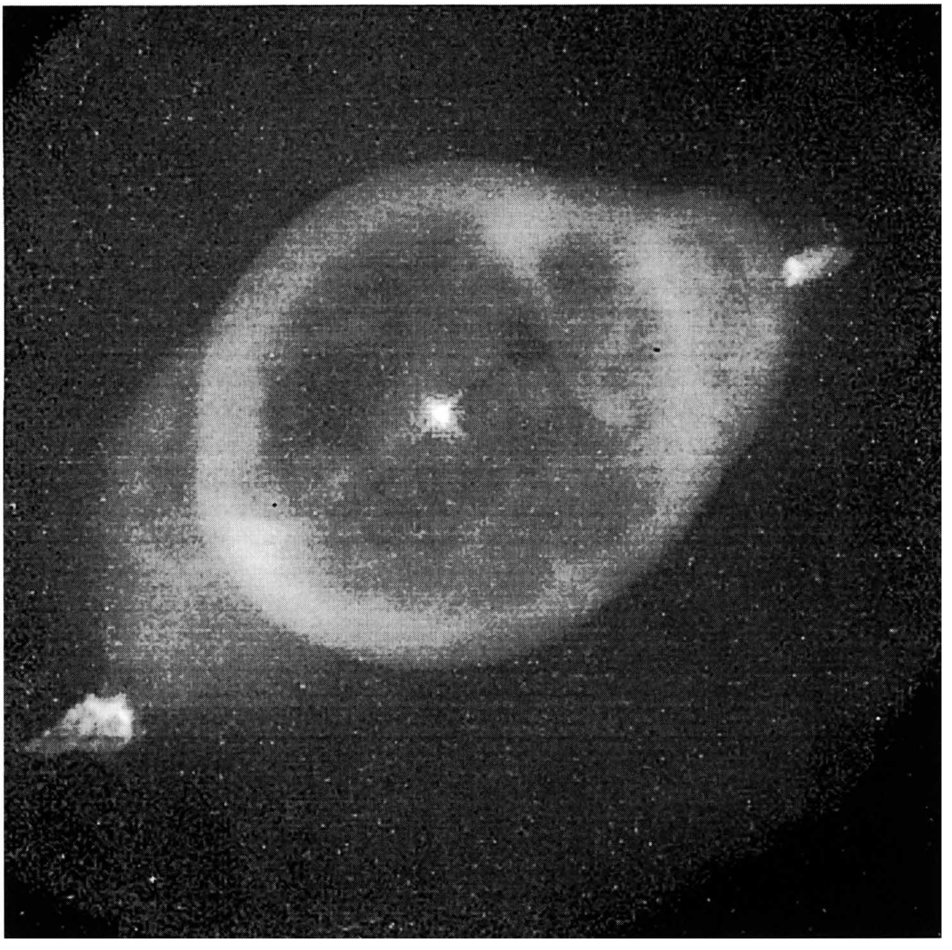
II. DISTANCES TO GALACTIC PLANETARY NEBULAE



NGC 3242 observed with the Planetary Camera of the Hubble Space Telescope in the light of [N II]658.3nm. In order of distance from the *stellar nucleus*, the main features are the sharp-edged elliptical *bright rim*, the smooth surrounding *shell*, and the pair of low-ionization *FLIERs* seen near the major axis.
Credit: *Narrowband HST images of Microstructures in Planetary Nebulae*,
Bruce Balick, J. Alexander, A. Hajian, Yervant Terzian, M. Perionotto, and P. Patriarchi.

EXPANSION DISTANCES OF PLANETARY NEBULAE

YERVANT TERZIAN
Cornell University, NAIC Ithaca, New York

Abstract.
The distances of planetary nebulae are discussed as derived from their angular expansions and radial expansion velocities. An assessment is given of distances derived by this method both at optical and radio wavelengths. The recent VLA radio data show promise in establishing a more accurate distance scale for planetary nebulae.

