

THE STRUCTURES OF AND DISTANCES TO BD +30°3639 AND NGC 6572

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ABSTRACT

We have made new high-resolution VLA maps of the dense planetary nebulae BD +30°3639 and NGC 6572. The structures of both nebulae are well fitted by prolate elliptical models of the sort we have previously used for NGC 7027 and NGC 6720, strengthening the suggestion that this model can account for the appearance of a large class of planetary nebulae.

We have also applied the recently developed technique of measuring expansion motions with the VLA to determine the distances to the dense planetary nebulae BD +30°3639 and NGC 6572. Both nebulae have significantly greater distances than expected from most previous determinations. The new estimate of the distance to BD +30°3639 is $2.8^{+4.7}_{-1.2}$ kpc, and the best estimate of the distance to NGC 6572 is $1.7^{+6.1}_{-0.8}$ kpc. The errors are quite large because of the unexpectedly great distances, but they should be reduced by a factor of 2 with a further epoch of data in 1990. The upward revision of the distances has important implications for the state of the nebulae, reducing their calculated densities and increasing their luminosities. The discrepancy between the new distances for dense nebulae and those calculated from statistical assumptions casts some doubt on the use of statistical methods for such objects. In particular, it is possible that luminous, optically thick nebulae may have been systematically undercounted, affecting studies of mass return to the interstellar medium and of the evolution of the central stars.

Subject headings: nebulae: individual (NGC 6572, BD +30°3639) — nebulae: internal motions — nebulae: planetary

I. INTRODUCTION

The distances to planetary nebulae are very important for calculations of their physical properties and the evolutionary state of the central stars, but they are very hard to measure. In most cases it is necessary to fall back on an assumption that all nebulae are alike in some way and calculate statistical distances. Such methods can never reveal the presence of very massive or very bright nebulae, since they rely on the assumption that all nebulae have the same modest mass or luminosity. Recently we introduced a new method of using the NRAO¹ VLA to measure proper motions in planetary nebulae in order to calculate distances by comparing radial Doppler velocities and transverse angular motions (Masson 1986, 1989a). Initially we studied the object NGC 7027, with the first epoch observation coming from the work of Basart and Daub (1987). The distance resulting from that study was much larger than that derived from statistical techniques, but in good agreement with other estimates. Subsequently we have made observations of two of the other objects studied by Basart and Daub, BD +30°3639 and NGC 6572, with the goal of determining their structures and distances.

BD +30°3639 is one of the brightest planetary nebulae. It is particularly strong in the infrared and has been the subject of several studies of emission lines (Greenberg, Dyal, and Geballe 1977; Beckwith, Persson, and Gatley 1978; Dinerstein *et al.* 1988; Hora *et al.* 1989). The structure of the nebula is something of a puzzle: although both radio maps (Basart and Daub 1987) and infrared maps (Bentley *et al.* 1982; Hora *et al.* 1989) show that the nebula is limb-brightened, indicating a hollow shell, the radio maps show enhanced emission on the northern and southern parts of the rim, while the infrared emission is

brighter east and west. This is in marked contrast to the well-known object NGC 7027, in which the infrared and radio images are very similar (Becklin, Neugebauer, and Wynn-Williams 1973). The distance to BD +30°3639 has been estimated from reddening as 600 pc (Pottasch 1984) and from the statistical method of Daub (1982) as 733 pc. At these distances, the nebula is one of the densest and most compact known, with $n_e \sim 5 \times 10^4 \text{ cm}^{-3}$.

NGC 6572 is also a very dense and bright nebula with strong far-infrared emission (e.g. Moseley 1980). The structure is somewhat more diffuse than the pronounced ring shapes of BD +30°3639 and NGC 7027, with a bright central region and a fainter north-south elongation. Distance estimates for this object range from 400 pc (Liller, Welther, and Liller 1966) to 1600 pc Seaton (1966). The estimate by Liller *et al.* is based on optical measurements of the proper motion of the nebula, while that of Seaton is derived from a statistical technique.

Because of their high brightness, both of the nebulae are good candidates for the recent developed VLA expansion distance method (Masson 1986, 1989a). At a distance of 600 pc, the proper motions should be greater than $\sim 8 \text{ mas yr}^{-1}$. Therefore, in 1986 we made VLA maps to compare with the 1982 data of Basart and Daub (1987). At the same time, high-resolution (0".44) maps were also made to clarify the structure of the objects. Both nebulae have sharp edges to the ionized regions, indicating that they are surrounded by neutral material. We analyze the structures in terms of the model presented by Masson (1989b) and show that they are both well represented by a prolate ellipsoidal form nearly identical to that which describes the Ring nebula and NGC 7027.

II. OBSERVATIONS

The parameters of the observations are summarized in Table 1. The first epoch maps were made by Basart and Daub (1987)

¹ The National Radio Astronomy Observatory is operated by Associated Universities Inc., under contract to the National Science Foundation.

