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THE DISTANCE TO NGC 6302

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ABSTRACT

Using VLA data, we applied new radio techniques to derive the distance to the bright planetary nebula NGC 6302. Previous estimates of this distance range from 0.15 to 2.4 kpc. The first technique relies on measuring the electron pressure broadening of radio recombination lines to obtain an average value of the electron density. Combining this information with a geometric model for the nebula and its radio flux density, we obtain a distance of 2.2 ± 1.1 kpc. The second technique involves a direct measurement of the angular expansion rate of the nebula using radio interferometric data obtained over a period of a few years. We obtained a lower limit of 0.8 ± 0.3 kpc for the distance. Adopting a distance to the nebula of 2.2 kpc, we derive the following parameters: an *IRAS* luminosity of $1.3 \times 10^4\ L_\odot$, and ionized nebular mass of $\sim 0.2\ M_\odot$, a neutral hydrogen mass of $\sim 0.05\ M_\odot$, and from CO observations obtained at SEST, a molecular hydrogen mass of $\sim 0.5\ M_\odot$. The total mass of the planetary nebula may be as much as $0.75\ M_\odot$.

Subject headings: interferometry — nebulae: individual (NGC 6302) — nebulae: planetary — radio sources: lines

I. INTRODUCTION

NGC 6302 (PK 349+1°.1) is one of the brightest planetary nebulae known. It is projected close to the Galactic plane, and the central star has not been detected yet. In the optical region, NGC 6302 exhibits a bipolar structure with lobes extending approximately in the east-west direction. This nebula is classified as type I (Peimbert 1978; Peimbert and Torres-Peimbert 1983), meaning that it is overabundant in helium and nitrogen, which is indicative of a massive progenitor.

Most of the radio emission in NGC 6302 arises in a compact central source of ~10″ (Terzian, Balick, and Bignell 1974), while the size of the optical nebula is about 1′. Rodríguez and Moran (1982) reported H I associated with NGC 6302. They found a blueshifted absorption feature at a velocity of -40 km s^{-1}, which probably is caused by gas in the outer parts of a dense toroid whose inner ionized wall produces the background free-free radiation (Rodríguez *et al.* 1985). A total H I mass of $\sim 0.06\ M_\odot$, a luminosity of $\sim 10^4\ L_\odot$, and a very high effective temperature of $\sim 2 \times 10^5$ K for the central star are estimated by Rodríguez *et al.* (1985).

NGC 6302 has an extraordinarily rich spectrum. There is evidence for emission in the $S(1)\ v = 1 \rightarrow 0$ vibrational line of the H_2 molecule (Phillips, Reay, and White 1983). The CO $J = 1 \rightarrow 0$ line (Zuckerman and Dyck 1986), has a broad, flat profile that resembles a circumstellar line rather than an interstellar line. Payne, Phillips and Terzian (1988) recently reported OH maser emission at 1612 MHz associated with the nebula. Zuckerman and Lo (1986) searched unsuccessfully for H_2O maser emission. There is evidence of high-velocity (> 300 km s^{-1}) flows detected in Ne V lines and interpreted as an energetic stellar wind (Elliot and Meaburn 1977; Meaburn and Walsh 1980*a*). Its near-IR, optical, and UV spectra show the presence of a wide range of excitation conditions, with lines such as [S I] 7726 Å (Aller and Czyzak 1978) and [Si VII] 2.48 μm (Ashley and Hyland 1988).

Knowledge of the distance to a planetary nebula is essential to determine its physical properties and Galactic location. In particular, one needs a reliable estimate of the distance to determine the luminosity of the central star and the masses of ionized and neutral gas (Pottasch 1984; Gathier 1987). The determination of accurate distances to planetary nebulae is a difficult problem. There are various methods to calculate these distances (see, e.g., Pottasch 1984), but only a few of them can be applied to NGC 6302. Its Galactic longitude (349°) makes a distance derived from the 21 cm hydrogen absorption unreliable. The central star has not been detected yet, and this precludes the application of the methods of spectroscopic parallax and stellar atmosphere analysis. Nevertheless, there are several estimates of the distance to this nebula. Meaburn and Walsh (1980*a*) interpreted the broad [Ne V] 3426 Å wings they observed as emission from a radiatively ionized stellar wind, and, adjusting the observed intensity to a model for the wind of the central star, they obtained a distance of ≃0.15 kpc. Rodríguez and Moran (1982), using the Shklovsky (1956) method, which assumes a fixed ionized mass for planetary nebulae of $0.16\ M_\odot$, obtained a distance of 2.4 kpc. Using an estimate of electron density derived from optical forbidden lines and a specific geometric model for the nebula, Rodríguez *et al.* (1985) derived a distance to NGC 6302 of 1.7 kpc. Based on the method suggested by Milne (1982) for young, density-bounded planetary nebulae that assumes a constant ionizing photon rate, Altschuler *et al.* (1986) and Schneider *et al.* (1987) estimated the distance as 0.5 kpc.

The discrepancy among the above results shows that there is considerable uncertainty about the value of the distance to NGC 6302. Furthermore, NGC 6302 is clearly not a typical planetary nebula, and it does not seem appropriate to derive a distance under the assumption that the nebula is an average planetary nebula. In this paper we apply to NGC 6302 some relatively new radio techniques for the determination of distances to planetary nebulae. The first technique uses the electron pressure broadening of radio recombination lines to obtain an average value of electron density. Combining this result with a geometric model for the nebula and a measurement of the radio flux density, we can estimate the distance.

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The second technique, developed by Masson (1986), involves a measurement of the angular expansion rate of the nebula from radio interferometric data obtained over a period of a few years. A distance estimate can be obtained based on a kinematic model for the nebula. Both techniques have the advantage that no *a priori* assumptions have to be made about the nebular mass or the luminosity of the central star. We describe our observations and results in § II and present our conclusions in § III.

II. OBSERVATIONS AND RESULTS

a) H110α *Observations*

To our knowledge, the only measurements of radio recombination lines from NGC 6302 are those of the H76α line made by Rodríguez *et al.* (1985) and of the H76α and $\mathrm{He}^+121\alpha$ lines made by Gómez, Rodríguez, and García-Barreto (1987), all of which were obtained with the VLA. The line parameters for the H76α line agree very well, and their average is listed in Table 1. We made observations of the H110α ($\nu = 4874.157$ MHz) line using the Very Large Array of NRAO[4] during 1988 June 9. The VLA was in the C/D configuration, providing an angular resolution of $\sim 10''$ at the southern declination of NGC 6302. The absolute amplitude calibrator was 3C 286, the phase calibrator was 1622-297, and the bandpass calibrator was 3C 273. We observed in the spectral line mode with 64 channels, each of 195 kHz (12.0 $\mathrm{km\ s^{-1}}$) width. After Hanning-weighting, our data had a velocity resolution of 24.0 $\mathrm{km\ s^{-1}}$. A continuum channel contained the central 75% of the total bandwidth of 12.5 MHz. The on-source integration time for NGC 6302 was approximately 2.5 hr. Figure 1 shows the H110α spectrum obtained from the peak values of line maps made with natural weighting. Since the source is nearly unresolved for the natural-weight beam of $\sim 15''$, this spectrum is equivalent to an integrated spectrum over the core of the nebula.

