MASSIVE EXPANDING TORUS AND FAST OUTFLOW IN PLANETARY NEBULA NGC 6302

Dinh-V-Trung
Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; trung@asiaa.sinica.edu.tw

Valentín Bujarrabal
Observatorio Astronómico Nacional, Apartado 112, 28803 Alcalá de Henares, Madrid, Spain; v.bujarrabal@oan.es

Arancha Castro-Carrizo
Institut de Radioastronomie Millimétrique, 300 Rue de la Piscine, 38406 Saint Martin d’Hères, France; ecarrizo@iram.fr

Jeremy Lim
Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; jlim@asiaa.sinica.edu.tw

AND

Sun Kwok
Department of Physics, Hong Kong University, Pokfulam Road, Hong Kong, China; sunkwok@hku.hk

Received 2007 June 13; accepted 2007 October 10

ABSTRACT

We present interferometric observations of $^{12}$CO and $^{13}$CO $J = 2–1$ emission from the butterfly-shaped, young planetary nebula NGC 6302. The high angular resolution and high sensitivity achieved in our observations allow us to resolve the nebula into two distinct kinematic components: (1) a massive expanding torus seen almost edge-on and oriented in the north-south direction (roughly perpendicular to the optical nebula axis), which exhibits very complex and fragmented structure; and (2) high-velocity molecular knots moving at more than 20 km s$^{-1}$ and located in the optical bipolar lobes. These knots show a linear position-velocity gradient (Hubble-like flow), which is characteristic of fast molecular outflow in young planetary nebulae. From the low but variable $^{12}$CO/$^{13}$CO $J = 2–1$ line intensity ratio, we conclude that the $^{12}$CO $J = 2–1$ emission is optically thick over much of the nebula. Using the optically thinner line $^{13}$CO $J = 2–1$, we estimate a total molecular gas mass of $\sim 0.1 M_\odot$, comparable to the ionized gas mass; the total gas mass of the NGC 6302 nebula, including the massive ionized gas from the photon dominated region, is found to be $\sim 0.5 M_\odot$. From radiative transfer modeling, we infer that the torus is seen at an inclination angle of 75$^\circ$ with respect to the plane of the sky, and is expanding at a velocity of 15 km s$^{-1}$. Comparison with recent observations of molecular gas in NGC 6302 is also discussed.

Subject headings: circumstellar matter — planetary nebulae: individual (NGC 6302)

1. INTRODUCTION

Low- and intermediate-mass stars ($1 M_\odot \leq M_* \leq 8 M_\odot$) evolve through the asymptotic giant branch (AGB) phase, which is characterized by copious mass loss in the form of a slow dusty wind, before emerging as planetary nebulae (PNe). The mass-loss process is commonly assumed to be isotropic, and to result in the formation of a spherically symmetric envelope around the central AGB star. However, a significant fraction of the circumstellar envelope around post-AGB stars and PNe possess bipolar and even multipolar morphology. The mechanisms responsible for such a departure from spherical symmetry are still unknown (e.g., Balick & Frank 2002). The interaction between collimated fast outflows and the surrounding envelope or the influence of a binary companion are often cited as possible shaping mechanisms. Large expanding or rotating disks/tori have frequently been inferred to exist in bipolar nebulae such as the Egg Nebula (Sahai et al. 1998) and the Red Rectangle (Bujarrabal et al. 2005). These disks or tori might confine and channel the wind from the central star into bipolar directions. If the disks/tori are dense enough, the strong interaction (i.e., the oblique shock) between the wind and the disks/tori could focus and collimate the outflow (Frank et al. 1996). Thus, more detailed studies of the structure and kinematics of such a disk/torus could provide better understanding of the formation of the nebula.

NGC 6302 is a young planetary nebula and belongs to the class of the highest excitation PNe (Pottasch et al. 1996). From the presence of numerous emission lines from highly ionized species, Pottasch et al. (1996) concluded that the central star is a white dwarf or approaching a white dwarf, and that its excitation temperature is very high, $\sim 380,000$ K. In optical images, NGC 6302 appears as a butterfly-shaped nebula with two huge bipolar lobes separated by a dark equatorial lane (Matsuura et al. 2005), which is presumably the location of a massive disk or torus. An expanding H$\alpha$ region is detected at the center of the nebula in the radio continuum (Gómez et al. 1989). The presence of a massive molecular envelope is known through the detection of strong CO rotational lines in NGC 6302 (Huggins et al. 1996, Hasegawa & Kwok 2003). The CO lines have very peculiar and complex shapes, with a double-peaked profile and high-velocity wings, extending up to $\sim 40$ km s$^{-1}$ from the systemic velocity. Such a line shape suggests that the molecular envelope is likely nonspherical and could contain a fast molecular outflow, similar to fast bipolar outflows observed in some protoplanetary nebulae and young planetary nebulae.

