the lines of Hα, [NII], [SII] and [OIII] of the ionized gas. The details of the observations are given in Section 4.

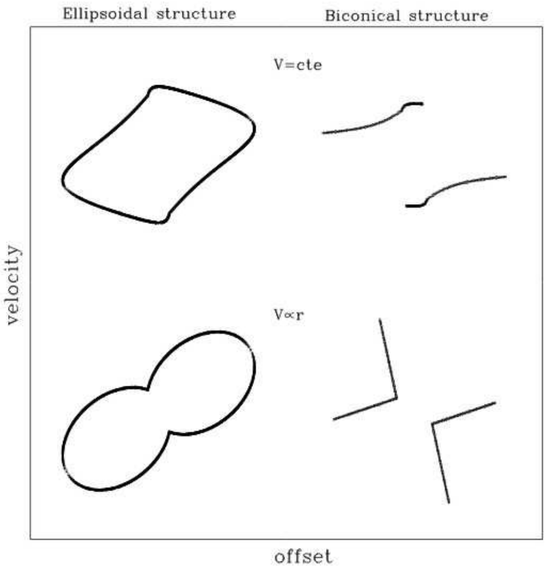

Fig. 6. Position-velocity diagrams predicted from the 3-D geometrical models considered: two ellipsoidal shells or a biconical structure, and, the expansion-velocity laws considered: a constant or proportional to the distance to the central star.

6.1. *The sample of PNe considered*

We have selected five PNe with reported H_2 emission: NGC 2346, NGC 3132, NGC 6720, NGC 6781 and NGC 7048. Figure 4 shows the optical emission of the ionized gas (in the lines of Hα, [NII] and [OIII]) of one of these objects (NGC 6781). One can see from the images (not all shown in this work) that, while only NGC 2346 has a clear bipolar shape, the remaining objects present some indication of the existence of bipolar lobes, mainly in their [NII] emission. We have discussed in the Introduction that the detection of molecular hydrogen in PNe is dominated by bipolar nebula, so that, it has been proposed that it is very likely that each and every H_2 emitting nebula possesses bipolar morphology (Kastner et al. 1996) and, therefore, that ring-like PNe with molecular emission are expected to be nebulae with a high inclination of the polar axis with respect to the line of sight. From our images and kinematics we confirm that the morphology of the studied PNe is more complicated than a simple ring.

6.2. *The H_2 excitation mechanism for the PNe of the sample*

We obtained direct images of the PNe in the molecular hydrogen emission lines at 2.122 μm and 2.248 μm, corresponding to the S(1) 1-0 and S(1) 2-1 transitions respectively (Figure 5 shows an example of these images for the PN NGC 6781). The S(1) 2-1 emission is weak in all the cases. In the case of

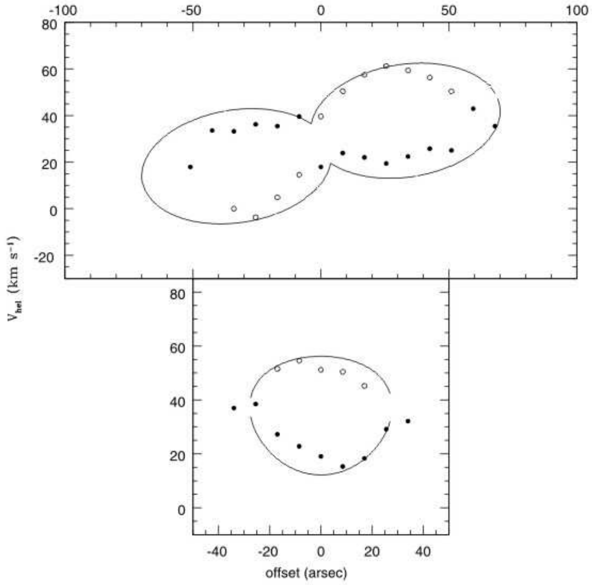

Fig. 7. Comparison between the position-velocity diagrams obtained from our H_2 FP kinematics and the predictions of the geometrical models for NGC 2346 (from Arias et al. 2001).

fluorescence a value of about 0.5 is expected for the intensity ratio of the S(1) 2-1 line to the S(1) 1-0 line. On the other hand, this ratio is typically 0.1 in shocked regions and tends to a limiting value of 0.3 for strong shocks. For the PNe of our sample we have found that the line ratio has values between 0.08 and 0.15 for the regions with stronger emission, indicative of shock excitation of the H_2 lines.