TABLE 1
PARAMETERS OF OBSERVATIONS

Source	Date	Wavelength	No. of Visibilities	Synthesized Beam	Total Flux Density
BD +30°3639	1982 Aug 9	6 cm	71×10^3	$1''.21 \times 1''.07$; p.a. 75°	0.616 ± 0.010
NGC 6572	1982 Aug 9	6 cm	53×10^3	1.01×1.01 ; p.a. 0°	1.222 ± 0.010
BD +30°3639	1986 Sep 14	6 cm	158×10^3	0.98×0.94 ; p.a. -69°	0.625 ± 0.010
NGC 6572	1986 Sep 13	6 cm	146×10^3	1.02×1.00 ; p.a. -70°	1.204 ± 0.018
BD +30°3639	1986 Sep 13	2 cm	59×10^3	0.49×0.39 ; p.a. -70°	0.60 ± 0.03
NGC 6572	1986 Sep 13	2 cm	59×10^3	0.465×0.425 ; p.a. -81°	> 1.07

on 1982 August 9, using the B-array of the VLA at a wavelength of 6 cm. The second epoch maps, with the same observing conditions, were made on 1986 September 14, after a time interval of 4.09 yr. At that time, the raw 1982 data set was retrieved and reprocessed to ensure consistency with the 1986 data set. The phase calibrator for BD +30°3639 was 1848 + 283, and that for NGC 6572 was 1821 + 107. The amplitudes were calibrated relative to an assumed flux density of 7.41 Jy for 3C 286. The estimated flux density error of 1.5% is consistent with the measured differences between the two epochs for the several sources observed.

The 2 cm data from 1986 yielded higher resolution maps for both objects. The amplitudes were calibrated by assuming a flux density of 3.44 Jy for 3C 286, and the error was estimated to be 5%. The total flux density of NGC 6572 could not be accurately determined at 2 cm, since the nebula was slightly resolved, even at the shortest baseline.

III. THE STRUCTURE OF THE NEBULAE

Both the 1986 data sets were self-calibrated to reduce phase and amplitude errors, before being mapped and CLEANed. After CLEANing, the maps were restored with circular Gaussian beams, to avoid distorting the appearance of the maps. A $0''.96$ beam was used for BD +30°3639, and $1''.06$ for NGC 6572, while a $0''.44$ beam was used at 2 cm for both objects. The CLEAN maps are presented in Figure 1.

a) BD + 30°3639

It is immediately evident that the maps in Figures 1a and b resemble those of NGC 7027 (see, e.g. Masson 1989a), with a strongly limb brightened, elongated structure, having its greatest intensity on the apparent minor axis. BD +30°3639, however, is less elongated than NGC 7027 and has dramatically larger limb brightening, a factor of 9 in the high-resolution map. In the model presented by Masson (1989b) in which such nebulae have the shape of prolate, ellipsoidal shells, the ends of the shells emit less strongly than the equatorial regions, because they are farther from the central source of ionizing radiation. When such a nebula is viewed in projection, the apparent minor axis always corresponds to the bright, equatorial region and the apparent major axis is fainter, because it corresponds to the polar region. The structure of BD +30°3639, then, should be similar to that of NGC 7027, but viewed more nearly along the major axis.

We have therefore attempted to fit a model of this type to the observations of BD +30°3639. As before, the model consists of a set of nested ellipsoidal shells arranged such that the thickness of each shell is nearly constant. All shells had the same electron density in the equatorial plane. To account for inverse square dilution of the ionizing radiation (cf. Masson 1989b),

the density within each shell was varied as r^{-1} , where r is the distance to the central star; the radio emissivity therefore fell as r^{-2} . The parameters of the best-fitting model are listed in Table 2, along with a comparison between the model results and the observations. The tabulated dimensions are unprojected semiaxes. A contour map of the model emission is shown in Figure 2a. The model parameters are determined to an accuracy of about 10% and the inclination angle cannot change by more than 5° without significantly degrading the fit.

While there are no published spatially resolved velocity data which would unambiguously confirm the prolate model, it is encouraging that the best-fitting model for BD +30°3639 is very similar to those required by NGC 7027 and NGC 6720. As in the case of the other two nebulae, the model assumes that the nebula is surrounded by neutral material, as indicated by the sharp boundary to the ionized region and the detection of molecular hydrogen (Beckwith *et al.*; Dinerstein *et al.* 1988).

The model does not account for the enhancement of infrared radiation at the ends of the apparent major axis (Bentley *et al.* 1982; Hora *et al.* 1989). One possibility is that, as in the case of NGC 7027, the poles are hotter than the equator. In this case, a low-frequency radio map, in which the optically thick emission is proportional to temperature, should show an asymmetry along the major axis similar to that seen by Basart and Daub (1987) in NGC 7027. The map by Basart and Daub (1987) is not at a sufficiently low frequency to resolve the issue, but the minor axis limb brightening is less than in the 6 cm map, suggesting that the polar regions are indeed hotter than the equator.

b) NGC 6572

The maps of NGC 6572 presented by Basart and Daub (1987) showed a sharp-edged nebula, with a hint of limb brightening. The higher resolution maps in Figures 1c and d confirm that the nebula is indeed limb-brightened on the minor axis, although to a much smaller extent than NGC 7027 or BD +30°3639 and is therefore also hollow. Along the major axis, the brightness decreases steadily away from the center. In the context of our ellipsoidal model, such an appearance can be produced when the prolate ellipsoid is viewed nearly in its equatorial plane. The best-fitting model for NGC 6572 had an inclination angle of 50° between the major axis and the line of sight. To match the large width of the limbs seen in the 2 cm map, and the small degree of limb brightening, it was necessary to use a fairly thick shell for the nebula. The computer model was originally intended for thin-shelled structures and it does not give a very good account of radial structure in the thick nebula, but the resemblance between the model contours in Figure 2b and the appearance of NGC 6572 indicates that the

