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NEW KINEMATIC DISTANCES OF NGC 7009 AND BD+30°3639 FROM UV AND RADIO DATA

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Abstract. Measurements of the equivalent width of the interstellar Lyman α line from IUE spectra in the direction of the planetary nebulae NGC 7009 and BD+30°3639 are used to infer the H column density in these directions. Hydrogen 21 cm profiles are also used in connection with the ultraviolet data so that the expected rotation velocities and distances can be determined. The results are compared with recently published distances, in an attempt to distinguish between the "short" and "long" PN distance scales as applied to these objects.

1. Introduction

Distances of galactic planetary nebulae (PN) are still poorly known, as both individual and statistical methods frequently show uncertainties of a factor 2 or higher (Kwok, 1994; Terzian, 1993; Pottasch, 1992; Peimbert, 1990a). Recent work has tried either to provide a large number of reasonable distances using some kind of statistical approximation (cf. Cahn *et al.*, 1992), or has focussed on a small number of objects for which detailed individual measurements are expected to produce more accurate distances (cf. Hajian *et al.*, 1993).

Two particularly interesting objects are the galactic planetary nebulae NGC 7009 (PK 037-34 1) and BD+30°3639 (PK 064+05 1). For both nebulae, recent distance determinations seem to indicate either a "short" (500–900 pc) or "long" (1200–2700 pc) distance, as discussed in section 4. Moreover, this discrepancy can be observed in distances determined both by *individual* and *statistical* methods, so that it cannot be completely ascribed to the uncertainties of the latter, as often argued in the literature.

In fact, the distinction of a short or long distance scale, when applied to a large set of galactic objects, is a long-standing problem in the study of planetary nebulae, and has far-reaching consequences on the space distribution and birthrates of these objects, (cf. Peimbert, 1990a,b; Cahn *et al.*, 1992). Therefore, it is interesting to investigate an independent method that could be applied to these objects, so that a choice between the short and long distance scales could be made, at least for some particular nebulae.

In the present work, both ultraviolet (IUE) and radio (21 cm) data are used in order to determine kinematic distances of NGC 7009 and BD+30°3639. Measurements of the interstellar Lyman α line in the direction of the nebulae give the total H column density in these directions, which can be compared with the

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TABLE I

IUE data for NGC 7009 and BD+30°3639

object	spectra	exposure time (s)	date	class*
NGC 7009	SWP 8679L	240.0	06 Apr 80	71
NGC 7009	SWP 1709L	600.0	03 Jun 78	70
NGC 7009	SWP 23382L	360.0	02 Jul 84	71
NGC 7009	SWP 14394S	420.0	04 Jul 81	70
NGC 7009	SWP 8579L	180.0	27 Mar 80	70
BD+30°3639	SWP 1896L	240.0	01 Jul 78	70
BD+30°3639	SWP 8590L	300.0	29 Mar 80	70
BD+30°3639	SWP 41868L	300.0	18 Jun 91	70
BD+30°3639	SWP 1895L	720.0	01 Jul 78	70
BD+30°3639	SWP 4923L	330.0	12 Apr 79	70

* class 70 = nebula + central star; 71 = central star

corresponding density derived from 21 cm hydrogen profiles. This permits to infer the rotation velocity at the nebular position and their distances, with the aid of a known galactic rotation curve. Preliminary results using a similar method were presented by Maciel and Pottasch (1983).

2. IUE Spectra of NGC 7009 and BD+30°3639

A large quantity of ultraviolet spectra taken in the direction of planetary nebulae and/or their central stars is part of the low resolution spectral data archive of the International Ultraviolet Explorer (IUE) satellite (Wamsteker *et al.*, 1989). These include spectra of both NGC 7009 and BD+30°3639 (central star HD 184738), which show the Lyman α line in absorption of interstellar origin. We have used several of these spectra (cf. Table I) in order to determine the equivalent width of the interstellar line. Figure 1a, b shows representative spectra of NGC 7009 and BD+30°3639, respectively.