The detailed observations of Matsuura et al. (2005) with the Very Large Telescope (VLT) and the Hubble Space Telescope (HST) show the presence of a large warped disk oriented perpendicular to the bipolar lobes, seen prominently in the optical images. The
disk is massive and has a large extinction. Strong emission from crystalline silicates together with polycyclic aromatic hydrocarbon (PAH) bands have also been detected in NGC 6302 (Kemper et al. 2002). We note that, interestingly, OH maser emission, which is usually associated with oxygen-rich circumstellar envelopes, has also been detected in NGC 6302 (Payne et al. 1988). Thus, NGC 6302 is chemically peculiar, containing a mixture of carbon-rich and oxygen-rich material.

The distance to NGC 6302 is uncertain, with estimates ranging from 0.15 to 2.4 kpc. From the expansion proper motion of the central H II region, Gómez et al. (1989) estimate a distance of 2.2 ± 1.1 kpc. However, Matsuura et al. (2005) note that a distance much larger than 1 kpc would lead to very high luminosity and shell mass, which would exceed the highest luminosity of post-AGB stars and PNe predicted by stellar evolution models with even the highest core mass. More recently, Meaburn et al. (2005) directly detected the proper motion of the prominent optical lobes in the NGC 6302 nebula, and inferred a distance of 1 kpc. We will adopt a distance of 1 kpc for NGC 6302, similar to Matsuura et al. (2005) and Kemper et al. (2002).

In this paper, we present high angular resolution observations of the J = 2−1 line of 12CO and its isotope 13CO, in order to study the spatial distribution and kinematics of the molecular gas in the envelope of NGC 6302, especially the massive equatorial disk and the gas moving at higher velocities.

After the submission of our paper for publication, we learned of a recent paper by Peretto et al. (2007), which also presents maps of molecular gas in NGC 6302. Although the spatial distribution of CO emission is similar in both papers, our higher sensitivity (by a factor of 2) observations allow us to produce maps for more velocity channels and to better understand the spatial kinematics of the circumstellar envelope. We are able, in particular, to image and study the fast molecular outflows, which are barely detected in the lower sensitivity data of Peretto et al. (2007). Where appropriate, we will compare our results with those obtained by Peretto et al. (2007).

2. OBSERVATIONS

We used the Submillimeter Array (SMA), which consists of eight antennas of 6 m in diameter, to observe NGC 6302. The observation was carried out during the night of 2006 May 1 under excellent weather conditions. The zenith opacity of the atmosphere at 230 GHz was around 0.1, resulting in antenna temperatures (single-sideband) in the range of 300−400 K. In our observation, the SMA provided projected baselines in the range between 6 and 78 m. The total on-source integration time of our observation was about 4 hr. The coordinates of NGC 6302 taken from Kerber et al. (2003), R.A. (J2000.0) = 17h13m44.21s, decl. (J2000.0) = −37°06'15.9", were used as phase center in our observation. The nearby and relatively strong quasar 1626−298, together with a weaker quasar 1802−396, which is located closer than 1626−298 and to the south of our target source, were monitored frequently to correct for gain variation due to atmospheric fluctuations. Saturn and the Jovian moon Ganymede were used as bandpass and flux calibrators, respectively. The large bandwidth (~2 GHz) of the SMA correlator allows us to cover...
simultaneously the $^{12}$CO $J = 2-1$ line in the upper sideband and the $^{13}$CO $J = 2-1$ and $^{18}$O$^J = 2-1$ lines in the lower sideband. In our observation, the SMA correlator was set up in normal mode, providing a frequency resolution of 0.825 MHz or $\sim$1 km s$^{-1}$ in velocity resolution. The visibilities were edited and calibrated using the MIR/IDL package, which was developed specifically for SMA data reduction. The calibrated data were then exported for further processing with the MIRIAD package. Continuum emission was subtracted from the visibility data in the $u$-$v$ plane using the task uvlin of the MIRIAD package. The resulting line data were then Fourier-transformed to form dirty images. Deconvolution of the dirty images was done using the task clean. The resulting synthesized beam for $^{12}$CO $J = 2-1$ channel maps is $5.95'' \times 2.7''$ at P.A. = $-3.7^\circ$. The corresponding conversion factor between flux and brightness temperature is 1.4 K Jy$^{-1}$. The rms noise level for each channel of 1 km s$^{-1}$ is 60 mJy beam$^{-1}$. $^{13}$CO $J = 2-1$ emission has also been detected and imaged. For the sake of clarity, the channel maps of $^{12}$CO and $^{13}$CO $J = 2-1$ are presented in Figures 1 and 2 with a lower velocity resolution of 2 km s$^{-1}$. The $^{18}$O$^J = 2-1$ line is found to be very faint, and the emission could be mapped only around $-40$ km s$^{-1}$ LSR. Therefore, we will not discuss this line any further in this paper.