A Gaussian fit to the H110α line gives the parameters that are listed in Table 1. There is also emission near the expected frequency of the He110α line (see Fig. 1). However, the velocity centroid of this feature is blueshifted by ~ 10 $\mathrm{km\ s^{-1}}$ from the expected velocity of the He110α line. We believe that this emission could be due to a blend of He110α emission with 110α emission from carbon or another heavy element. A spectrum with better velocity resolution and signal-to-noise ratio would be required to verify this possibility.

In Table 1 we also give the LTE electron temperatures, T_e^*, derived from the equation

$$\left(\frac{T_e^*}{10^4\ \mathrm{K}}\right) = 1.15 \times 10^{-2}\left[\left(\frac{\nu}{\mathrm{GHz}}\right)^{1.1}\left(\frac{S_c}{S_L}\right) \times \left(\frac{1}{1 + y^+ + 4y^{++}}\right)\left(\frac{30\ \mathrm{km\ s^{-1}}}{\Delta v}\right)\right]^{0.87}, \quad (1)$$

where y^+ and y^{++} are the number ratios of singly and doubly ionized helium to ionized hydrogen. We used $y^+ = 0.115$ and $y^{++} = 0.065$ (Aller *et al.* 1981). The electron temperatures derived from the H76α and H110α lines are in good agreement (see Table 1) and we adopt $T_e^* = T_e = 20{,}000 \pm 2{,}000$ K. Note that equation (1) is derived for a Gaussian profile but is accurate enough for the present purpose for a Voigt line profile.

The H110α line is significantly broader than the H76α line (see Fig. 2). We attribute the additional broadening of the H110α line to electron pressure broadening. A Voigt profile fit to the H110α line gives a FWHM of 55 ± 2 $\mathrm{km\ s^{-1}}$. Including the correction for instrumental broadening, we note that the FWHM linewidth, Δv_I, due to electron impacts for the H110α line is given approximately by (Walmsley, Churchwell, and Terzian 1981)

$$\Delta v(\mathrm{H110}\alpha) = \frac{\Delta v_I}{2} + \left[\frac{\Delta v_I^2}{4} + \Delta v_\mathrm{D}^2(\mathrm{H110}\alpha) + \Delta v_\mathrm{C}^2(\mathrm{H110}\alpha)\right]^{1/2}, \quad (2)$$

where Δv_C is the correction for instrumental broadening, and Δv_D is the Doppler line width. Assuming that the H76α line is not broadened by electron pressure, we obtain a value for Δv_D(H76α), after deconvolution with the instrumental broadening of 16 $\mathrm{km\ s^{-1}}$, of 37 ± 3 $\mathrm{km\ s^{-1}}$. Assuming that $\Delta v_\mathrm{D}(\mathrm{H110}\alpha) = \Delta v_\mathrm{D}(\mathrm{H76}\alpha)$, we then obtain from equation (2): $\Delta v_I = 20 \pm 4$ $\mathrm{km\ s^{-1}}$.

In a constant density nebula the electron density, n_e, derived from the Δv_I of $n\alpha$ lines is given by (Brocklehurst and Seaton 1972):

$$\left(\frac{n_e}{10^4\ \mathrm{cm^{-3}}}\right) = 0.233\left(\frac{\Delta v_I}{\mathrm{km\ s^{-1}}}\right)\left(\frac{n}{100}\right)^{-7.4}\left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{0.1}. \quad (3)$$

From this equation and our data we obtain $n_e = (2.5 \pm 0.5) \times 10^4\ \mathrm{cm^{-3}}$. Note that the error in T_e contributes very little to the error in n_e. This electron density is in good agreement with the value of $2 \times 10^4\ \mathrm{cm^{-3}}$ derived for the core of the nebula from optical data (Meaburn and Walsh 1980*a*). We now use our estimate of the electron density, the flux density, and a geometric model to determine the distance. The flux density of

TABLE 1

PARAMETERS OF THE H76α AND H110α RADIO RECOMBINATION LINES FROM NGC 6302

Parameter[a]	H76α	H110α
Peak flux density, S_L (mJy)	78 ± 5	13.3 ± 0.4
Full width at half-power, Δv ($\mathrm{km\ s^{-1}}$)	40 ± 3	56 ± 2
Radial velocity with respect to the LSR, v_LSR ($\mathrm{km\ s^{-1}}$)	-31 ± 2	-31.5 ± 0.8
Continuum flux density, S_c (Jy)	2.4 ± 0.2	2.4 ± 0.1
LTE electron temperature, T_e^* (K)	$18{,}000 \pm 2{,}000$	$21{,}000 \pm 1{,}000$

[a] Line parameters are from a least-squares Gaussian fit. Note that the line width of a Gaussian function fitted to the profile of the H110α line is slightly different than that of the Voigt function.