The equivalent width of the Lyman α line can be written as

$$W_\lambda = \int_0^\infty \frac{F_c - F_\lambda}{F_c}\, d\lambda = \int_0^\infty \left[1 - e^{-\tau(\lambda)}\right] d\lambda \qquad (1)$$

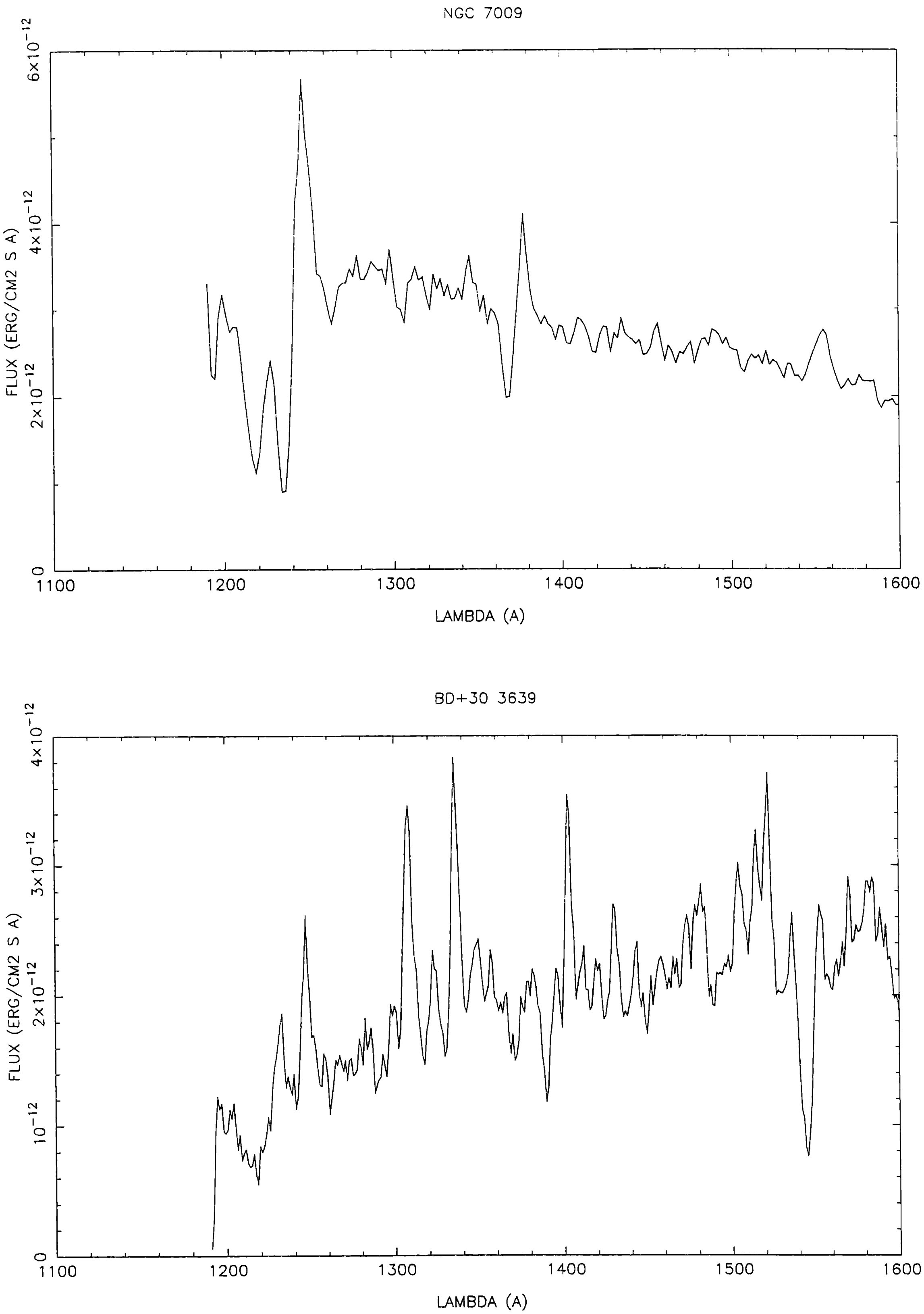

Fig. 1. Representative IUE spectra in the direction of (a) NGC 7009 and (b) BD+30°3639.