We have searched the James Clerk Maxwell Telescope (JCMT) archives at the Canadian Astronomy Data Centre (CADC) for $^{12}$CO $J = 2-1$ observations of NGC 6302. We found usable observations, which were carried out on 1999 August 26. To convert the scale of the archival data in the antenna temperature $T_A^*$, which has been corrected for the atmospheric absorption, to main beam temperature $T_{mb}$, we used the relation $T_{mb} = T_A^* / \eta_{mb}$, assuming a value of 0.69 for the main beam efficiency $\eta_{mb}$ similar to Hasegawa & Kwok (2003). After convolving the SMA $^{12}$CO $J = 2-1$ channel maps to the same angular resolution of 20$''$ as the JCMT, we find a peak brightness temperature of $\sim$2 K for the $^{12}$CO $J = 2-1$ emission. By comparison with the peak main beam temperature of $\sim$2.3 K for the JCMT spectrum of the same line, we estimate that our SMA observation recovers more than 80% of the $^{12}$CO $J = 2-1$ flux from NGC 6302.

We also form the continuum image by averaging line-free channels in the upper sideband. The rms noise level of the continuum image is 7.5 mJy beam$^{-1}$. The synthesized beam is $5.6'' \times 2.3''$ at P.A. = $-2.5^\circ$.

3. RESULTS

3.1. 1.3 mm Continuum Emission

We detected and resolved the continuum source at the center of NGC 6302. The map of the continuum emission is shown in Figure 1 (bottom right). The continuum emission is extended and elongated in the north-south direction. The position of the continuum peak (with a flux of $\sim$0.5 Jy beam$^{-1}$) is R.A.(J2000.0) = 17$^h$13$^m$44.496$^s$, decl.(J2000.0) = $-37^\circ$06'11.936''. and coincides with the location of the free-free emission from ionized gas mapped previously by Gómez et al. (1989) at 6 cm. The deconvolved size at half maximum of the continuum emission is estimated to be $7.0'' \times 4.8''$ at P.A. = $-6^\circ$, comparable to the size of the H$\alpha$ region mapped by Gómez et al. (1989). The total flux...
detected by the SMA is about 1.87 Jy. The total continuum flux detected by Hoare et al. (1992) at a similar wavelength of 1.1 mm using the single-dish JCMT is ∼1.7 Jy, which is in good agreement with our measurement. From fitting of the SED in the radio and FIR, Hoare et al. (1992) suggested that there is no significant contribution from cool dust to the millimeter and centimeter continuum emission, but that intensities in that wavelength range are likely to be due to the free-free emission from ionized gas. Therefore, it is very likely that the continuum emission we detect with the SMA originates mainly from the central H II region.

### 3.2. The Molecular Torus

In Figure 1, we show the channel maps of the $^{12}$CO $J = 2-1$ line superposed on the Hα image of NGC 6302 (Matsura et al. 2005). Figure 2 shows the maps of the $^{13}$CO $J = 2-1$ line. The integrated line profiles of both transitions are given in Figure 3.

The $^{12}$CO $J = 2-1$ emission clearly shows very complex spatial distribution and several distinct kinematic components. At the systemic velocity, $V_{LSR} = -33$ km s$^{-1}$, there is a clear central minimum in brightness distribution. The brightest part of the emission appears in channels around the systemic velocity, with $V_{LSR}$ from $-48$ to $-20$ km s$^{-1}$, and located spatially close to the 230 GHz continuum emission peak. The $^{12}$CO-emitting region is strongly elongated in the north-south direction, similar to the morphology of the continuum emission. The deconvolved size of $^{12}$CO emission at velocity $V_{LSR} = -38$ km s$^{-1}$ is $10.8'' \times 2.1''$. At velocities from $-36$ to $-32$ km s$^{-1}$, the emission breaks into two separate clumps in the north-south direction, of which the northern clump dominates in intensity. Toward even more redshifted velocities ranging from $-30$ to $-18$ km s$^{-1}$, the $^{12}$CO $J = 2-1$ emission still maintains the overall north-south elongated shape, but displays noticeable positional shift of the emission centroid toward the center of the nebula at higher redshift velocities. In the channel maps with velocities in the range $-48$ km s$^{-1}$ to $-33$ km s$^{-1}$, i.e., blueshifted from the systemic velocity, the $^{12}$CO emission appears more complex and consists of three extended clumps. Although these clumps are roughly aligned in the north-south direction, the distribution of emission is irregular in comparison to that seen at redshifted velocities. In the position-velocity diagram along the cut in the north-south direction (see Fig. 4, bottom), a clear ringlike structure can be seen between velocities $V_{LSR} \sim -50$ and $-18$ km s$^{-1}$. Our SMA maps of the $^{12}$CO emission then indicate that most of the molecular gas essentially occupies an expanding ring perpendicular to the nebula axis. We will then assume that this ring corresponds to an equatorial torus expanding at low velocity, $\sim 15$ km s$^{-1}$, which is similar to the circumstellar velocity in AGB stars. This torus would contain most of the molecular gas.