1. Introduction

Even though galactic PNe have been extensively studied and we clearly understand that they represent the late stages of stellar evolution for stars between about one and several solar masses, some of their fundamental parameters such as their stellar luminosities and nebular masses remain uncertain because their distance estimates are very poorly known (Terzian 1993). The issue of determining accurate distances to PNe has important implications to the derivation of their total numbers in the galaxy, and hence to the total UV radiation emitted by these objects that affects the state of the diffuse interstellar matter, and to the total amount of processed material (particularly C, N and O) enriching the galaxy.

Classes of PNe have reasonably determined distances such as the several hundred PNe detected in other nearby galaxies, and a few hundred PNe in the direction of the Galactic Bulge that are presumably close to the distance of the Galactic Center. However, for most of the PNe in our galaxy their distances are uncertain by at least a factor of 2.

Very few PNe are close enough to determine trigonometric parallaxes of their central stars (Pier, et al. 1993, Harris, et al. 1996) and few PNe central stars are known to be members of binary stellar systems in order to derive spectroscopic parallaxes. And again only very few are members of

H. J. Habing and H. J. G. L. M. Lamers (eds.), Planetary Nebulae, 29–39.

stellar clusters where independent distances can be derived. The predominant methods of claiming distances to PNe have been statistical ones by making general initial assumptions such as a constant mass ejected from the PN central star (Shklovsky method). Such methods are extremely uncertain and for individual PNe may have errors even larger than factors of two or three.

2. Expansion distances

Distances for PNe can also be determined by the parallax expansion method as is usually done for resolved novae. As a nebula expands its rate of motion appears as a proper motion measurable in arcseconds per year. Spectra obtained at the same period of time give the expansion velocity directly in kilometers per second. If the expansion is uniform then the proper motion corresponds to the same velocity. The geometry of the expansion allows to find the distance D to the nebula as:

$$\begin{aligned} llD_{pc} &= 211\frac{V_{\mathrm{km/sec}}}{\dot{\Theta}_{\mathrm{mas/yr}}} \\ &= 21.1\frac{V_{\mathrm{km/sec}}}{\dot{\Theta}_{\mathrm{arcsec/century}}} \end{aligned} \tag{1}$$

where V is the radial velocity and $\dot{\Theta}$ is the proper motion. This method has been applied both at optical and radio wavelengths to determine distances to PNe.

The early work at optical wavelengths began with Latypov (1957) who tried to measure the angular expansion of NGC 6720NGC 6720 with a time baseline (Δt) of 50 years. Čudovičera (1964) followed these attempts by studying NGC 6853NGC 6853 and NGC 7662NGC 7662 with Δt of 22 and 26 years respectively. W. Liller (1965) investigated NGC 7009NGC 7009 with Δt of about 50 years. The first systematic work at optical wavelengths was reported by Liller, et al. (1966).

Liller, et al. (1966) described measurements of angular dimensions of 14 PNe on plates taken at intervals ranging form 44 to 62 years, dating back to 1898. Some of the excellent first epoch plates were made between 1898 and 1918 with the 36-inch Crossley reflector at Lick Observatory by Keeler (1908) and by Curtis (1918). In 1961 W. Liller (1965) used the same Crossley reflector to obtain images of 28 PNe. The results of this work indicated that four objects had measurable expansions at least three times the mean error, these were NGC 3242NGC 3242, NGC 6572NGC 6572, NGC 7009NGC 7009 and NGC 7662NGC 7662. The object NGC 246NGC 246 had an expansion measurement 2.8 times the mear error.

However, Orlova (1973) argued that the angular expansions derived at optical wavelengths have a very low accuracy due to the use of different photographic emulsions at the different epochs, and in some cases also due to the use of different telescopes, thus introducing unknown systematic errors.

Terzian (1980) first noted that radio brightness temperature distributions of PNe obtained at high resolution using the VLA, when observed at two different epochs separated by several years, may show measurable angular nebular expansions from which distances to these objects can be derived. For PNe radio measurements have the advantage of high surface brightness, good signal to noise ratio, and almost zero interstellar extinction. This method was applied by Masson (1986) who showed that the angular expansion of NGC 7027NGC 7027 could indeed be measured with a baseline of only 2.8 years. The detailed methods of extracting the angular expansions have been described by Masson (1986, 1989), Seaquist (1991), Hajian, et al. (1993), and Hajian (1995).