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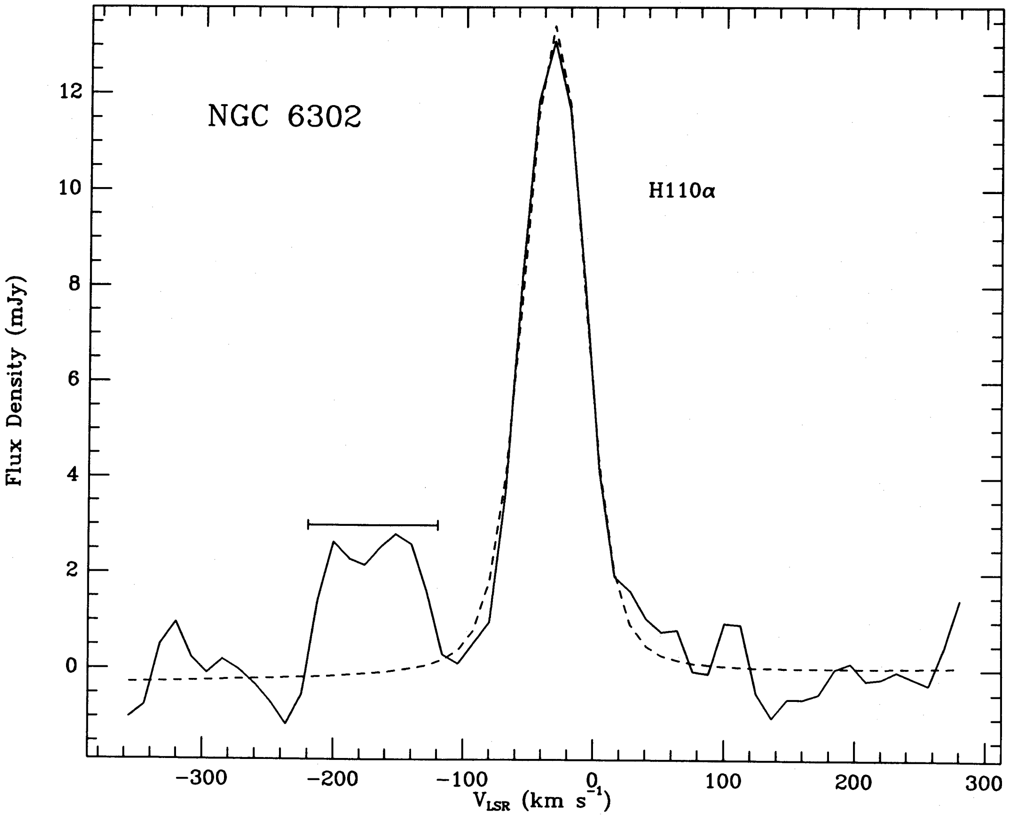

FIG. 1.—Spectra of the H110α line from NGC 6302. The velocity resolution is 24 km s^{-1} after Hanning-weighting. The dashed lines show the Voigt fit to the spectra. The region between -120 and -220 km s^{-1} was not included in the fit.

an optically thin nebula is given by

$$S_c = \frac{V j_c}{D^2} , \qquad (4)$$

where D is the distance to the nebula, j_c is the emission coefficient for free-free radiation taken from Spitzer (1978), and V is the volume of the nebula. Analysis of optical, infrared, and radio data (Meaburn and Walsh 1980*a*; King, Scarrott, and Shirt 1985; Lester and Dinerstein 1984; Rodríguez *et al.* 1985) suggests that the core of NGC 6302 can be described as a toroid with circular cross section. In this case, its volume will be given by

$$V = 2\pi^2 \left(\frac{\theta_o - \theta_i}{2}\right)^2 \left(\frac{\theta_o + \theta_i}{2}\right) D^3 , \qquad (5)$$

where θ_o and θ_i are the outer and inner angular radii of the toroid given in radians. The distance is then

$$D = \frac{S_c}{2\pi^2[(\theta_o - \theta_i)/2]^2[(\theta_o + \theta_i)/2] j_c} . \qquad (6)$$

For $T_e = 20{,}000 \pm 2{,}000$ K, $\nu = 4.9$ GHz, $n_e = (2.5 \pm 0.5) \times 10^4$ cm^{-3}, we obtain $j_c = (1.5 \pm 0.7) \times 10^{-31}$ ergs cm^{-3} s^{-1} sr^{-1} Hz^{-1}. From a cut along the major axis of the source in our 6 cm map (see Figs. 3 and 4), we estimate $\theta_o = 5''.3 \pm 0''.2$ and $\theta_i = 2''.0 \pm 0''.2$. The outer radius was measured at the 10% level and the inner radius at the peak of the emission. The flux density of 2.4 Jy was obtained from the map of Figure 3. From equation (6) we finally obtain $D = 2.2 \pm 1.1$ kpc. Note that a distance of about the same value could have been derived from the density obtained from optical measurements.

Most of the error in our estimate of the distance comes from the uncertainty in the electron density, which appears squared in the emission coefficient, and from the angular dimension, which appears cubed in the volume. If the nebula were clumpy, this distance would be a lower limit. On the other hand, a geometric model of a filled sphere with angular radius of $5''.3$ (enclosing most of the emission) gives the smallest distance estimate compatible with the data, $D = 0.7 \pm 0.4$ kpc. We

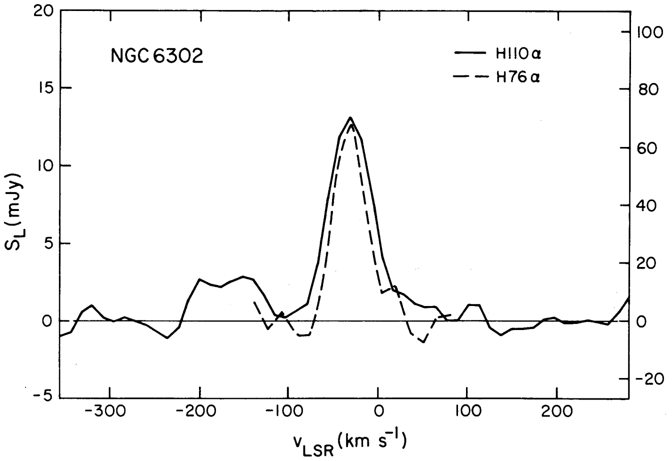

FIG. 2.—These spectra show the H110α (*solid*), and H76α (*dashed*) lines from NGC 6302. The velocity resolutions are 24 km s^{-1} and 16 km s^{-1}, respectively. Note the larger width of the H110α line.

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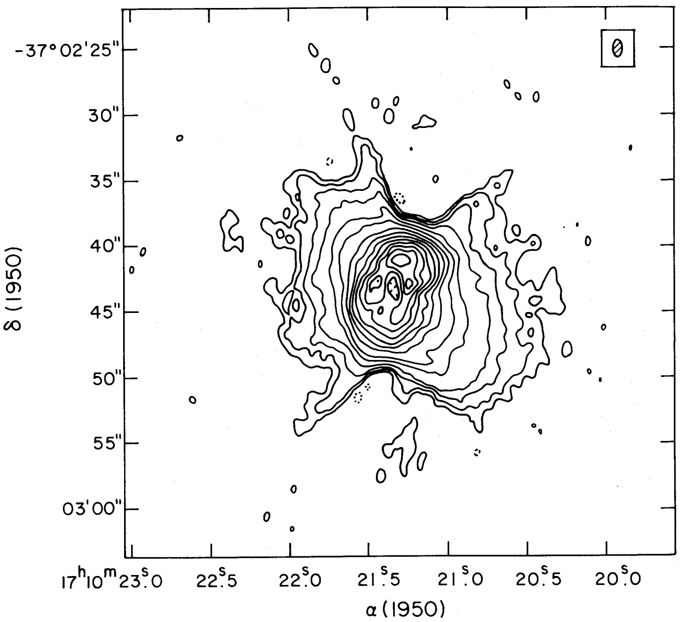

FIG. 3.—Self-calibrated 6 cm map of NGC 6302. The synthesized beam was 0″.8 × 1″.3 FWHM. The contour levels are −0.003, 0.003, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 of the peak flux of 60 mJy per beam.

prefer the toroid geometry because it accounts for the bipolar appearance of the nebula.