### 3.3. Fast Outflow

In our SMA observations, we also detect $^{12}$CO $J = 2-1$ emission at more extreme velocities. At both redshifted (from about $-18$ to $-10$ km s$^{-1}$) and blueshifted velocities (from about $-75$ to $-48$ km s$^{-1}$), the emission appears as discrete knots (see Fig. 1). The $^{12}$CO emission at blueshifted velocities between $-75$ and $-64$ km s$^{-1}$ was not detected in the previous work of Peretto et al. (2007) due to lower sensitivity (see their Fig. 3 and Table 3). We note that the molecular knots detected in our channel maps have a more rounded shape, which is very different from the elongated appearance of the emission from the expanding torus. Such a difference is clearly seen in velocity channels at $-20$ km s$^{-1}$, where the emission mainly comes from the expanding torus, and at $-16$ km s$^{-1}$ or blueshifted velocities around $-64$ km s$^{-1}$, where discrete knots are located. The properties of these knots can be analyzed in more detail by examining the position-velocity diagrams. In the position-velocity diagrams of cuts along the east-west direction, all the knots in the blueshifted high-velocity part of the envelope (denoted in Fig. 4 as A, B, and C, respectively) clearly show a linear velocity gradient or Hubble-type flow. We note that all these components are located within the optical bipolar lobes of the nebula, but offset from the major nebula axis (in the east-west direction) and to the south of the central region marked by the continuum emission. Component A, which shows the highest outflow velocity, is very compact and covers a small range in velocity. Such a structure, sometimes termed a molecular
bullet, has been seen in other young PNe such as CRL 618 (Ueta et al. 2001) and BD +30 3639 (Bachiller et al. 2000). The Hubble-type flow is often seen in young PNe such as CRL 618 (Sánchez-Contreras et al. 2004). Such a flow could result from the interaction between fast collimated outflows from the central star and the ambient gas in the slowly expanding envelope.

3.4. Spatial Distribution of \( ^{13}\text{CO} J = 2–1 \) Emission

Comparison between the channel maps of the \( ^{13}\text{CO} J = 2–1 \) emission (Fig. 2) and that of the \( ^{12}\text{CO} J = 2–1 \) emission (Fig. 1) shows that the spatial distribution of \( ^{12}\text{CO} \) and \( ^{13}\text{CO} \) is very similar. However, as we will discuss in § 4, the \( ^{12}\text{CO}/^{13}\text{CO} \) line intensity ratio presents strong spatial variations within the nebula.

4. THE MOLECULAR GAS IN NGC 6302

4.1. Temperature

The kinetic temperature \( (T_k) \) of the molecular gas detected in our maps can be estimated from the brightness temperature distribution \( (T_{mb}) \), particularly for the \( J = 2–1 \) transition. We can see that values as high as \( T_{mb} \sim 30 \) K are found in the brightest regions. In many channels, we find brightness values larger than \( 20 \) K; \( T_{mb} \) is approximately equal to \( T_k = T_{bg} \) (where \( T_{bg} \) is the cosmic background temperature, \( 3 \) K) in the limit of thermalized level populations, high opacities, and resolved spatial distribution. Otherwise, \( T_k \) must be larger than \( T_{mb} + T_{bg} \), except for very peculiar excitation states. The last condition (resolved spatial structures) is probably not completely fulfilled, since the observed distribution extent is often comparable to the beam size, mainly in the direction of the nebula axis (§ 3). Nevertheless, the deconvolved extent of the emitting region is not found to be smaller than the telescope resolution and, unless small-scale clumpiness is present, a high dilution is not expected. As we will show in §§ 4.2 and 5, the \( ^{12}\text{CO} J = 2–1 \) line is likely optically thick, and the gas densities are high enough to thermalize the CO low-\( J \) lines. Therefore, we conclude that the kinetic temperature in the molecular gas in NGC 6302 is relatively high, typically \( \sim 30 \) K or slightly higher.

4.2. CO Line Opacity

In NGC 6302, the \( ^{12}\text{CO} J = 2–1 \) transition is very likely optically thick. This is supported by two observational results: the relatively intense \( J = 1–0 \) line and the relatively high and variable \( ^{12}\text{CO}/^{13}\text{CO} J = 2–1 \) intensity ratio.