The nebular expansions are very small, of the order of a few mas per year, and structural changes are not resolved with the typical VLA resolution of $\sim 1''$. Hence very careful map comparisons are necessary at different epochs to deduce any angular expansions.

Comparisons of maps made at different epochs have two errors - one calibration errors, and two, errors due to synthesized beams between the two epochs. A process called self-calibration which is an iterative method is used where the radio map is fitted to the observations to establish the calibration errors and to result into a new map. This iterative process converges to accurate epoch maps which are then cross-calibrated. Any beam shape differences between the two epoch maps are minimized by using the CLEAN deconvolution and comparing one map with the cross-calibrated map of the other epoch. Differences in beam shape result from differences in the sampled UV plane observed several years apart.

Normally the difference maps will show the nebular expansions as a negative ring at the outside of a positive nebular ring. The magnitude of this expansion is indicated by the peak intensity of the difference map and can be determined by the flux gradients across the minor axis of a nebula at the positions corresponding to the peaks of the difference maps. Figure 1 shows the brightness temperature distribution of the PN NGC 7027 observed with the VLA at λ 6cm, with a synthesized beam of $\sim$1 arcsec (Hajian, et al. 1993). Figure 2 shows the comparison of two processed difference maps of NGC 7027 (a) from Masson (1986) and (b) from Hajian, et al. (1993). These figures show the negative (dashed lines) and positive contours as expected

https://doi.org/10.1017/S0074180900129754 Published online by Cambridge University Press

from the expansion parallax method described above showing real angular expansion and in good agreement between two independent studies.

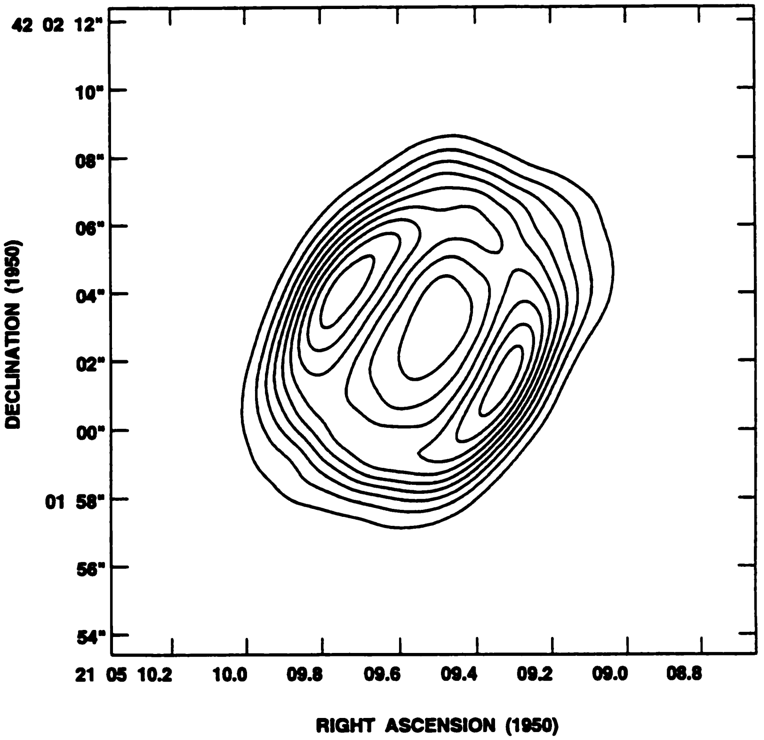


Figure 1. VLA λ6cm map of NGC 7027NGC 7027 (Hajian, et al. 1993).

It is very encouraging indeed that independent radio synthesis observations of PNe obtained at different epochs by different researchers have produced similar results for the angular expansions of several PNe. The excellent signal to noise radio maps have opened a new important method in determining the distances to these objects, in testing dynamical models and in deriving the ages of the nebulae in a direct way.