TABLE II

Equivalent widths and column densities

object	W_λ (A)	N_H (cm^{-2})
NGC 7009	14.0 ± 5.0	$(3.7 \pm 2.7) \times 10^{20}$
BD+30°3639	16.8 ± 8.5	$(5.4 \pm 4.0) \times 10^{20}$

where F_c is the continuum flux, F_λ is the line flux, and $\tau(\lambda)$ is the line optical depth. At the line centre the optical depth is extremely large, with progessively weaker radiative wings. In this case the optical depth can be straightforwardly computed as a function of the H column density N_H, so that the latter can be written as

$$N_H = 1.9 \times 10^{18} \, W_\lambda^2 \tag{2}$$

where N_H is given in cm^{-2} and W_λ in A (cf. Jenkins, 1970; Morton, 1967).

From the UV spectra, the equivalent widths and H column densities have been computed for the direction of both nebulae, and are given in Table II along with the estimated uncertainties. In order to do this, we have first approximately drawn the continuous flux line from neighbouring wavelengths in the spectra listed in Table I. The actual equivalent widths were measured only for those spectra showing a reasonably well defined Lyman α line. Since all spectra are calibrated with absolute fluxes, we have taken as the baseline the zero flux line. In this way, we were able to determine an "average profile" from the best exposures. The standard deviation relative to the average profile is negligible near the line wings, but may reach up to 35% for NGC 7009 and somewhat higher values for BD+30°3639 near the line centre. A similar uncertainty, corresponding to 5 A, can be anticipated for the equivalent width of NGC 7009, which is larger than the spectral width of the stellar line. This can be further confirmed by the fact that both nebular and stellar spectra, when available, indicate approximately the same widths for the interstellar line. Also, the large column densities derived from eq. (2) ($N_H > 1 \times 10^{20}$ cm^{-2}) are in agreement with the assumption of a pure damping profile, and suggest that the stellar/wind contributions are probably negligible, owing to the characteristics of the PN central stars (Morton, 1967; Savage and Panek, 1974; Spitzer and Jenkins, 1975; Bohlin *et al.*, 1978).

A more difficult problem is the presence of the geocoronal Lyman α line, especially in the case of BD+30°3639. As discussed by Pwa *et al.* (1986), this contribution cannot be completely removed, which led those authors to propose an upper limit of 23 A for the interstellar line in the direction of this nebula. We made an effort to separate the interstellar line by considering several spectra and carefully eliminating any observed emission. Our result (cf. Table II) agrees well with the limit set by Pwa *et al.* (1986), so that we can estimate an upper limit for the uncertainty in the equivalent width of about 50%.

Before we proceed to the determination of the distances, it is interesting to investigate how reasonable are the column densities derived, since a number of hypotheses had necessarily to be made which are not self evident. We have then compared the column densities given in Table II with the values predicted by the gas-to-dust ratio as given by Bohlin *et al.* (1978). For NGC 7009, an average colour excess $E(B-V) \simeq 0.1$ mag has been determined (Tylenda *et al.*, 1992; Cahn *et al.*, 1992), so that the total column density of H nuclei is essentially the same as the HI density, that is, $N \simeq 5.8 \times 10^{20}$ cm^{-2}, which is in good agreement with our derived value. For BD+30°3639 there are evidences of a heavier extinction, $E(B-V) \simeq 0.2-0.3$ mag (Cahn *et al.*, 1992), but up to half of this can be attributed to the internal reddening (Pwa *et al.*, 1986). The predicted column density $N \simeq 10^{21}$ cm^{-2} further includes some amount of molecular hydrogen (Bohlin *et al.*, 1978), so that it can be considered as an upper limit, in agreement with the value given in Table II. Also, for this nebula the derived H column density agrees well with the average ($N_H \simeq 6.7 \times 10^{20}$ cm^{-2}) obtained by Pwa *et al.*, (1986) on the basis of abundance determinations of the undepleted elements S and Zn.