The \( ^{12}\text{CO} J = 1–0 \) transition was observed by Zuckerman & Dyck (1986). Converting to the same beam size as JCMT, the \( ^{12}\text{CO} J = 1–0 \) spectrum has a main beam temperature of \( \sim 1.7 \) K, which is comparable in strength to the JCMT spectrum (\( \sim 2.3 \) K) or our JCMT-scale spectrum (see § 2) of the \( ^{12}\text{CO} J = 2–1 \) line. As a result, the intensity ratio of \( ^{12}\text{CO} J = 2–1 \) and \( J = 1–0 \) is close to 1. When these lines are optically thin and for the high excitation temperatures deduced in the previous subsection, such an intensity ratio should approach 4 (the ratio of the squares of the upper level \( J \)-value for each transition), which is the opacity ratio in the high-excitation limit. The measured line ratio of 1 is clearly incompatible with optically thin emission. We conclude that both the \( ^{12}\text{CO} J = 1–0 \) and \( J = 2–1 \) lines are optically thick.

Although the \( ^{12}\text{CO}/^{13}\text{CO} J = 2–1 \) overall brightness distributions are similar, the intensity ratio significantly varies for the different parts of the nebula. This can be readily seen from the total spectra in main-beam brightness units. Values as low as 2 are reached in the most intense features (about \( 40 \) to \( 45 \) km s\(^{-1} \) LSR). In weaker features, particularly in the wing at \( -55 \) to \( -60 \) km s\(^{-1} \), the ratio reaches values as high as 5. Ratios of \( \sim 3 \) are found in particular in the relative maxima at \( -50 \) km s\(^{-1} \) and at \( -20 \) to \( -25 \) km s\(^{-1} \). Such a trend in the line ratio, i.e., one that depends on the intensity, is expected if the most intense clumps have the highest opacities. These values of the \( ^{12}\text{CO}/^{13}\text{CO} \) intensity ratio are, on the other hand, too low to represent the abundance ratio, as would be the case if both lines were optically thin. For instance, in NGC 7027, a similar high-excitation PN with a massive molecular component, the \( ^{12}\text{CO}/^{13}\text{CO} \) line intensity ratios are \( \sim 30 \) (Bujarrabal et al. 2001), which is closer to the \( ^{12}\text{CO}/^{13}\text{CO} \) abundance ratios often found in evolved-star nebulae.

4.3. Mass of the Relevant Components

We have calculated the mass of the molecular gas emitting at various velocity ranges using the method described by Bujarrabal et al. (2001). We have used the \( ^{13}\text{CO} J = 2–1 \) line, assuming optically thin emission, a typical temperature of \( 30 \) K, and a \( ^{13}\text{CO} \) relative abundance of \( 2 \times 10^{-5} \) with respect to H\(_2\). We assume a distance \( D = 1 \) kpc (§ 1). From the discussion in §§ 4.1 and 4.2, we are confident that the method is reliable and will lead to results comparable to those often obtained from CO data in PNe.

We note that the value of the mass deduced from this formulation depends on the assumed rotational temperature. The minimum value is obtained for temperatures of about \( 15 \) K, but for our temperature of \( 30 \) K the mass value is also low, \( \sim 15\% \) over that minimum. Our mass values may then be lower limits, if the temperature is higher than deduced above.

As mentioned in § 3, we have tentatively divided the observed lines into four velocity ranges. The line core extends from \( -48 \) to \( -18 \) km s\(^{-1} \), probably representing an unaccelerated (or slightly accelerated) remnant of the AGB circumstellar envelope, with a systemic velocity of \( \sim 33 \) km s\(^{-1} \) and a moderate expansion velocity of \( \sim 15 \) km s\(^{-1} \). The line wings, for velocities outside these limits, would come from regions significantly disturbed and accelerated during the post-AGB evolution of NGC 6302. The mass values calculated for these regions are summarized in Table 1. The total molecular mass from our \( ^{13}\text{CO} J = 2–1 \) data is \( 0.086 \) \( M_\odot \).

The total mass derived from our data of \( ^{12}\text{CO} J = 2–1 \) is slightly smaller than the value of \( 0.022 \) \( M_\odot \), obtained by Huggins et al. (1996) from this line, after correcting for the difference in the assumed distance; the discrepancy is due to the different temperature (\( \sim 77 \) K) assumed by Huggins et al.