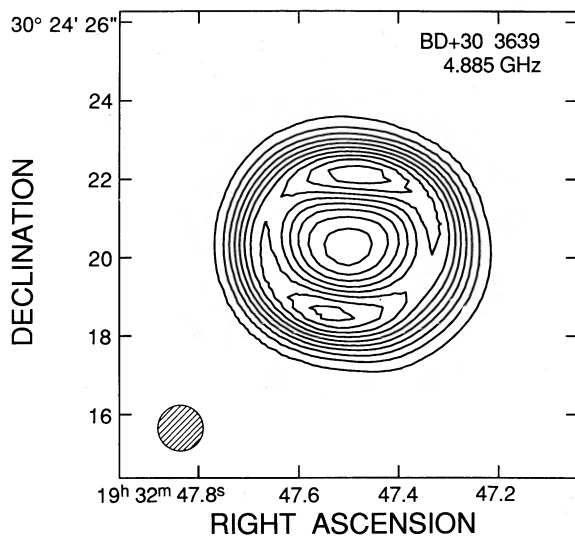


FIG. 1a

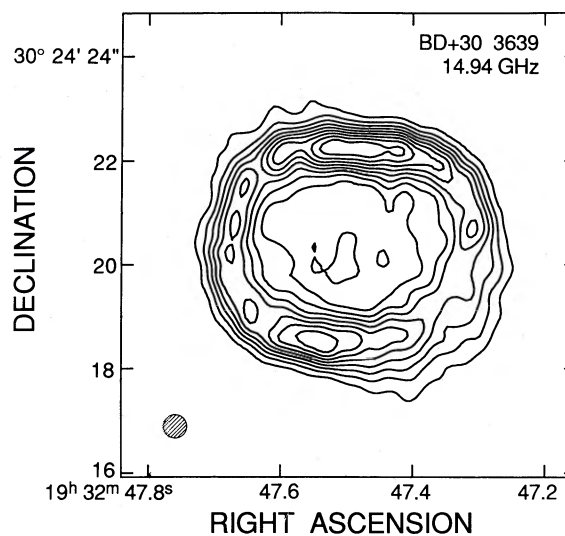


FIG. 1b

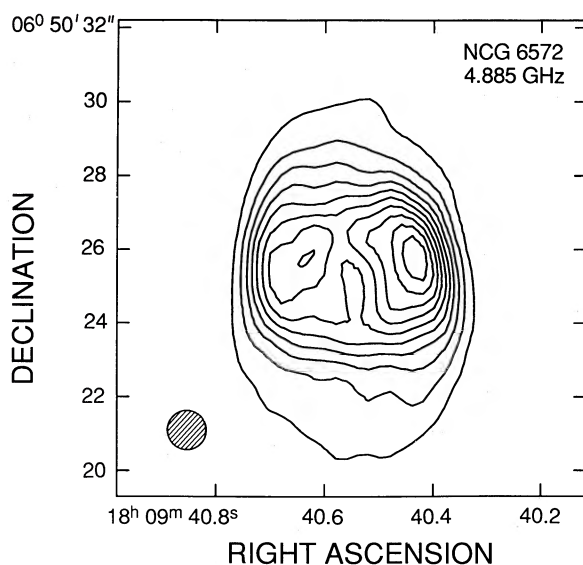


FIG. 1c

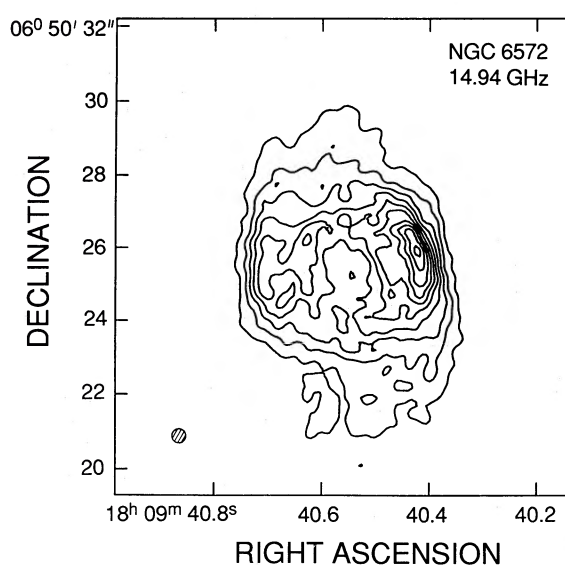


FIG. 1d

FIG. 1.—VLA CLEAN maps of the nebulae: (a) BD + 30°3639 at 4.885 GHz, with a Gaussian beam of $0''.96$ FWHM and a contour interval of 5 mJy beam^{-1} ; (b) BD + 30°3639 at 14.94 GHz, with a Gaussian beam of $0''.44$ FWHM and a contour interval of $1.35 \text{ mJy beam}^{-1}$; (c) NGC 6572 at 4.885 GHz, with a Gaussian beam of $1''.06$ FWHM and a contour interval of 7 mJy beam^{-1} ; (d) NGC 6572 at 14.94 GHz, with a Gaussian beam of $0''.44$ FWHM and a contour interval of $1.6 \text{ mJy beam}^{-1}$.

basic structure and inclination angle must be approximately correct.