In Table 1 we summarize the available data on PNe distances from optical and radio measurements. If we judge the comparison of the various measurements for the same objects then the distance to NGC 7027 seems determined with very high degree of confidence. Other cases show larger differences, but one could argue that a few of the optical measurements may have systematic errors as discussed by Orlova (1973).

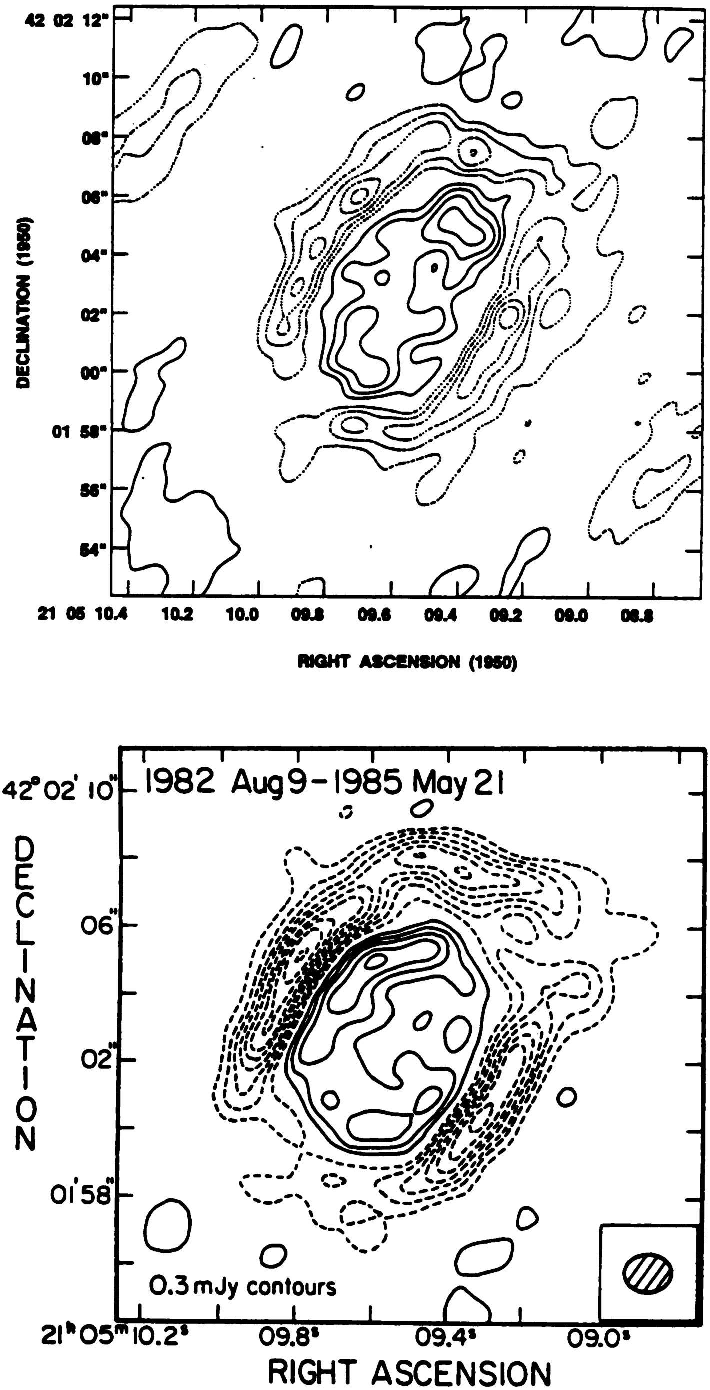


Figure 2. (a) Difference map from two VLA observations (October 1983 and March 1989) from Hajian, et al. 1993, and (b) Difference map from two VLA observations (August 1982 and May 1985) from Masson (1986).