The molecular mass that we have derived in NGC 6302 is comparable to that of the ionized gas mass. Gómez et al. (1989) estimated a mass of \( 0.02 \) \( M_\odot \), for the region detected in radio continuum (about \( 10'' \) wide). Using the observations of emission lines from several highly ionized species, Pottasch & Beintema

| Component | Velocity Range (LSR) (km s\(^{-1} \)) | Mass \((M_\odot)\) |
|-----------|----------------------------------------|-----------------|
| Dense ring: approaching hemisphere | -48 to -33 | 0.046 |
| Dense ring: receding hemisphere | -33 to -18 | 0.021 |
| High-velocity flow: approaching knots | -75 to -48 | 0.016 |
| High-velocity flow: receding knots | -18 to -10 | 0.002 |

Table 1: Different Molecular Components of NGC 6302 and Their Masses Derived from our \(^{13}\text{CO} \) Data.
Peretto et al. estimated a total molecular mass of about 1.4 M☉ compared with those obtained very recently by Peretto et al. (2007). The values derived above for the total gas mass are compatible with the total mass deduced from dust emission at 25 μm by Gómez et al. (1989) of 4 × 10⁻³ M☉, if we assume a reasonable gas/dust mass ratio of ~100. However, the gas mass values are too low compared to the dust mass estimate by Matsuura et al. (2005) of 0.03 M☉ obtained by fitting the nebula SED using a spherically symmetric model. This discrepancy might be due to the uncertainty in the SED fitting, the adopted dust opacity, or the contribution of dust grains with different sizes.

A major discrepancy exists only when our results are compared with those obtained very recently by Peretto et al. (2007). Peretto et al. estimated a total molecular mass of about 1.4 M☉, fitting their CO observations by means of the online CO excitation code RADEX (Schöier et al. 2005). This large discrepancy is probably due to the low CO relative abundance assumed in that paper and the geometry-dependent conversion of the column density provided by RADEX into total molecular gas mass.

We will see an independent derivation of the mass of the molecule-rich nebula in §5, where a value of about 0.1 M☉ is obtained from a sophisticated modeling of the main (probably toroidal) component, including a large velocity gradient non-LTE treatment of the excitation. Therefore, the total mass values from both methods are very similar, and as we have seen, are compatible with other mass estimates.

5. GEOMETRY AND KINEMATICS OF THE MOLECULAR TORUS

In order to better understand the structure of the torus and the excitation of the CO molecules, we have constructed a simple model, using a previously developed radiative transfer code (Chiu et al. 2006). Because the torus is very complex, we do not attempt to fit the observations, but simply try to capture its overall geometry and spatial kinematics with our model.

The torus is assumed to be axisymmetric and radially expanding at a constant velocity of 15 km s⁻¹. The thickness of the torus is also assumed to be constant with radius. In our code, the torus is then projected onto a regular three-dimensional grid. The physical conditions of the molecular gas, i.e., temperature and gas density, at each grid point are calculated from the specified mass-loss rate and temperature profile. We take into account 11 rotational levels, which are necessary for the calculation of the line opacity and source function at each grid point, are determined by solving the statistical equilibrium equations within the framework of the large velocity gradient formalism. The collision rates between CO and molecular hydrogen are taken from Flower & Launay (1985) and calculated for different temperatures using the prescription of de Jong et al. (1975). CO intensity is calculated for each line of sight by integrating the standard radiative transfer equation. The local line profile, which is needed to integrate the radiative transfer equation, is determined through the turbulence velocity of the molecular gas. We assume a turbulence velocity of 1 km s⁻¹ in the torus. The calculated intensity is then used to form a model image of the CO emission from the torus. To compare with our SMA observation, we convolve the model image using a Gaussian beam of the same size as the synthesized beam. A sketch of our model for the torus is shown in Figure 5, and the parameters used in our model are summarized in Table 2.

Using a constant gas temperature of 30 K in the torus and an abundance [¹³CO/H₂] of 2 × 10⁻⁵, we find that we can reproduce the strength of the ¹³CO line observed with SMA using a mass-loss rate of 1.5 × 10⁻⁴ M☉ yr⁻¹. We present the predicted channel maps of the ¹³CO J = 2−1 emission in Figure 6, and the total intensity of this line in Figure 7. Because of the high mass-loss rate, the gas density in the torus is substantial, about 2 × 10⁴ cm⁻³ on average. At this high density, the J = 2−1 transition is thermalized throughout most of the torus.

As presented in Figure 7, the ¹³CO J = 2−1 line profile calculated by our model is strongly double-peaked, similar to the observed ¹³CO J = 2−1 line shape shown in Figure 3. We also find that the maximum optical depth in the tangential direction is about 0.3, confirming that the ¹³CO J = 2−1 line is really optically thin. The total molecular gas mass derived from our model is ~0.087 M☉. This model estimate agrees closely with the estimate of molecular gas mass in the torus presented in § 4.3.