IV. THE DISTANCES TO THE NEBULA

a) BD + 30°3639

The distance to BD + 30°3639 was determined in the same way as that to NGC 7027 (Masson 1986, 1989a). To calculate the angular expansion we computed a map of the difference between the two epochs, shown in Figure 3a, and divided the peak difference by the emission gradient at the same position on the 1986 map, convolved to the same resolution. It is immediately obvious that the difference map in Figure 3a shows the signature of expansion, but that the amplitude is very low. For comparison, an expansion rate of 8 mas yr^{-1} , appropriate to a distance of 600 pc, would have produced a peak signal of 1.5

mJy, 5 times the observed value. From the maps in Figure 1 and 3, we compute a radial displacement of 5.8 mas on the minor axis. In order to correct this value for the excess motion of the ionization front, and for the effect of the finite resolution, a simulation was done, using the model. This indicated that the apparent displacement of 5.8 mas corresponds to a physical motion of 6.9 mas, or 1.69 mas yr^{-1} . By combining this measured angular expansion with velocity information, the distance can be calculated.

The velocity field in BD + 30°3639 is not well known and no velocity maps are available in the literature. The most useful velocity is that of the undisturbed neutral gas, since lines arising in the ionized medium are subject to various biases due to the varying emission of the different ions as a function of position in the nebula. The predominant effect is an under-

TABLE 2
NEBULAR MODELS

PARAMETER	BD + 30°3639		NGC 6572	
	Model	Observed	Model	Observed
Temperature	9000 K		11,000 K	
Inner boundary	1".8 × 4".68		1".45 × 5".09	
Outer boundary	2".4 × 5".18		2".60 × 6".24	
Inclination angle	18°		50°	
τ (4.885 GHz)/arcsec	0.12		0.099	
Flux density:				
1.465	0.25 Jy	0.25 Jy	0.56 Jy	0.55 Jy
4.885	0.61	0.61	1.20	1.20
14.940 GHz	0.62	0.60	1.19	> 1.07
14.94 GHz map:				
Peak	351 K	345 K	431 K	344 K
Center	42	40	188	160
4.885 GHz map:				
Peak	2134	2171	3140	3037
Center	490	362	1925	1840
Proper motion correction:				
true/observed	1.19		1.02	
Flux variation effect	2.0 mas (%) ⁻¹		3.9 mas (%) ⁻¹	

estimation of the expansion velocity when the weak emission from the fast-moving ends of the nebula is blended with the strong emission from the slow-moving equator (cf. Masson 1989*b*), particularly when the nebula is barely resolved.

The most accurately determined velocity is that of blue-shifted absorption by neutral gas along the line of sight to the star, 36 km s⁻¹, relative to the central velocity of the nebula (Dinerstein and Sneden 1988; Pwa, Pottasch, and Mo 1986). The interpretation of this number depends on the location of the neutral absorbing gas relative to the ionized shell. If this velocity pertains to a shocked shell with the same velocity as the ionized gas, the inferred equatorial velocity is a factor of 2.0 less for our geometric model, or 18 km s⁻¹. If, on the other hand, the neutral gas is farther away it should have a lower velocity than the ionized gas and the deduced value of 18 km s⁻¹ is only a lower limit. The expansion velocities deduced from a number of emission lines by Wilson (1950) and Sabbadin (1984) range from 22 to 30 km s⁻¹, although the

position in the nebula is not specified. For comparison, the expansion velocities measured by Wilson for BD + 30°3639 are typically about 20% higher than those found for NGC 7027, for which we deduced an equatorial expansion velocity of 16.5 km s⁻¹ on the basis of more complete information. Taken all together, these data suggest a pretty firm lower bound of 18 km s⁻¹ for the neutral gas velocity, and an upper bound of about 25 km s⁻¹. We therefore adopt a value of 22 km s⁻¹ with an uncertainty of 20%. When the flux density variability of the nebula is measured with more accuracy, the velocity will become the largest source of uncertainty in the distance determination, and it will be necessary to make an accurate kinematic model of the nebula.