TABLE 1. Planetary Nebulae expansion distances

hline PN	Θ("/100 yrs)	Vexp(k/sec)	Distance (pc)	Method	Ref.
NGC 246NGC 246	1.4± 0.5	38	570	Optical	1
NGC 2392NGC 2392	0.72± 0.06	55	1600	Optical	2
NGC 3242NGC 3242	0.83± 0.25	20	510	Optical	1
	1.32± 0.47	26± 4	420	Radio	3
NGC 6210NGC 6210	0.31± 0.04	23± 5	1570	Radio	3
NGC 6302NGC 6302	0.18± 0.03	13	1600	Radio	4
NGC 6572NGC 6572	0.81± 0.10	17	440	Optical	1
	0.25± 0.08	14± 4	1180	Radio	3
	0.25± 0.06*	14± 4	1200*	Radio	5
BD 30-3639BD 30-3639	0.173± 0.051	22± 1.5	2680	Radio	6
	0.30± 0.05*	22± 4	1500*	Radio	5
NGC 7009NGC 7009	0.70± 0.3	21	600	Optical	1
NGC 7027NGC 7027	0.47± 0.7	21	940	Radio	7
	0.42± 0.06	17.5± 1.5	880	Radio	8
	0.525± 0.1	17.5± 1.5	700	Radio	6
NGC 7662NGC 7662	0.56± 0.15	21	790	Optical	1
	1.0± 0.6	26	550	Optical	9
	0.26± 0.09	21	1700	Optical	2
	0.56± 0.5	21	790	Radio	10

* Corrected for constant flux between epochs.
1. Liller, et al. (1966); 2. Liller and Liller (1968); 3. Hajian, et al. (1995); 4. Gomez, et al. (1993); 5. Kawamura and Masson (1996); 6. Hajian, et al (1993); 7. Masson (1986); 8. Masson (1989); 9.Čudovičeva (1964); 10. Hajian and Terzian (1996)

3. Limitations of expansion distances

Even though the expansion parallax method in deriving distances to PNe is one of the best methods we have developed, it has its limitations and should be applied with good understanding of the underlying assumptions. To begin with to derive distances one needs both a knowledge of the angular (arcsec/yr) expansion and the radial (km/sec) expansion presumably of the same volume element of the nebula. The velocity of expansion is normally adopted from optical [OIII], or Hα radial velocity measurements. Kinematical models are needed for each nebula to correct the measured values for such effects as nebular shape and inclination. The angular expansions are very small and are of the order of $\sim$0.2 arcsec per century for a typical nebula 1000 pc away, hence the time baselines can be large in some cases. Angular expansion measurements at optical wavelengths using photographic emulsions can be unreliable particularly when Δt is large. Modern CCD images are now greatly superior. One also has to assume that the ionization front moves much faster than the expansion motion of the gas. Other effects are the possible changes in the ionizing luminosity of the central star which could be assessed from small radio flux density changes of the nebula.

Kawamura and Masson (1996) have discussed a correction to take into account the overall decrease of the surface brightness as the nebula expands at constant flux. Assuming that the flux density is constant within the few years between observation epochs then as the nebula expands the surface brightness should decrease if the total flux remains constant. This correction is appropriate for expansion measurements where the beam is comparable to the size of the observed source. Kawamura and Masson (1996) have applied this correction to the small nebulae BD+30°3639BD+$30^0$3639 and NGC 6572NGC 6572. We should point out that nebular filaments, knots or other features may not decrease in brightness uniformly and if these are resolved this correction is negligible. In their analysis these authors also show that beam dilution and the excess movement of the ionization front corrections are very small and close to unity.

In the case of BD+30°3639 the correction of the decrease of the surface brightness applied by Kawamura and Masson is surprisingly significant, and even though the measured angular expansion rate for this nebula by them and independently by Hajian, et al. (1993) agree very well, the derived distances differ due only to this correction. These same authors have also observed and analyzed independently the angular expansion of NGC 6572 and in this case the derived final distances are in good agreement with those derived by Hajian, et al. (1993). (see Table 1).

We have made an attempt to combine the expansion distances from Table 1 with available trigonometric and spectroscopic parallax distances of PNe. In Table 2 such a summary is presented. These are then compared to two recent independent distance determinations for these objects, one using the Shklovsky statistical method by Cahn, et al. (1992), and the other using the new statistical method by van de Steene and Zijlstra (1994) based on an empirical correlation between radio continuum brightness and radius of the nebulae. Table 3 shows a comparison of these data. There is only mild agreement between the distances derived by statistical methods and the direct distance methods.