Another evidence in favour of the column densities given in Table II can be obtained from the volume densities in the considered lines of sight. As we will see in Section 4, the derived distances are in the range $1-2$ kpc, so that the volume densities are $0.1-0.2$ cm^{-3}, which is typical of the interstellar gas in the direction of hot stars in the Galaxy (see for example Morton, 1967; Jenkins, 1970).

As a conclusion, although some of these comparisons are necessarily qualitative or semi-quantitative, it seems clear that the densities are quite reasonable, so that we can be sure that no quantity has been grossly over(under)estimated.

3. Hydrogen 21 cm Profiles

Hydrogen 21 cm profiles in the direction of the planetary nebulae in this study are included in the Berkeley surveys (Weaver and Williams, 1973, 1974a,b; Heiles and Habing, 1974). The survey was made with the automated 85-foot telescope and the 100-channel receiver at the Hat Creek Observatory. The frequency resolution of the receiver was 10 kHz, which corresponds to 2.11 km s^{-1} at half power. The angular resolution was $35.5'$ (HPBW), and the RMS temperature fluctuations were estimated as 0.38 K (cf. Weaver and Williams, 1973). We have used a magnetic tape version of the survey, which allows higher accuracy than the printed version.

The profiles consist of plots of the brightness temperature T_b as a function of the LSR radial velocity for a given pair of galactic coordinates. Assuming the HI region in the intervening interstellar clouds to be optically thin to radiation in the 21 cm line, the density of neutral H in a given line of sight can be written as

$$N_H = 1.8 \times 10^{18} \int T_b(V)\, dV \tag{3}$$

where N_H is again in cm^{-2}, T_b in K and the velocity in km s^{-1} (cf. Spitzer, 1978; Jenkins, 1970; Morton, 1967; Mihalas and Binney, 1981). The integration limits are defined for the particular line of sight considered. Figure 2a, b shows the adopted 21 cm profiles for the direction of NGC 7009 and BD+30°3639, respectively. Both objects are located in the first quadrant ($0^\circ < \ell < 90^\circ$), so that the observed peaks at negative velocities can be attributed to features at large distances from the sun in comparison with the peaks at positive velocities.

For NGC 7009 (Figure 2a), the Berkeley survey (Weaver and Williams, 1973, 1974b) gives temperature profiles and contours at longitude and latitude intervals of $\Delta\ell = 0.5^\circ$ and $\Delta b = 0.25^\circ$, respectively. An inspection of the 21 cm profiles for longitude $\ell = 37^\circ$ and negative latitudes reveals several features at negative velocities, apart of the main peak at positive velocities. The features at negative velocities are interpreted as structures that are relatively far away from the sun, which is supported by an inspection of the maps by Heiles and Habing (1974). Although at the nebular latitude these features are weak in comparison with the positive main peak (cf. Figure 2a), their existence is made clear when we inspect the remaining profiles at the given longitude for different values of the galactic latitude, as shown for example by the plots of Weaver and Williams (1973, p. 77) or Weaver and Williams (1974a, p. 274). Only the last of these features, centered at about -3 km/s, has some influence on the main, nearby peak. However, even in this case the effect is relatively small, since at the nebular latitude the intensity of this feature is small, as already mentioned. In order to determine the velocity associated with the position of the nebula, we have decomposed the profile and removed this feature, so that the integration (3) could be done essentially from the position of the sun. In this case, the column density given in Table II was reached at a velocity of 18.0 km/s.