One effect which could possibly lead to an erroneous value for the proper motion is a change in the ionizing luminosity of

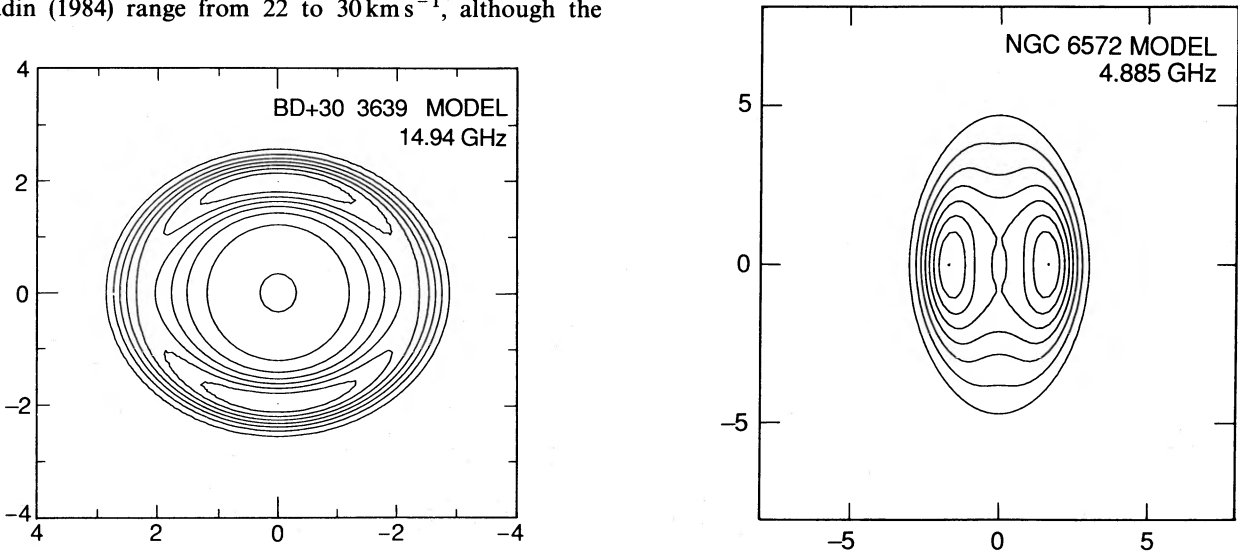


FIG. 2.—Maps of the nebular models: (a) BD + 30°3639 at 14.94 GHz, convolved with a beam of 0".44 FWHM, with a contour interval of 12.5% of the peak. (b) NGC 6572 at 4.885 GHz, convolved with a beam of 1".06 FWHM, with a contour interval of 12.5% of the peak.

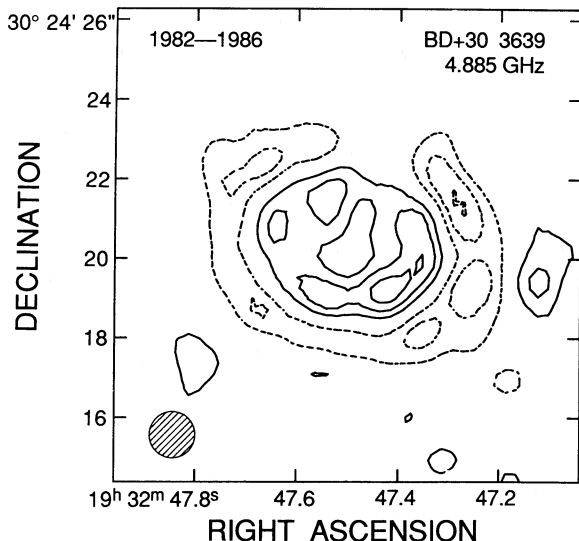


FIG. 3a

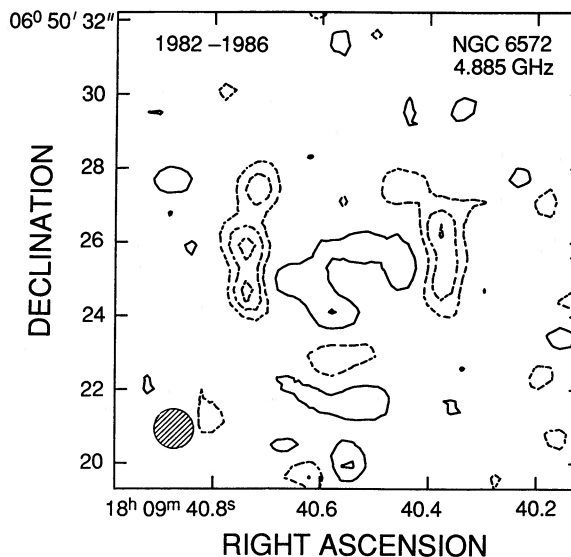


FIG. 3b

FIG. 3.—Maps of the change in nebular emission, in the sense 1982–1986: (a) BD + 30°3639 at 4.885 GHz, with a Gaussian beam of 1'20 FWHM and a contour interval of 0.2 mJy beam⁻¹; (b) NGC 6572 at 4.885 GHz, with a Gaussian beam of 1'06 FWHM and a contour interval of 0.15 mJy beam⁻¹.

the central star. Any variation of this sort, however, would also be reflected in a change in the flux density of the nebula. We have compiled a set of flux density measurements for BD + 30°3639, over two decades, reduced them to the same scale, and plotted them in Figure 4a. Since the earlier measurements have somewhat lower quality, it is not possible to rule out small variations in the flux density of BD + 30°3639, but all the data are consistent with a constant value of 0.62 Jy. If any trend is evident, it is a slight increase with time, rather than the decrease required to explain the discrepancy in distance.