We infer from our model that the torus is seen at an inclination angle of 75° with respect to the plane of the sky, i.e., very close to...
edge-on. A comparison between the predicted channel maps of $^{13}$CO $J = 2\rightarrow 1$ emission from the inclined torus and our SMA data shows that the model reproduces the observed spatial kinematics between $-48$ and $-18$ km s$^{-1}$. The centroid of the emission clearly exhibits an east-west positional gradient between the receding half of the torus (with a redshifted velocity from $-33$ to $-18$ km s$^{-1}$) and the approaching half of the torus (with a blueshifted velocity between $-48$ and $-33$ km s$^{-1}$). Because the bipolar lobes are expected to be oriented perpendicular to the expanding torus, we deduce that the eastern lobe is closer to the observer, while the western lobe is pointed away from the observer. In the optical image of the NGC 6302 nebula (Matsuura et al. 2005), the eastern lobe is brighter, suggesting that it is closer to the observer, following the common expectation of elevated extinction/obscuration toward the western lobe due to the presence of the intervening dust in the torus. Indeed, the extinction inferred from the measurement of the H$\alpha$/H$\beta$ ratio by Bohigas (1994) is larger in the western lobe, implying that the western lobe is located in the far side of the nebula. In addition, long-slit spectra of the H$\alpha$ emission line by Meaburn et al. (2005) show that the prominent northwest lobe is inclined by $\sim 13^\circ$ with respect to the plane of the sky and away from the observer. As a result, the inclination angle of the torus and the orientation of the bipolar lobes as inferred from modeling the $^{13}$CO $J = 2\rightarrow 1$ emission are entirely consistent with previous optical observations.

The three-dimensional and very complex structure of the molecular torus in NGC 6302 becomes evident by a comparison between our simple axisymmetric model and the SMA data. In the receding half of the torus, the southern part of the emission is clearly missing between velocities $-32$ and $-24$ km s$^{-1}$. The approaching part of the torus has a very irregular and disturbed morphology, consisting of several clumps (see Figs. 1 and 2). These clumps form a structure resembling the shape of a warped disk. Extinction by dust associated with the dense molecular gas...
in this approaching part of the torus would then produce a dark warped disk as seen in the optical images of Matsuura et al. (2005). Clearly, the molecular torus exhibits a very complex and fragmental structure. A more sophisticated three-dimensional model would be needed to disentangle the real structure of the torus.

The complex structure of the torus is also traced by OH maser emission at 1612 MHz. High angular resolution observation of Payne et al. (1988) shows strong maser emission coincident with the optical dark lane. The maser clump has a positional gradient in the north-south direction between $-54$ and $-35$ km s$^{-1}$. Comparison with our SMA data in Figures 1 and 2 suggests that the OH maser emission spatially coincides with the peak of the CO emission from the torus and the CO emission component at higher blueshifted velocities between $-56$ and $-52$ km s$^{-1}$. The north-south positional gradient seen in the OH maser emission can also be clearly identified in the $^{12}$CO and $^{13}$CO $J = 2$–1 channel maps (see Figs. 2 and 3) and the position-velocity diagram along the north-south direction (see Fig. 4).

The optical extinction of the dark lane deduced from the average density (about $2 \times 10^4$ cm$^{-3}$) and the size of the torus (about $1.5 \times 10^{17}$ cm) is $\sim$2 mag for a standard $A_V$ column density conversion. This estimate is compatible with the extinction of the equatorial dark lane measured in the visible, which ranges between 3 and 6 mag (Matsuura et al. 2005). This agreement supports our previous conclusion that the properties of molecular gas and dust components of the dark disk are fully compatible, while the contribution of the very extended dust regions to the total IR emission of the source seems poorly understood.

The large inner radius of the torus as shown by our observations and modeling results suggests that the torus is unlikely to play the role of confining and collimating the outflow from the central star in the bipolar direction. The high-velocity molecular knots along the optical bipolar lobes identified in our observations are probably the result of some brief but explosive and highly anisotropic episodes of mass ejection from the central star.

The torus might be formed by the interaction with a binary companion, which acts to focus the slow and dusty AGB wind from the central star toward the orbital plane. Hydrodynamic simulations by Mastrodemos & Morris (1999) show that a wide binary companion could redirect and concentrate the slow wind to form a radically expanding disklike structure. The complex morphology of the torus as traced by the CO $J = 2$–1 emission is probably the result of subsequent interaction with the high-velocity outflow.

6. CONCLUSIONS

We have imaged at high sensitivity and high angular resolution the envelope around the young planetary nebula NGC 6302 in $^{12}$CO $J = 2$–1 and $^{13}$CO $J = 2$–1 lines. Continuum at 1.3 mm wavelength is also imaged, and seems to come from the inner HII region.