4. Discussion and conclusions

The proper motion measurements of PNe envelopes lead directly to the calculation of the ages of these objects. Table 4 gives the computed ages for the nebulae listed in Table 1 having taken averages of the angular expansions in case more than one measurement is available. These ages are

https://doi.org/10.1017/S0074180900129754 Published online by Cambridge University Press

TABLE 2. Trigonometric and spectroscopic parallaxes of Planetary Nebulae

PN	Distance (pc)	Parallax Method	Ref.
S216S216	130	Trig.	1
NGC 7293NGC 7293	213, 190	Trig.	1,2
A35A35	200	Spect.	3
NGC 6853NGC 6853	380	Trig.	1
NGC 1514NGC 1514	400	Spect.	3
LoTr5LoTr5	420	Spect.	3
PW1PW1	433	Trig.	1
NGC 246NGC 246	500	Spect.	3
NGC 3132NGC 3132	510	Spect.	3
A21A21	541	Trig.	1
NGC 2346NGC 2346	690	Spect.	3
NGC 6720NGC 6720	704	Trig.	1
A74A74	752	Trig.	1
He2-36He2-36	780	Spect.	3

1. Harris, et al. (1996); 2. Harrington and Dahn (1980); 3. Pottasch (1996)

indeed very small and most have ages of about 1000 to 3000 years. NGC 7027 the youngest on this list is only 800 years old. It should be noted that these are first order approximations where any initial accleration of the gas has been ignored.

It is interesting to compare these ages with those derived in a recent study by Xilouris, et al. (1996) where they have studied a set of very faint PNe with very large angular extent (10 to 20 arcminutes). These objects must be only a few hundred parsecs in distance and their ages range from 10 to 45 thousand years, with an average age of close to 30 thousand years.

Expansion parallaxes have been used in the past to determine distances to novae by imaging these objects at optical wavelengths. Recently Ringwalt and Naylor (1996) reported the expansion parallax of the slow nova PW VulPW Vul from H images and have deduced an expansion rate of 0.12 $\pm$ 0.01 arcsec/yr. Such expansion rates are an order of magnitude larger than those found in PNe mostly due to the fact that novae expansion velocities are much higher than those of PNe. In the case of the nova PW Vul the expansion velocity is 470 km/sec. More recently Hollis, et al. (1966) have used the HST and detected proper motions of the jet component in the R AqrR Aqr symbiotic system over a period of only two years with a magnitude of about 0.2 arcsec/yr. Masson (1996 private communication) has used the VLA to detect the expansion of the compact HII region W3(OH)W3(OH) using the same techniques as used for PNe. In this case the desired quantity

TABLE 3. Planetary Nebulae comparative distances

PN	Distance (pc) From Table 1 & 2	CKS92	SZ94
S216S216	130	-	-
NGC 7293NGC 7293	200	157	400
A35A35	200	223	-
NGC 6853NGC 6853	380	262	400
NGC 1514NGC 1514	400	753	840
LoTr5LoTr5	420	6297	-
PW1PW1	433	141	-
NGC 3242NGC 3242	470	1083	870
NGC 3132NGC 3132	510	1251	-
NGC 246NGC 246	540	470	-
A21A21	541	-	-
NGC 7009NGC 7009	600	1201	1030
NGC 2346NGC 2346	690	1356	1780
NGC 6720NGC 6720	704	872	1000
A74A74	752	-	-
He2-36He2-36	780	2406	2910
NGC 7027NGC 7027	840	273	630
NGC 6572NGC 6572	940	705	1000
NGC 7662NGC 6772	960	1163	1110
NGC 6210NGC 6210	1570	2025	1630
NGC 2392NGC 2392	1600	1247	1290
NGC 6302NGC 6302	1600	525	540
BD+30°3639BD+30^{0}3639	2090	1162	1840