We found two other planetary nebulae, NGC 7027 and IC 418, for which sufficient data were available to estimate the distance by this technique. In Table 2 we show the parameters used and the derived distances for NGC 7027 and IC 418. The electron density for these sources was obtained also from pressure broadening in recombination line data given in the references listed in Table 2. For NGC 7027 we adopted the elliptical shell model of Masson (1989), with inner semiaxes of 2″.8 and 7″.7 and thickness of 1″. For IC 418 we adopted, from the map of Garay, Gathier, and Rodríguez (1989), a spherical shell with inner angular radius of 3″.4 and outer angular radius of 8″.3. The density distances are compatible with previous estimates (see Table 2). In particular, for NGC 7027, we derive $D = 1.0$ kpc, in excellent agreement with the distance derived from the angular expansion by Masson (1989).

b) *Low Angular Resolution 6 Centimeter Continuum*

We used the continuum channel of our H110α observations to produce a uniform-weighted, self-calibrated map of NGC 6302 with an angular resolution of ~10″. In Figure 5 we show this map superposed on an optical image. The radio map shows a bright, unresolved core with fainter extended emission.

c) *High Angular Resolution 6 Centimeter Continuum*

We made 6 cm observations of NGC 6302 with the VLA in the A configuration during 1987 July 14 and 24. The main purpose of these observations was to compare them with those acquired, also with the VLA-A, during 1981 February 20 to measure the angular expansion, following the technique of Masson (1986). The 1981 observations are described in Rodríguez *et al.* (1985). The 1987 observations were made during two 4 hr periods around 1700 LST. The amplitude calibrator was 3C 286, and the phase calibrator was NRAO 530. The 1987 July 14 data were found to be the best of the three epochs, and a uniform-weighted, self-calibrated map made from these data is shown in Figure 3. This high dynamic range map exhibits the morphology that inspired some astron-

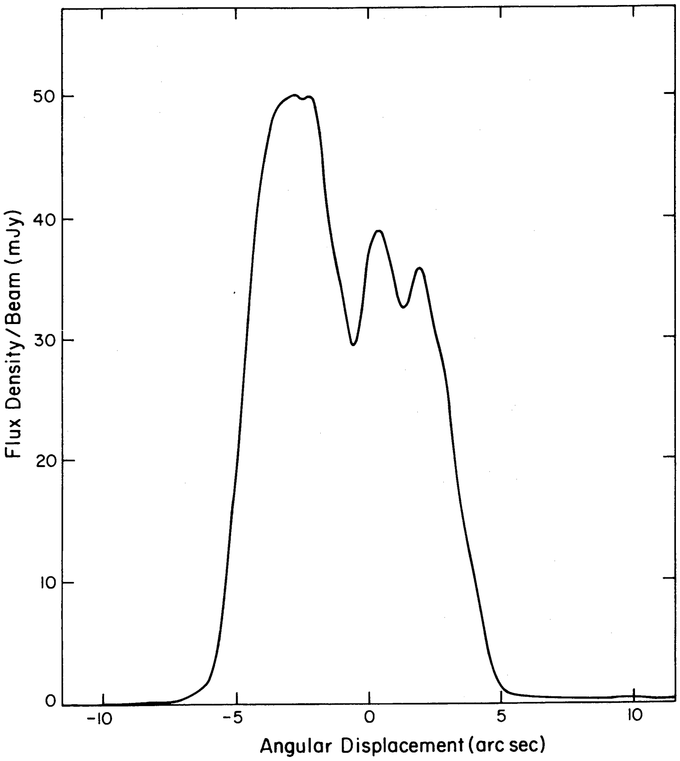

FIG. 4.—Profile for a cut through the center ($\alpha = 17^h10^m21^s.4$, $\delta = -37°02'44''$), along the major axis of the source (p.a. = 145°) in the high angular resolution 6 cm map (see Fig. 3).

TABLE 2

DENSITY DISTANCE OF PLANETARY NEBULAE

Source	Morphology Assumed	n_e (10^4 cm^{-3})	6 cm Flux Density (Jy)	T_e (K)	y^+	y^{++}	Derived Distance (kpc)	References	Range of Previous Distance Estimates (kpc)	References for Ranges
NGC 6302	Toroid	2.5	2.4	20,000	0.115	0.065	2.2	1, 2	0.15–2.4	7, 8
NGC 7027	Elliptical shell	4.6	5.3	14,500	0.072	0.044	1.0	3, 4, 5	0.18–1.8	9, 10
IC 418	Spherical shell	1.8	1.4	9,500	0.084	0.001	0.2	4, 6	0.30–1.9	10, 11

REFERENCES.—(1) This paper; (2) Aller *et al.* 1981; (3) Masson 1986 and 1989; (4) Pottasch 1984; (5) Chaisson and Malkan 1976; (6) Garay, Gathier, and Rodríguez 1989; (7) Meaburn and Walsh 1980*b*; (8) Rodríguez and Moran 1982; (9) Daub 1982; (10) O'Dell 1962; (11) Acker 1978.