The uncertainties in the distance measurement are quite large, since the apparent displacement is unexpectedly small. Because the signal in the difference map is so weak, we estimate that the uncertainty in the peak difference is 40%. Experiments indicate that the error from modeling could be as much as 20%, due to the low resolution of our maps. Finally, a possible flux density variation of 0.5% yr⁻¹ contributes an error of 1.0 mas yr⁻¹. Combining these factors, we calculate the proper

motion on the minor axis as 1.69 ± 1.30 mas yr⁻¹; the distance to BD + 30°3639 is then $2.8^{+4.7}_{-1.2}$ kpc. The relatively large uncertainty is dominated by the flux density variation.

Several previous estimates of the distance to BD + 30°3639 are tabulated in Table 3. The new determination of the distance gives a much larger value than the previous ones based on statistical methods or on mean extinction. Despite the large uncertainty, there is no plausible way that the measurements presented here could be consistent with a distance as low as 600 pc for the nebula. Because of the inverse relation between proper motion and distance, that value differs by nearly 5 standard deviations from the result found here. Such a low distance would require that the flux density dropped by 11% in only 4.1 yr, or that the expansion velocity is as low as 4 km s⁻¹. Both of these eventualities are highly unlikely. Such a large variation in flux density is excluded by the data already presented above, and a velocity of 4 km s⁻¹ is significantly below that usually found for the winds of red giants (Knapp and Morris 1985;

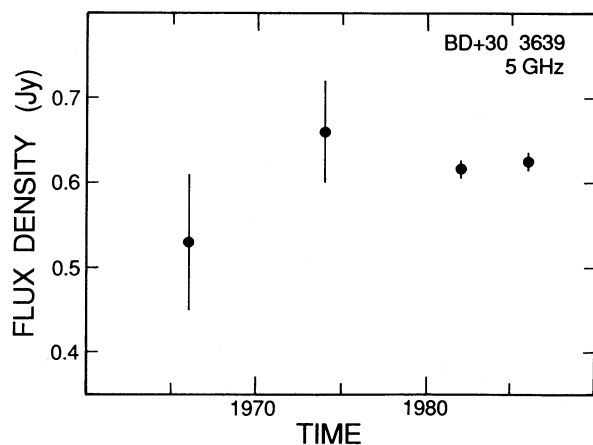


FIG. 4a

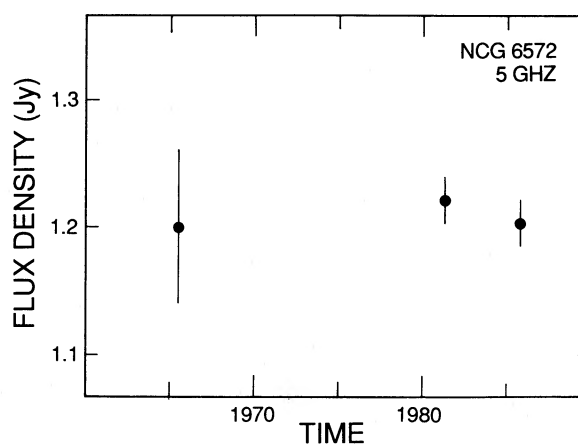


FIG. 4b

FIG. 4.—Flux density histories for the nebulae between 1966 and 1986: (a) BD + 30°3639; (b) NGC 6572. The 1966 points are taken from Kaftan-Kassim (1969), the 1973 point for BD + 30°3639 is from Scott (1975), and the remaining points are from the present work.

TABLE 3
DISTANCE ESTIMATES

Study	BD + 30°3639	NGC 6572	Method
Present work	$2.8^{+4.7}_{-1.2}$ kpc	$1.7^{+6.1}_{-0.8}$ kpc	Proper motion
Maciel and Pottasch 1980	...	814 pc	Statistical
Daub 1982	733 pc	474 pc	Statistical
Liller <i>et al.</i> 1966	...	440 pc	Proper motion
Pottasch 1984	600 pc	700 pc	Mean extinction

Zuckerman, Dyck, and Claussen 1986). Some observational support for a larger distance comes from the work of Gathier, Pottasch, and Goss (1986), who reported a weak detection of H I absorption at a velocity of $+18 \text{ km s}^{-1}$, implying a distance greater than or equal to 2.5 kpc for the nebula. At the time, however, they discounted the larger distance because the evidence was weak and because it conflicted with the previously determined value of 600 pc.

b) NGC 6572

In the case of NGC 6572, comparison of the difference map (Fig. 3b) with the 4.885 GHz map at $1''.06$ resolution gave an apparent radial displacement of 7.4 mas on the minor axis. Since the structure of this nebula is more amorphous than that of NGC 7027 or BD + 3639, it is possible that application of the cross-calibration could broaden the synthesized beam and smear out the source structure, artificially diminishing the difference between the two epochs. To guard against this, we have tried another cross-calibration, heavily weighting the short spacings ($< 20 \text{ k}\lambda$) and calibrating only phase. This attempt did not produce a significantly different result, so we conclude that the difference map presented in Figure 3b is an accurate representation.