In the case of BD+30°3639 (Figure 2b), the 21 cm profiles show two peaks at positive velocities (5 and 18 km s^{-1}), and three features at negative velocities, namely -105, -85, and -15 km s^{-1}. The profiles at the given longitude and latitudes close to zero can be seen for example in Weaver and Williams (1973, p. 131) or Weaver and Williams (1974b, p. 296). The last of the features at negative velocities, namely -15 km s^{-1}, is barely seen in Figure 2b, but its presence is made evident by an inspection of the profiles at latitudes $b \simeq 0^\circ$, as can be observed, for example, in the plot by Weaver and Williams (1973, p. 131). Analogously to the case of the previous nebula, we have assumed that the features at negative velocities are formed in clouds that are far away from the sun, so that only the clouds at velocities -15, +5 and +18 km s^{-1} should be taken into account in the integration procedure. For this object, some results obtained with the Dwingeloo 25 m telescope (Gathier *et al.*, 1986) were also used. From the column density given in Table II we derive a velocity of 8.4 km s^{-1}.

The main sources of error in this procedure are due to optical depth effects in the 21 cm line and deviations from the circular motion. The former can be investigated by a simple estimate of the total optical depth τ(21 cm) in the direction of the

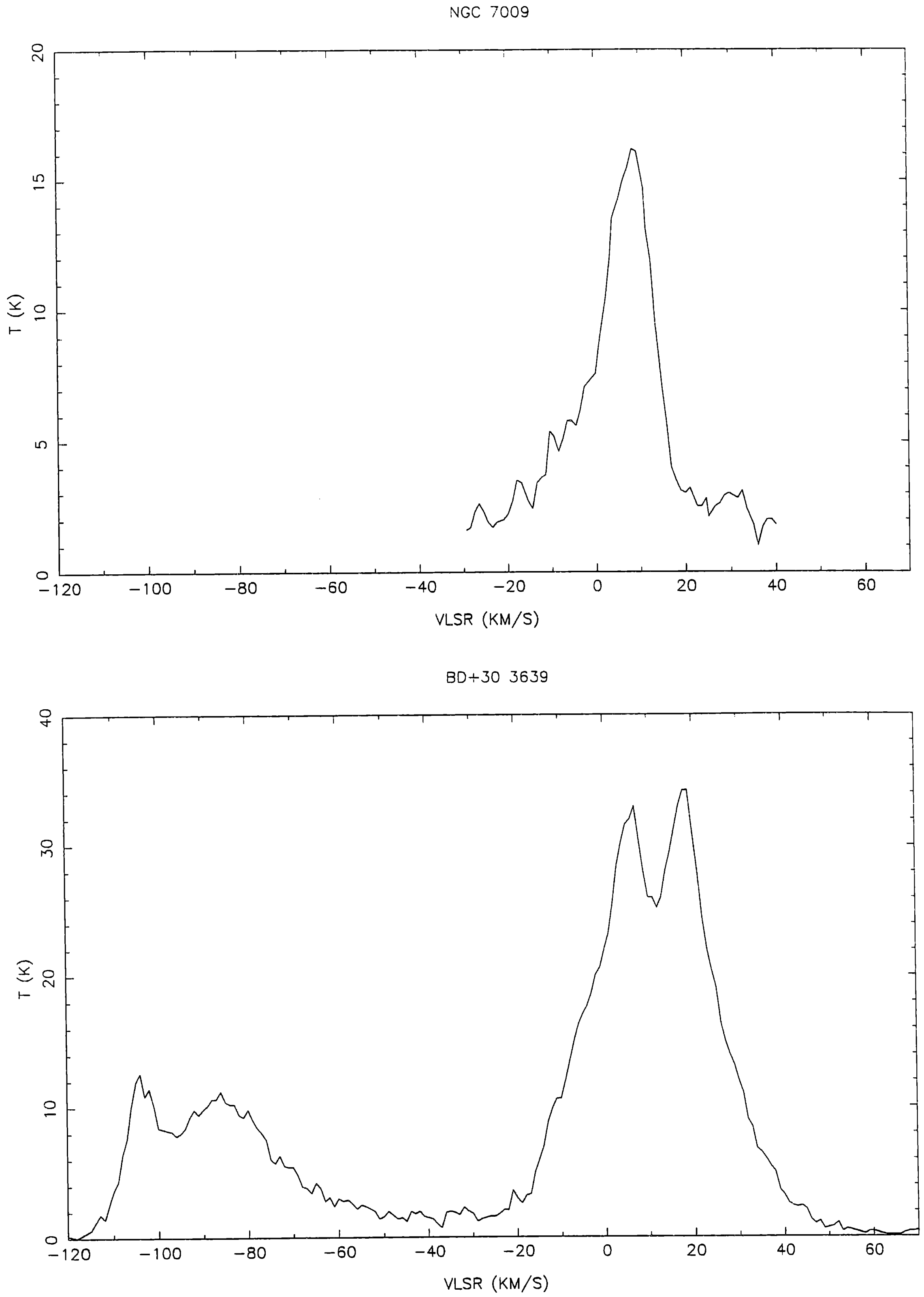

Fig. 2. Brightness temperature profiles for the 21 cm line in the direction of (a) NGC 7009 and (b) BD+30°3639.

nebulae. It results that $\tau(21\ \text{cm}) \ll 1$ for all cases, provided that the kinetic temperature $T > 50$ K. Therefore, the main source of error can be attributed to departures from circular motion, either from random components or from any systematic variations from circular velocity, especially for NGC 7009, which has a relatively high galactic latitude. In a study of distance determinations of planetary nebulae from HI absorption measurements at 21 cm, Gathier *et al.* (1986) quote average random motions of the order of 6 km/s. From the hydrogen profiles an average uncertainty under 8 km/s can be estimated. As we will see in the next section, the derived distances are close to the limit of about 1 kpc for which the use of the 21 cm H profiles are recommended (Bohlin *et al.*, 1978).