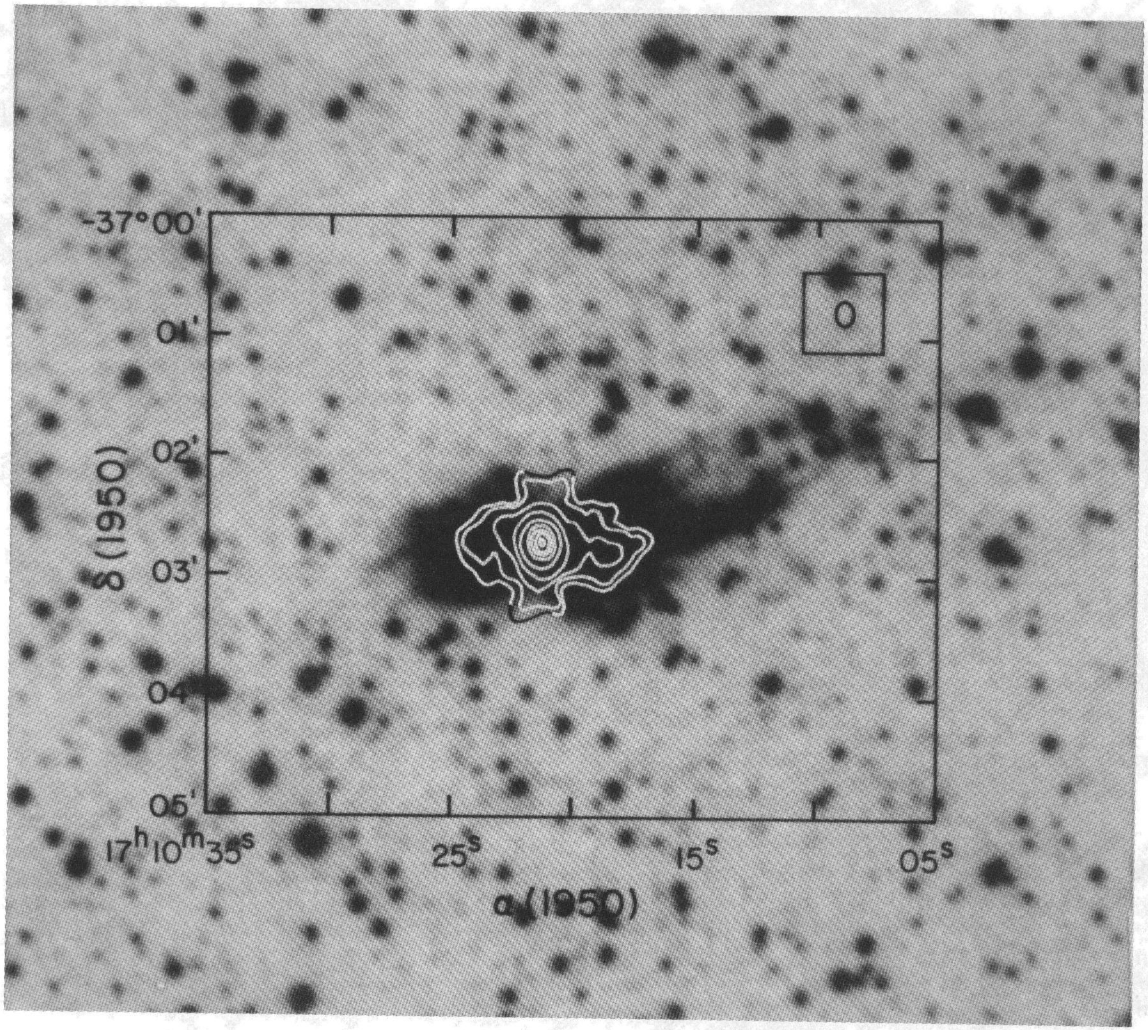

FIG. 5.—Self-calibrated 6 cm map of NGC 6302 superposed on the red plate of the Palomar Sky Survey. The synthesized beam was 8″ × 12″ FWHM. The contour levels are −0.001, 0.001, 0.002, 0.005, 0.02, 0.1, 0.3, 0.5, 0.7, and 0.9 of the peak flux of 2.1 Jy per beam.

omers to refer to NGC 6302 as the Butterfly nebula. However, most of the emission comes from the toroid-shaped core, which justifies the geometric model used in § II*a*. Although the radio map is relatively symmetric, short exposures made in the optical (Evans 1959; Minkowski and Johnson 1967; Rodríguez *et al.* 1985) show the west "wing" to be significantly fainter. This implies that the west side of the nebula is more obscured than the east one, a result that can be understood in terms of the geometry proposed by Meaburn and Walsh (1980*a*) and Rodríguez *et al.* (1985), which we depict in Figure 6. Silvestro and Robberto (1987), based on the model of Barral and Cantó (1981), have modeled the morphology of NGC 6302 as the steady state configuration resulting from the interaction of a stellar wind and a surrounding disk embedded in a tenuous ambient medium of constant density.

The best VLA data set (1987 Jul 14) was used to cross-calibrate the 1981 February 20 and 1987 July 24 data, following the technique of Masson (1986). The final difference maps, made with natural weighting and visibilities in the 0–150 kλ range, are shown in Figure 7. We did not detect the characteristic residuals expected for angular expansion at a 1 σ level of 0.40 mJy per beam (differencing the maps of 1981 Feb 20 and 1987 Jul 14) and 0.15 mJy per beam (differencing the maps of

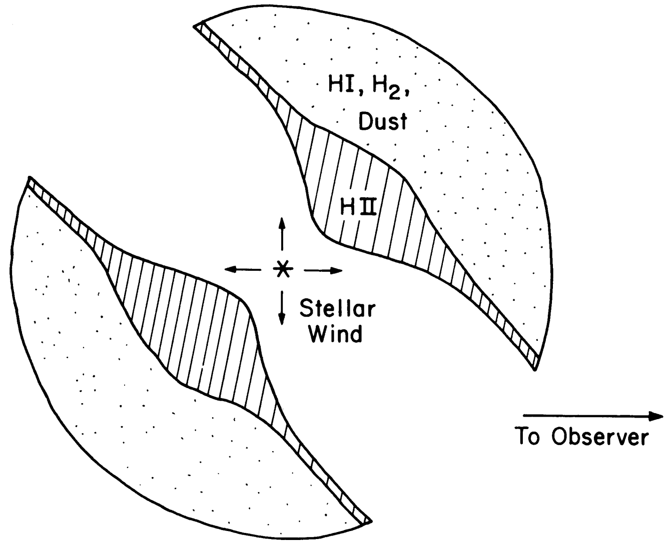

FIG. 6.—A schematic representation of NGC 6302. The stellar wind has cleared a bipolar cavity in the envelope. The inner parts of the envelope are ionized while the outer remain neutral.