The modeling of NGC 6572 also presented some difficulties. Although the structure is fairly well reproduced by the model described in Table 2 and shown in Figure 2b, the details are a little uncertain since the shell of the nebula is rather thick ($\Delta r/r = 0.5$), and our model is designed to represent thin-shelled nebulae. A better model could probably be obtained by allowing for some radial variation in density and temperature. Nevertheless, the basic model does a fairly good job of accounting for the appearance of NGC 6572 and is certainly accurate enough to calculate the correction factor to derive the kinematic motion from the apparent displacement calculated above. The factor is 1.02, giving a true kinematic motion of 7.5 mas, or 1.84 mas yr^{-1} .

The velocity field in NGC 6572 is even less well determined than in BD + 30°3639, but again, this does not give rise to the greatest source of uncertainty. Measurements by Wilson (1950), Osterbrock, Miller, and Weedman (1966), and Robinson, Reay, and Atherton (1982) give values of expansion velocity ranging from 15 to 17 km s^{-1} . When similar ions are compared, the values are about 25% lower than those found for NGC 7027. However, as our modeling shows, the major axis of NGC 6572 lies more nearly in the plane of the sky than that of NGC 7027 and BD + 30°3639, so the measured velocities should correspond more closely with the actual equatorial velocity in this object. Based on the geometry of our model and an assumed self-similar expansion, the line of sight velocity in NGC 6572 should be 1.25 times the equatorial velocity. Since the greater intensity of emission in the equatorial regions is likely to bias the observed line splittings to low values, the best estimate of the equatorial expansion velocity is found by divid-

ing the largest line splitting of 17 km s^{-1} by 1.25. We therefore adopt an equatorial velocity of 14 km s^{-1} , with an uncertainty of 4 km s^{-1} to allow for the unknown kinematics. Combining this velocity with the measured angular motion, we find a distance of 1.65 kpc for NGC 6572.

As before, possible flux density variations must be considered. In Figure 4b we plot flux density over a time interval of 2 decades; it can be seen that there is apparently no change in flux density over this time, to a limit of $\pm 0.3\% \text{ yr}^{-1}$, which would correspond to a proper motion error of $\pm 1.17 \text{ mas yr}^{-1}$. As was the case for BD + 30°3639, there is significant uncertainty in the measurement of proper motion, about 30%, or 0.55 mas yr^{-1} . Modeling contributes another 20%, or 0.37 mas yr^{-1} , and we allow a further 29%, or 0.53 mas yr^{-1} , for error in the velocity. Combining these values in quadrature gives a final motion of $1.84 \pm 1.45 \text{ mas yr}^{-1}$, and a distance of $1.7^{+6.1}_{-0.8}$ kpc for NGC 6572.

This new determination of the distance is greater than several recent determinations summarized in Table 3. An estimate based on mean extinction (Pottasch 1984) gives a distance of 0.7 kpc, while H I absorption (Gathier, Pottasch, and Goss 1986) gives an upper limit of 2 ± 0.4 kpc. The statistical method of Daub (1982) yields a value of 0.5 kpc, although it should be noted that this method severely underestimated the distance to the other optically thick nebulae NGC 7027 and BD + 30°3639. Interestingly, NGC 6572 is one of the few nebulae for which optical motions have been measured. The quoted proper motions (Liller *et al.* 1966) are $12.7 \pm 1.3 \text{ mas yr}^{-1}$ on the minor axis and $2.0 \pm 1.5 \text{ mas yr}^{-1}$ on the major axis. The large discrepancy between these two belies the quoted error of $\pm 1.0 \text{ mas yr}^{-1}$ for the mean of 8.1 mas yr^{-1} . A better estimate would seem to be $7 \pm 5 \text{ mas yr}^{-1}$. This is larger than the value measured in the present paper, but the significance of the discrepancy is small because of the large error. Once again, because of the inverse relation between proper motion and distance, the difference between the current measurement and the earlier, lower values is significant. For example, the statistical distance of 474 pc (Daub 1982) would imply a proper motion of 6.4 mas yr^{-1} , differing by 3 standard deviations from our result. As was the case for BD + 30°3639, the expansion velocity required to account for the lower distance is the implausibly low value of 4 km s^{-1} .

V. DISCUSSION

The distances we have determined for both of these nebulae are significantly larger than the previous estimates based on various methods. We can find no plausible sources of error which could account for the discrepancy. Modeling of the ionization front typically produces a correction factor of 20% or less. The assumption that the ionized nebula expands in a self-similar fashion causes the density to fall as f^{-3} , where f is the expansion factor. To test the effect of a different physical assumption we repeated the calculations for a case in which the

work done by the hot gas on the expanding ionized shell is balanced by a constant energy input by a wind from the central star (cf. Kahn and West 1985), leading to a density falling as f^{-2} . This changed the results by only 1%. Most other effects, such as a net flow of material toward the poles of the nebulae, would tend to increase the observed proper motion and increase the discrepancy. In any case, such corrections should be small.

Variations in the ionizing luminosities of the central stars are ruled out by the directly observed flux densities, and our estimates of the errors in measuring the proper motions are probably conservative. We are therefore forced to consider whether the previous distance estimates may be in error. The optically determined proper motion for NGC 6572 (Liller *et al.*) can be discounted because of the internal inconsistencies in that study. In addition to the discrepant results for the major and minor axes of NGC 6572, another nebula in the study, NGC 6720, showed an apparent contraction of 2.5 mas yr^{-1} , when the actual expansion should have been $5\text{--}10 \text{ mas yr}^{-1}$. Therefore we conclude that, despite the claimed accuracy of 1 mas yr^{-1} , the optical measurements have a true error of $5\text{--}10 \text{ mas yr}^{-1}$.