4. Determination of Kinematic Distances

In a recent work, Maciel and Dutra (1992) showed that planetary nebulae of types I and II according to the Peimbert (1978) classification system have a closer association with the galactic rotation curve than the remaining PN types. The objects considered in the present study are of type II, for which the peculiar velocities are in average $|\Delta V| \leq 20$ km/s, indicative of relatively small deviations from the circular motion associated with the rotation curve. In this case, the distance d to the nebulae can be related to the galactocentric distance R projected onto the galactic plane by

$$R^2 = R_0^2 + (d\ \cos b)^2 - 2R_0 d \cos b \cos \ell \tag{4}$$

where R_0 is the LSR distance to the galactic centre. The radial velocity at the position of the nebula is given by

$$V_{LSR} = R_0 \left[\frac{\Theta(R)}{R} - \frac{\Theta_0}{R_0} \right] \sin \ell \cos b \tag{5}$$

where Θ_0 is the linear velocity at the sun's position.

We have solved equations (4) and (5) for R and d using two different assumptions. First, we adopted the rotation curve $\Theta(R)$ by Clemens (1985) with $R_0 =$ 8.5 kpc and $\Theta_0 = 220$ km/s, however making a correction to take into account the recent determinations of the distance of the sun to the galactic centre (cf. Reid, 1989; Maciel, 1993). We have adopted the value $R_0 = 7.6$ kpc obtained by Maciel (1993) from an analysis of a complete sample of globular clusters in the Galaxy with measured metallicities. The results are $d(\text{NGC7009}) = 1400$ pc and $d(\text{BD}+30°3639) = 700$ pc. Second, better results can be obtained by the use of the PN rotation curve as derived by Maciel and Dutra (1992), since this curve has been defined in terms of the motion of type I and II planetary nebulae themselves. Again, we corrected for $R_0 = 7.6$ kpc, and obtained $d(\text{NGC7009}) = 1550$ pc and $d(\text{BD}+30°3639) = 750$ pc, with slightly larger values for $R_0 = 8.5$ kpc. This leads to the adopted distances

$$\begin{aligned} d(\mathrm{NGC7009}) &= 1600\,\mathrm{pc} \\ d(\mathrm{BD}+30°3639) &= 800\,\mathrm{pc}. \end{aligned} \tag{6}$$