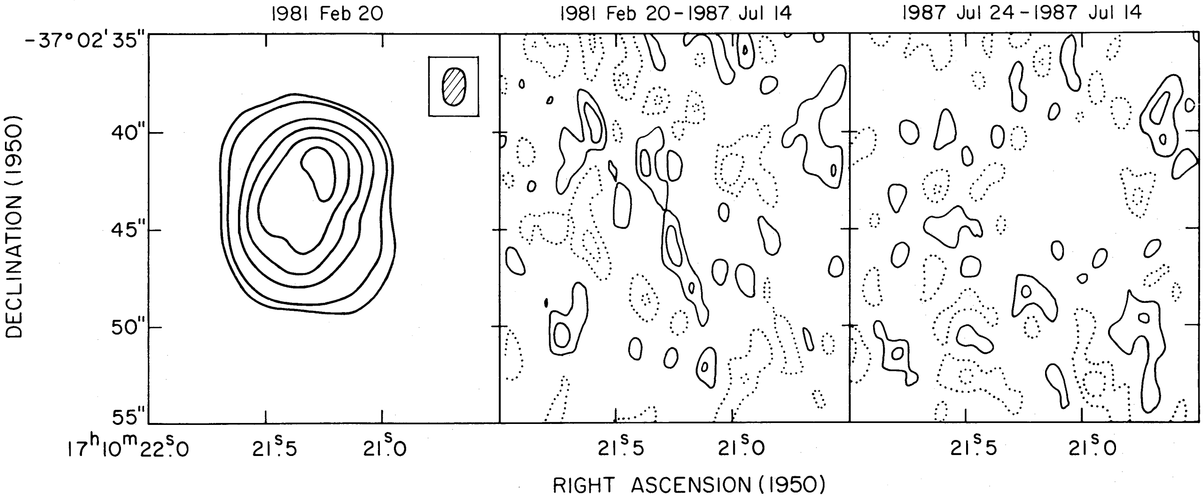

FIG. 7.—*Left*: CLEAN map of NGC 6302 from the 1981 data. The synthesized beam was 1″1 × 1″9 FWHM. Contours are 0.05, 0.1, 0.3, 0.5, 0.7, and 0.9 of the peak flux of 160 mJy per beam. *Center*: Map of the 1981 February 20 minus 1987 July 14 data. Contours are −1.0, −0.5, 0.5, and 1.0 mJy per beam. *Right*: Map of the 1987 July 24 minus 1987 July 14 data. Contours are −0.4, −0.2, 0.2, and 0.4 mJy per beam. All three maps were made with natural weighting and data in the 0 to 150 kλ (*u*, *v*) range.

1987 July 24 and 1987 Jul 14). Our noise level for the 1981–1987 map is relatively high; Masson (1986, 1989) has obtained noise levels several times lower in his difference maps. We attribute our poorer results to the modest integration on-source time of the 1981 data (about 20 minutes) and to the fact that we overresolved the object. A better experiment conducted over a larger time base should make it possible to detect the angular expansion of NGC 6302. In any case, our upper limit to the angular expansion can be used to derive a lower limit to the distance of NGC 6302. The distance is given by

$$D \simeq \frac{\Delta r/\Delta t}{\Delta\theta/\Delta t}, \tag{7}$$

where $\Delta r/\Delta t = v_{\rm exp}$ is the (tangential) expansion velocity of the nebula and $\Delta\theta/\Delta t$ is the angular expansion rate. On the other hand,

$$\frac{\Delta\theta}{\Delta t} \simeq \frac{1}{\Delta t}\frac{\delta S}{\Delta S/\Delta\theta}, \tag{8}$$

where Δt is the period of time between the observations, δS is the peak value of the residuals, and $\Delta S/\Delta\theta$ is the angular gradient in flux density across the outer edge of the nebula. For our data, $\Delta t = 6.4$ yr, $\delta S \lesssim 1.2$ mJy (3 σ upper limit), and from Figure 3, $\Delta S/\Delta\theta \simeq 54 \pm 6$ mJy arc sec^{-1}. We then obtain

$$\frac{\Delta\theta}{\Delta t} \lesssim 0\rlap{.}''0035 \text{ yr}^{-1}. \tag{9}$$

From optical observations, Robinson, Reay, and Atherton (1982) give an expansion velocity of 10 ± 3 km s^{-1} for the line-of-sight component of the total expansion velocity. Assuming again a toroidal geometry for the core of NGC 6302, we estimate an inclination angle of 50° ± 10° between the line of sight and the axis of rotational symmetry of the toroid. This estimate is based on the ratio of minor to major axis of the emission contours at half-maximum in Figure 3. We then obtain $v_{\rm exp} \simeq 10/\sin(50°) \simeq 13 \pm 4$ km s^{-1}, which is our estimate for $\Delta r/\Delta t$. By combining this result and the limit for $\Delta\theta/\Delta t$, we obtain a lower limit of 0.8 ± 0.3 kpc for the distance to NGC 6302. If the expansion of the ionization front were significant with respect to the expansion velocity of the neutral gas and if it were included in the estimate, the lower limit of the distance would increase correspondingly.

Adopting a distance of 2.2 kpc, we obtain an *IRAS* luminosity for NGC 6302 of $1.3 \times 10^4\ L_\odot$, making it one of the most luminous planetary nebulae known. This *IRAS* luminosity was obtained by integrating the fluxes from the *IRAS* Point Source Catalog, and applying color corrections for a νB_ν function, where B_ν is the Planck function at a temperature of 75 K (see below). We also estimated the luminosity of NGC 6302 in the optical and near-infrared from published magnitudes (Radlova, Katc, and Dokucaeva 1949; Whitelock 1985) to be $\sim 150\ L_\odot$, about 10^{-2} times the *IRAS* luminosity.

d) *Mass Estimates*

NGC 6302 is the only planetary nebula where hydrogen has been detected in its ionized, atomic (neutral) and molecular forms (Rodríguez 1989). We can therefore derive mass estimates for the H II, H I, and H_2 contents of this object.

i) *Ionized Hydrogen Mass*

If the temperature and electron density in the nebula are constant and the ionized gas is distributed in a volume shaped as a toroid (see eq. [5]), then the ionized mass M(H II) for NGC 6302 is given by the relation

$$\frac{M(\text{H II})}{M_\odot} = 5.6 \times 10^{-8}\left(\frac{\theta_o - \theta_i}{2}\right)^2\left(\frac{\theta_o + \theta_i}{2}\right) \times \left(\frac{D}{\text{kpc}}\right)^3\left(\frac{n_e}{\text{cm}^{-3}}\right)\left[\frac{1 + 4(y^+ + y^{++})}{1 + y^+ + 2y^{++}}\right], \tag{10}$$

with θ_o and θ_i in arcsec. Adopting a distance of 2.2 kpc and taking the parameters given in Table 2, we estimate an ionized mass for NGC 6302 of about $0.2 \pm^{0.2}_{0.1}\ M_\odot$.