We find that the very complex molecule-rich nebula is well resolved and can be separated into two components: a massive low-velocity torus seen nearly edge-on and high-velocity knots. The image of the dense torus is very accurately coincident with the dark lane that separates the conspicuous two lobes in the optical image of NGC 6302. The fast knots are located within the optical lobes and show a linear velocity gradient characteristic of fast molecular gas in young PNe.

We find that the $^{12}$CO/$^{13}$CO $J = 2$–1 brightness ratio is low and varies between 2 and 5, decreasing with increasing line intensity. We conclude that the $^{13}$CO $J = 2$–1 emission is optically thick over much of the nebula, but that the $^{12}$CO $J = 2$–1 is optically thin. The most velocity-integrated lines of sight. Using our observations of this line, we estimate masses for the different components, yielding a total molecular gas mass of $\sim$0.1 $M_{\odot}$. We discuss the value of the total mass of the NGC 6302 nebula, including the ionized gas, whose mass is comparable to that of the molecular gas, and the massive PDR, which is probably the dominant component. We find a total mass of $\sim$0.5 $M_{\odot}$, but we recall that the very uncertain contribution from the very outer layers could be significant.

Using a radiative transfer model, we infer that the torus is seen at an inclination angle of 75° with respect to the plane of the sky and expanding at a velocity of 15 km s$^{-1}$. The mass-loss rate is found to be very high, $\sim$1.5 $\times$ 10$^{-4}$ $M_{\odot}$ yr$^{-1}$, resulting in a dense (average gas density $\sim$2 $\times$ 10$^{4}$ cm$^{-3}$) and massive torus.

We are grateful to the SMA staff for carrying out the observations. We thank the anonymous referee for constructive criticisms that helped to improve our paper significantly. V. B. acknowledges support from the Spanish Ministry of Education and Science, projects AYA2003-7584 and ESP2003-04957. Help from Sebastien Muller is gratefully acknowledged. This research has made use of NASA's Astrophysics Data System Bibliographic Services and the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Bachiller, R., Forveille, T., Huggins, P. J., Cox, P., & Maillard, J. P. 2000, A&A, 353, L5
Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Bohigas, J. 1994, A&A, 288, 617
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Neri, R. 2005, A&A, 441, 1031
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sánchez-Conteras, C. 2001, A&A, 377, 868
Castro-Carrizo, A., Bujarrabal, V., Fong, D., Meixner, M., Tielens, A. G. G. M., Latter, W. B., Barlow, M. J. 2001, A&A, 367, 674
Chiu, P.-J., Hoang, C.-T., Dinh-V-Trung, Lim, J., Kwok, S., Hirano, N., & Muthu, C. 2006, ApJ, 645, 605
de Jong, T., Chu, S.-I., & Dalgarno, A. 1975, ApJ, 199, 69
Flower, D. R., & Launay, J. M. 1985, MNRAS, 214, 271
Frank, A., Balick, B., & Livio, M. 1996, ApJ, 471, L53
Gómez, Y., Moran, J. M., Rodriguez, L. F., & Garay, G. 1989, ApJ, 345, 862
Hasegawa, T. I., & Kwok, S. 2003, ApJ, 585, 475
Hoare, M. G., Roche, P. F., & Cleeg, R. E. S. 1992, MNRAS, 258, 257
Huggins, P. J., Bachiller, R., Cox, P., & Forveille, T. 1996, A&A, 315, 284
Kemper, F., Molster, F. J., Jäger, C., & Waters, L. B. F. M. 2002, A&A, 394, 679
Kerber, F., Mignani, R. P., Guglielmetti, F., & Wicenec, A. 2003, A&A, 408, 1029
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Matsuura, M., Zijlstra, A. A., Molster, F. J., Waters, L. B. F. M., Nomura, H., Sahai, R., & Hoare, M. G. 2005, MNRAS, 359, 383
Meaburn, J., López, J. A., Steffen, W., Graham, M. F., & Holloway, A. J. 2005, AJ, 130, 2303
Payne, H. E., Phillips, J. A., & Terzian, Y. 1988, ApJ, 326, 368
Peretto, N., Fuller, A., Zijlstra, A. A., & Patel, N. A. 2007, A&A, 473, 207
Pottasch, S. R., & Beintema, D. 1999, A&A, 347, 975
Pottasch, S. R., Beintema, D., Dominguez-Rodriguez, F. J., Schaeidi, S., Valentijn, E., & Vandenbussche, B. 1996, A&A, 315, L261
Sahai, R., et al. 1998, ApJ, 492, L163
Sánchez-Conteras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2004, ApJ, 617, 1142
Schoier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
Ueta, T., Fong, D., & Meixner, M. 2001, ApJ, 557, L117
Zuckerman, B., & Dyck, H. M. 1986, ApJ, 311, 345