Furthermore, from the H_2 Fabry-Perot data, we derived velocity maps from which integrated radial velocity profiles were extracted. When one or more velocity peaks are present, the heliocentric radial velocity of each component can be obtained by a Gaussian profile fitting. We have tried to reproduce the kinematical data using a 3-D geometry. The best fit results when we take a double ellipsoidal shells model with a law for the expansion velocity proportional to the distance to the star. The tilt of the polar axis is one of the parameters of the model. The comparison between our optical and near IR Fabry-Perot data has shown that the kinematics of the ionized and molecular (both H_2 and CO, when available in the literature) are quite similar. Figure 6 shows the predicted "position-velocity diagrams" obtained by assuming that the geometry of the objects is: a) an ellipsoidal shell or b) a biconical structure. In both cases we considered two expansion laws: a con-

TABLE 1

MEASURED AND DERIVED QUANTITIES FOR THE PLANETARY NEBULAE OF THE SAMPLE

PN	**Tilt angle**	**V_{sh}** km s^{-1}	**S(1) 1-0** ergs $s^{-1}cm^{-2}sr^{-1}$	**n_o** cm^{-3}	**H_2 mass** $M_\odot$
NGC 6720	25	20	$9.24\ 10^{-3}$	$1.3\ 10^4$	0.3
NGC 6781	23	13	$1.02\ 10^{-4}$	$2.7\ 10^4$	0.2
NGC 3132	30	24	$2.19\ 10^{-4}$	$3.5\ 10^4$	0.4
NGC 2346	65	16	$6.25\ 10^{-5}$	$7.0\ 10^3$	0.8
NGC 7048	20	15	$1.25\ 10^{-5}$	$2.5\ 10^3$	0.1

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stant velocity law or a velocity proportional to the distance to the exciting PN nucleus. In Figure 7 (from Arias et al. 2001) we reproduce the observed position-velocity diagrams of the H_2 line at 2.122 μm (along and across the bipolar projected axis) of the PN NGC 2346. A comparison with Figure 6 shows that the geometry that better reproduces the FP kinematics of NGC 2346 we obtain is that of two ellipsoidal shells with an expansion velocity proportional to the distance to the central star. In general, as stated earlier, all the objects in the sample have H_2 kinematics well reproduced by a two ellipsoidal shells geometry.

An important result based on the kinematical data we obtained is the measure of the expansion velocities of the bipolar lobes and rings or torii of the PNe. The expansion velocities we measure for the central rings or torii of the studied PNe vary between 20 to 30 km s^{-1}. Expansion velocities this high for the molecular gas are supersonic and consequently we have shown, by independent means, that the excitation mechanism of the H_2 molecule in the sampled PNe is shock excitation.

In Table 1 we list preliminary values of the shock velocities of the central ring or torus of our sample of PNe. In obtaining the shock velocity, V_S, we have considered that this quantity corresponds to the expansion velocity, V_{EXP}, with respect to a previously ejected ambient medium, moving with a velocity, V_{RG}. Thus, $V_S = V_{EXP} - V_{RG}$. We have assumed that the ambient medium comes from an isotropic ejection during the red giant phase of the exciting star and that $V_{RG} = 5$ km s^{-1}.

An interesting point also derived from these kinematical studies is that in some objects like NGC 2346 (Arias et al. 2001), the shock velocities at the lobes are larger than the value of 25 km s^{-1} which is the critical value for non-dissociative J-type shocks. This suggests that maybe C-type shocks (and thus, magnetic fields; Burton 1992) could be present in the molecular gas of the studied PNe.

6.3. *Mass estimates of the molecular gas in PNe*

An important issue is to estimate the mass of the molecular gas from the H_2 kinematics. Using a Boltzmann population distribution we can obtain the mass of the shocked H_2. We obtained that the mass of shocked H_2 is, in general, quite low ($\sim 1.29 \times 10^{-4}$ $M_\odot$ for the torus of NGC 2346, for example). But the shocked H_2 is in a thin sheet enveloping the unshocked H_2. In order to estimate the mass of the molecular torus we obtained the pre-shock density, n_0, according to (Kwan 1977): $n_0 = S_{1-0}\ (V_S)^{-1.7}$, where S_{1-0} is the surface brightness of the 2.12 μm line and the shock velocity, V_S, has been defined previously. In Table 1 we also list these quantities for the five PNe of our sample together with an estimate of the mass of H_2. This is an independent way of estimating the mass of molecular PN envelopes. From the values reported in Table 1 one can see that these mass estimates point towards massive progenitors for the H_2 emitting PNe of the sample. That progenitors of bipolar PNe are more massive than progenitors of PNe with other morphological types has been found by Corradi & Schwarz (1995) using very different arguments from the ones presented in this study.

7. CONCLUSIONS

The study of the kinematics of ionized and molecular gas in bipolar PNe is very fruitful as it provides an independent means for the discrimination of the excitation mechanism of the H_2 emission lines and a complementary way for estimating the mass of the PNe envelopes.

The work that we are conducting on five PNe has revealed that shocks are the main excitation mechanism of the H_2 emission in all the objects. The mass estimates of the molecular gas in these objects imply that a large amount of matter in the envelopes of these PNe is in the molecular phase even if the photoionizing stellar flux is quite intense. These mass estimates, together with mass determinations of the ionized gas and of the PN nucleus, point towards PN progenitors more massive than the typical PN progenitors.

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