Following the same procedure, we estimate the ionized mass for NGC 7027 and IC 418 using the geometric model and parameters given in Table 2. The ionized masses are found to be $\sim 0.05\ M_\odot$ and $\sim 0.001\ M_\odot$ for NGC 7027 and IC 418, respectively.

ii) *Neutral Hydrogen Mass*

H I has been detected in absorption in NGC 6302 (Rodríguez and Moran 1982). Assuming that the absorption comes from gas surrounding the ionized toroid and multiplying by 2 to account approximately for H I on the far side of the nebula, we obtain

$$\left[\frac{M(\mathrm{H\ I})}{M_\odot}\right] = 2.1 \times 10^{-6}\left[\frac{\theta_o(\theta_o - \theta_i)}{\mathrm{arcsec}^2}\right]\left(\frac{D}{\mathrm{kpc}}\right)^2 \times \left(\frac{T_{\mathrm{ex}}}{\mathrm{K}}\right)\left(\frac{\Delta v}{\mathrm{km\ s^{-1}}}\right)(\tau_{\mathrm{H\ I}})\,, \quad (11)$$

where T_{ex} is the excitation temperature of the neutral hydrogen, D is the distance to the nebula, θ_o and θ_i are the outer and inner radii, and $\tau_{\mathrm{H\ I}}$ is the total optical depth. Assuming that the absorption is optically thin and taking the absorption profile of Rodríguez *et al.* (1985), we estimate $\tau_{\mathrm{H\ I}} = 0.36$ and a linewidth of 10 km s^{-1}. The dust temperature was estimated using the *IRAS* fluxes at 25, 60, and 100 μm and fitting them with a function of the form $\nu^\alpha B_\nu(T_d)$, where ν is the frequency, $B_\nu(T_d)$ is the Planck function for a dust temperature T_d and α is a constant. A least-squares fit gives $T_d = 75$ K and $\alpha = 1$ (see Fig. 8). The 12 μm flux was not considered, because it probably arises from a hotter dust component and may also include contamination by lines (Pottasch *et al.* 1984). Assuming that the excitation temperature equals the dust temperature, we obtain an estimate of $M(\mathrm{H\ I}) \simeq 0.05 \pm ^{0.06}_{0.04}\ M_\odot$ for NGC 6302.

The H I may originate in a photodissociation region, where the excitation temperature could be in the 500–1000 K range (Tielens and Hollenbach 1985). If this is the case, the H I mass could be an order of magnitude larger than estimated. For IC 418, Taylor and Pottasch (1987) proposed, from absorption and emission observations of atomic hydrogen, that the H I excitation temperature is ~1000 K.

iii) *Molecular Hydrogen Mass*

The 2μ $S(1)$ $v = 1 \rightarrow 0$ transition of molecular hydrogen has been observed in NGC 6302 (Phillips, Reay, and White 1983). However, this line cannot be used for a derivation of the total $\mathrm{H_2}$ mass in the planetary nebula since it is believed to trace only a small, highly excited fraction of the molecular gas. Zuckerman and Dyck (1986) detected CO ($J = 1 \rightarrow 0$) emission toward NGC 6302 and proposed that it could be associated with the planetary nebula.

We observed the CO ($J = 1 \rightarrow 0$) rotational transition during 1988 May using the 15 m Swedish ESO Submillimeter Telescope (SEST). The system temperature referred to a point above the atmosphere was 600 K. The antenna beam width was ~40″ at 115 GHz and the pointing accuracy was estimated to be ~3″. We show in Figure 9 a spectrum smoothed to a velocity resolution of 1.0 km s^{-1} obtained with position switching and an off-source position of α (1950) = $17^{\mathrm{h}}09^{\mathrm{m}}30\overset{\mathrm{s}}{.}0$; δ (1950) = −37°22′00″ and an on-source position of α (1950) = $17^{\mathrm{h}}10^{\mathrm{m}}21\overset{\mathrm{s}}{.}3$; δ (1950) = −37°02′44″. The CO spectrum shows several narrow features, probably of interstellar origin, plus broad emission in the −18 km s^{-1} to −56 km s^{-1} range. We assume that this broad emission is associated with NGC 6302. It is not clear how much of this broad emission is contaminated with interstellar contributions in the ON and OFF positions. A high angular resolution CO map of NGC 6302 is required to confirm the association of CO with the planetary nebula. This emission is centered at −37 km s^{-1}, has a width of 38 km s^{-1}, and a beam-corrected antenna temperature (T_A^*) of ~0.25 K.

We can estimate the mass of $\mathrm{H_2}$ from CO ($J = 1 \rightarrow 0$) obser-

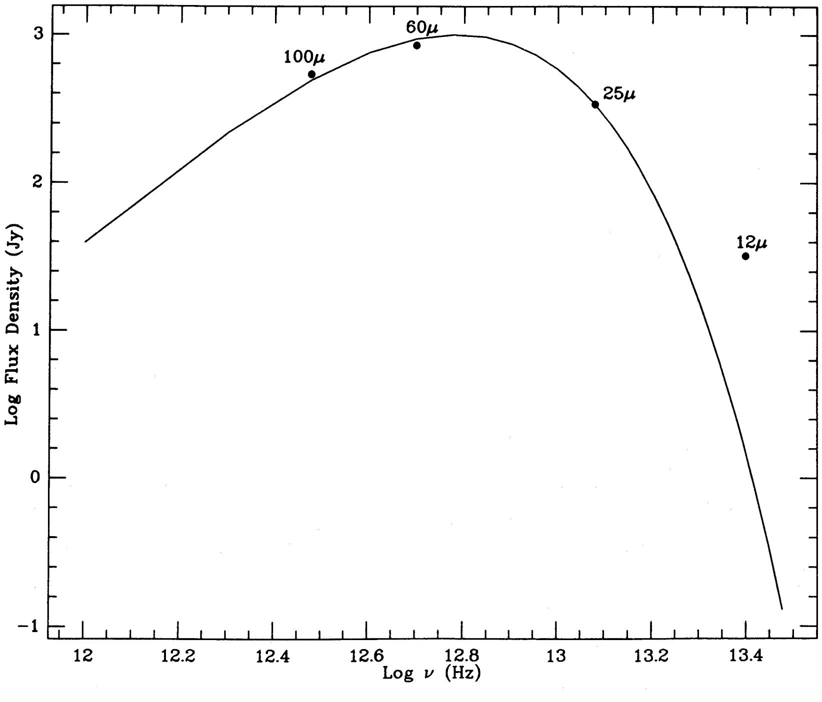

FIG. 8.—*IRAS* fluxes for NGC 6302 (*dots*) and fit with a νB_ν function (*solid line*) to the 100, 60, and 25 μm values. A dust temperature of 75 K is derived.