It should be mentioned that the distance ambiguity which occurs for both nebulae is easily removed, as the second distances are in the range 6 – 13 kpc, which is physically unacceptable, as they would imply for example extremely large intrinsic nebular radii or high luminosities for the PN central stars. A similar result would follow if we adopted the observed radial velocities of the nebulae (cf. Schneider *et al.*, 1983). In this case, the integration (3) would encompass all the positive velocities (all the line of sight for NGC 7009), which would produce column densities 3 – 5 times larger than the derived densities given in Table II, and thererfore extremely large distances.

A realistic estimate of the uncertainties of the results given by equation (6) is an extremely difficult problem, basically due to the lack of a calibrated sample of PN distances large enough for statistical studies. However, formal uncertainties can be obtained, provided the main assumptions made are correct. In the case of the present paper, the two main sources of errors in the distances given by (6) are (i) uncertainties in the determination of the Lyman α equivalent widths, and (ii) uncertainties in the H 21 cm column density × velocity (or distance) relation. As already discussed, uncertainties of class (i) include any spurious contribution to the Lyman α line, such as stellar, wind and geocoronal, and are probably less important than the second group, which includes optical depth effects in the 21 cm line and deviations from the circular motion. From the discussion in sections 2 and 3, and based on $N_H \times V$ and $N_H \times d$ relationships, we estimate an average uncertainty of about 50% in the distances of both nebulae, although for NGC 7009 this is probably an upper limit. Such uncertainties are similar to those attributed to most individual methods for obtaining distances of planetary nebulae, except perhaps the VLA expansion and model atmosphere methods, and are expected to be correct provided the main assumptions made in the previous sections are correct.

Table III shows the results of the present investigation, along with some selected distances for NGC 7009 and BD+30°3639 available in the literature. It can be seen that for these objects both “short” (500 – 900 pc) and “long” distances (1200 – 2700 pc) have been proposed, clearly showing that the actual uncertainties of most determinations are larger than usually reported. Our results seem to indicate that the correct distance to NGC 7009 is closer to the long scale. In view of the characteristics of the present method, in particular the presence of random or systematic motions at relatively nearby distances, this distance is probably well determined, as it is not strongly dependent on such motions. In fact, the use of 21 cm H profiles is better applied to objects which are relatively far away (Bohlin *et al.*, 1978), which is the case of this nebula. For BD+30°3639 our method indicates a distance consistent with the short scale, in contrast with some recent results (see

TABLE III

Distances of NGC 7009 and BD+30°3639

Ref.	Method	NGC 7009	BD+30°3639
Cahn & Kaler (1971)	Shklovsky-Hβ	1300	2700
Cahn & Kaler (1971)	Shklovsky-red	1600	2000
Cudworth (1974)	proper motion	1900	1100
Milne & Aller (1975)	Shklovsky-radio	1300	
Acker (1978)	synthetic	900	700
Pottasch (1980)	expansion/extinction	600	800
Daub (1982)	radio flux	800	700
Amnuel *et al.* (1984)	radio flux-diameter	600	700
Maciel (1984)	mass-radius relation	900	>600
Kaler *et al.* (1985)	wind	800	200
Sabbadin (1986)	adopted averages	500	600
Barlow (1987)	Hβ flux	2300	
Gathier (1987)	expansion	600	
Meatheringham *et al.* (1988)	electron density and excitation class	800	
Weidemann (1989)	central star mass	>1600	
Méndez *et al.* (1992)	model atmosphere	2100	
Cahn *et al.* (1992)	modified Shklovsky	1200	1200
Kingsburgh & Barlow (1992)	electron density	2300	
Zhang (1993)	mass-gravity	1000	2600
Hajian *et al.* (1993)	expansion		2700
This work	UV-radio kinematic	1600	800

Table III). However, this object seems to lie close to the limit of about 1 kpc, so that its distance is probably less well determined.

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