The statistical methods (e.g., Daub 1982; Maciel and Pottasch 1980; and references therein) are also suspect in any particular case, although they do have some general validity. For optically thick nebulae such as those under consideration here, these methods essentially proceed from the assumption that all nebulae have a similar ionizing luminosity. Necessarily, then, the more luminous objects will have their distances systematically underestimated, and the less luminous ones overestimated. Since there is no way to find the luminosity of a planetary nebula without knowing its distance, it is impossible to tell whether the statistical distance is in error.

Since distances could not be determined by H I absorption (Gathier, Pottasch, and Goss 1986), the only remaining measurement for each nebula is based on average extinction. The extinction method may be fairly accurate when extinction values can be determined for several stars close to a nebula, but it has limitations when the extinction is based on average values. In particular, systematic underestimates should be expected for nebulae, such as the two considered here, which are far enough from the Galactic plane that the scale height of the dust becomes significant. The discrepancy cannot be resolved until a more careful study is made of the extinction close to the line of sight to each nebula.

Based on the new measurements of distance, we have computed values for various physical properties of the nebulae. These are listed in Table 4, along with data for NGC 7027, which is apparently a very similar object. The total luminosity of a nebula is quite hard to determine, involving either an uncertain extrapolation of the spectrum of the central star, or a

complicated integration over the entire observed spectrum. These bright, dense nebulae, however, emit strongly in the infrared, and this portion of the spectrum accounts for a major portion of the total luminosity, possibly between 30% and 50%. Indeed, Moseley (1980) found that some of his measured infrared luminosities exceeded published estimates for the total luminosities of the central stars. For this reason, we have chosen to present the infrared luminosities as well-determined lower limits to the total luminosities of these objects. The other luminosity which is well determined is the $H\beta$ luminosity, which is proportional to the flux of ionizing photons from the central star. To avoid the effects of extinction, the $H\beta$ luminosities were calculated indirectly from the observed radio flux densities. All three objects have quite large values for these luminosities, but within the range found in samples of planetary nebulae at the relatively well-defined distance of the Galactic center (Gathier *et al.* 1983; Pottasch 1984), and the compilation of extragalactic nebulae shown by Pottasch *et al.* (1982). The luminosity of BD +30°3639 is at the high end of the range, however, which may indicate that our distance estimate is somewhat high.

Although the number in our sample is very small, it is striking that all three of the dense, infrared luminous objects are at distances much larger than indicated by statistical techniques and are therefore much more luminous and massive than previously believed. This suggests that there may have been a systematic undercounting of luminous nebulae in the solar neighborhood, affecting studies of stellar evolution and of mass return to the interstellar medium. It is important to determine the distance to more nebulae by this technique in order that such effects can be quantified, and to reduce the errors on the current determinations.

VI. CONCLUSIONS

We have presented new high-resolution maps of BD +30°3639 and have shown that it has an elongated, limb-brightened structure similar to that of NGC 7027. High-resolution maps of NGC 6572 also show some limb brightening. Our hollow, prolate-ellipsoidal model was able to account for the appearance of these nebula in quantitative detail, strengthening the suggestion of Masson (1989b) that this model is appropriate for many nebulae. We confirm that the radio appearance of BD +30°3639 differs from the infrared maps and we suggest that this may be due to the polar regions being hotter.

We have measured the changes in structure for both nebulae over a time interval of 4.1 yr and found them to be unexpectedly small, implying that the distances are significantly larger than previous estimates. The best estimate of the distance of BD +30°3639 is $2.8^{+4.7}_{-1.2} \text{ kpc}$ and that NGC 6572 is $1.7^{+6.1}_{-0.8} \text{ kpc}$, with the uncertainty being dominated by poor

TABLE 4
PHYSICAL PROPERTIES OF THE NEBULAE

Parameter	BD +30°3639	NGC 6572	NGC 7027	Unit
Distance	2.8	1.7	0.9	kpc
IR luminosity	5.1×10^{37}	1.2×10^{37}	2.1×10^{37}	ergs s ⁻¹
H β luminosity	190	100	130	$10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ kpc}^2$
Electron density	2.6×10^4	2.6×10^4	6.9×10^4	cm ⁻³
Age	1100	800	600	yr
Inner radius	0.024×0.064	0.012×0.042	0.011×0.037	pc
Outer radius	0.033×0.070	0.021×0.051	0.016×0.042	pc

knowledge of the radio flux density variation. A future measurement in 1990 should reduce the uncertainty by a factor of 2.

The new, larger distances change the status of the nebulae, making them larger, more luminous, and less dense. In these respects, the two objects studied here can now be seen to be comparable with the well-known object NGC 7027. In all three cases, the new distances are larger than estimated by statistical techniques, suggesting that luminous nebulae may have been

systematically undercounted in the solar neighborhood. This would have implications for studies of stellar evolution and of gas return to the interstellar medium, but the effects cannot be quantified until distances are measured to more objects, and the accuracy of the current estimates is improved.

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