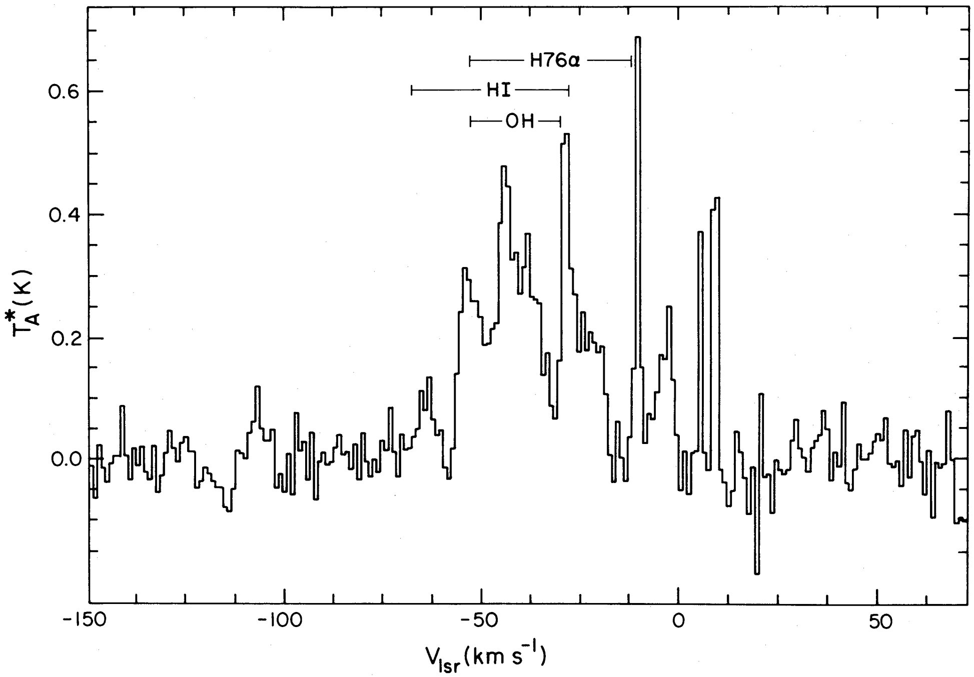

FIG. 9.—CO spectrum toward NGC 6302. The velocity resolution is 1.0 km s^{-1}. The radial velocity ranges of the H I absorption (Rodríguez *et al.* 1985), the OH (Payne, Phillips, and Terzian 1988), and the H76α (Gómez, Rodríguez, and García-Barreto 1987) emission are also shown.

vations for an optically thin, unresolved source with the relation:

$$\frac{M(H_2)}{M_\odot} = 0.064\left(\frac{D}{\text{kpc}}\right)^2\left(\frac{T_{\text{ex}}}{100\text{ K}}\right)\left(\frac{T_A^*}{0.1\text{ K}}\right) \times \left(\frac{\theta_A}{\text{arcmin}}\right)^2\left(\frac{\Delta v}{10\text{ km s}^{-1}}\right)\left(\frac{f}{10^{-4}}\right)^{-1}, \quad (12)$$

where D is the distance to the nebula, T_{ex} is the excitation temperature of the CO, T_A^* is the corrected antenna temperature, θ_A is the beam size, Δv is the width of the CO emission, and $f = [\text{CO}/H_2]$ is the number abundance of CO relative to H_2.

We do not have direct knowledge of the value of $[\text{CO}/H_2]$. Jura, Kahane, and Omont (1988), based on the results of Knapp and Morris (1985), suggest that $[\text{CO}/H_2] \simeq 2 \times 10^{-4}$ in oxygen-rich envelopes, as is the case for NGC 6302. The same value for $[\text{CO}/H_2]$ can be derived from the following argument. Aller *et al.* (1981) give $[\text{O/H}] = 5 \times 10^{-4}$ and $[\text{C/H}] = 1 \times 10^{-4}$ for the ionized component of NGC 6302. Assuming that the nebula has a constant [C/H] ratio and that in the molecular zone all carbon is in the form of CO, we obtain $[\text{CO}/H_2] = 2 \times 10^{-4}$. Using this value of $[\text{CO}/H_2]$, $\theta_A = 0\overset{\prime}{.}66$, $T_{\text{ex}} = T_d = 75$ K, and $D = 2.2$ kpc, we estimate $M(H_2) = 0.5 \pm^{0.6}_{0.4} M_\odot$.

We have also estimated the dust mass in the nebula, which is given by (Hildebrand 1983; Barlow 1983; Pottasch *et al.* 1984)

$$M_d = \frac{4}{3}\frac{a\rho}{Q_{25\,\mu\text{m}}}\frac{D^2 S_{25\,\mu\text{m}}}{B_{25\,\mu\text{m}}(T_d)}\text{ g}, \quad (13)$$

where a is the radius of the dust, ρ is the density of the dust material, D is the distance to the source, $S_{25\,\mu\text{m}}$ is the flux density at 25 μm, $Q_{25\,\mu\text{m}}$ is the dust emissivity at 25 μm, and $B_{25\,\mu\text{m}}(T_d)$ is the Planck function at the dust temperature and at 25 μm. For NGC 6302, $D = 2.2$ kpc, $S_{25\,\mu\text{m}} = 337.3$ Jy, and $T_d = 75$ K. Following Hildebrand (1983), we adopt $\alpha = 10^{-5}$ cm and $\rho = 3$ g cm^{-3}, and from Pottasch *et al.* (1984) we assume $Q_{25\,\mu\text{m}} = 1.25 \times 10^{-2}$. We obtain $M_d \simeq 0.02$ $M_\odot$. Since the total mass (H II + H I + H_2) of NGC 6302 is ~0.75 $M_\odot$, the ratio of dust to gas mass is ~0.03. This value is similar to that found by Pottasch *et al.* (1984) for other young, compact planetary nebulae. NGC 6302 is also believed to be young since its kinematic age (calculated as the inner radius of 0.02 pc divided by an expansion velocity of 13 km s^{-1}) is only ~1600 yr. We have taken the inner radius for this calculation because it appears appropriate to start counting the age of the planetary nebula when the massive wind present at the end of the asymptotic giant branch evolution ceases.

III. CONCLUSIONS

We present new 6 cm continuum and radio recombination line VLA observations, as well as SEST CO observations of NGC 6302. The data were used to estimate the distance and the ionized, atomic (neutral) and molecular masses of the planetary nebula. Our main conclusions are as follows.

1. The H110α line is significantly broader than the H76α line. This effect is attributed to electron pressure broadening, and an electron density of 2.5×10^4 cm^{-3} is derived. This value is in good agreement with previous optical estimates for the electron density in the core of NGC 6302. Adopting this electron density and a geometric model for the nebula, we derive a distance of 2.2 ± 1.1 kpc. If the nebula is clumpy, this value would be a lower limit.

2. Using 6 cm continuum observations taken in 1981 and 1987, we attempted to measure the angular expansion in the nebula using the technique of Masson (1986). Our failure to

measure any expansion implies a lower limit of 0.8 ± 0.3 kpc for the distance.

3. Adopting a distance of 2.2 kpc, we derive for NGC 6302 an *IRAS* luminosity of 1.3×10^4 $L_\odot$, an ionized nebular mass of ~ 0.2 $M_\odot$, a neutral hydrogen mass of ~ 0.05 $M_\odot$, and a molecular hydrogen mass of ~ 0.5 $M_\odot$. The luminosity and total mass of NGC 6302 are among the largest known for planetary nebulae.

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