TABLE 4. Planetary Nebulae ages

PN	$\Theta(''/100$ yrs)	$\Theta('')$	Age(yrs)
NGC 246NGC 246	1.4	118	8.4 x 103
NGC 2392NGC 2392	0.72	23	3.2 x 103
NGC 3242NGC 3242	1.08	20	1.9 x 103
NGC 6210NGC 6210	0.31	8.5	2.7 x 103
NGC 6302NGC 6302	0.18	22.3	12.4 x 103
NGC 6572NGC 6572	0.44	7.3	1.7 x 103
BD+30^{0}3639BD+30^{0}3639 30	0.24	2.5	1.0 x 103
NGC 7009NGC 7009	0.70	13.4	1.9 x 103
NGC 7027NGC 7027	0.48	4.0	0.8 x 103
NGC 7662NGC 7662	0.60	7.6	1.3 x 103

The angular radii $\Theta('')$ are from Pottasch (1984) is to determine the expansion elocity rather than the distance.

As indicated by Hajian and Terzian (1996) a set of objects have been observed by them with the VLA in April 1994. These had epoch 1 VLA observations available dating back as far as 1982. In some cases the epoch 1 observations were of marginal quality and new epoch 3 observations are needed to derive expansion distances for these objects. This list includes IC 418IC 418, K3-17K3-17, NGC 6881NGC 6881, IC 5217IC 5217, NGC 7026NGC 7026, Hb12Hb12, Hu1-2Hu1-2, NGC 2440NGC 2440 and NGC 6543NGC 6543. High resolution Epoch 2 colored VLA radio images of these objects are shown by Hajian and Terzian (1996).

At radio wavelengths, the best we can do at present is to measure angular expansions of $\sim$ 1 to 2 mas/yr with baselines of a few years. Assuming a velocity of expansion of about 20 km/sec the VLA could detect angular expansions to about two to three dozen radio bright PNe out to several kpc. Time baselines of up to 10 years may be necessary in a few cases.

A new opportunity has opened up by using the HST for expansion distances of PNe. Using the Wide Field Camera and a baseline of $\sim$3 years it will be possible to measure the expansion of about 40 PNe. Such a proposal has been submitted to the Space Telescope Institute for consideration by Hajian, Terzian, Balick, Bond and Panagia. In particular it should be possible to study the expansion of the FLIERs (Fast Low Ionization Emission Regions) when imaged at the [NII] lines (Balick, et al. 1993, 1994).

The last decade has shown significant progress in understanding the difficulties involved in determining accurate distances to PNe. At the same time new direct distance methods have provided more realistic results which will be very important in determining the physical state of PNe and their central stars. It may also be possible that with additional accurate distance measurements we may be able to calibrate a more definitive distance scale for this important galactic population.

I wish to thank A. Hajian, C. Masson, H. Harris, and S. Pottasch for useful discussions in preparing this paper. This work was in part supported by NAIC which is operated by Cornell University under a cooperative agreement with the NSF.

References

Balick, B., Rugers, M., Terzian, Y., and Chengalur, J., 1993, ApJ, 411, 778.
Balick, B., Perinotto, M., Maccioni, A., Terzian, Y., and Hajian, A. R., 1994, ApJ., 424. 800.
Cahn, J. H., Kaler, J. B., and Stanghellini, L., 1992, A & A, Suppl. 94, 399.
Čudovičera, O., 1964, Izv. Pulkova Obs., 23, 154.
Curtis, H. D., 1918, Publ. Lick Obs., 13, 55.
Gomez, Y., Rodriguez, L. F., and Moran, J. M., 1993, ApJ, 416, 620.

Hajian, A. R., Terzian, Y. and Bignell, C., 1993, AJ, 106, 1965.
Hajian, A. R., 1995, PH.D. Dissertation, Cornell University
Hajian, A. R., Terzian, Y. and Bignell, C., 1995, AJ, 109, 2600.
Hajian, A. R. and Terzian, Y., 1996, PASP, 108, 419.
Harrington, R. S. and Dahn, C. C. 1980, AJ, 85, 454.
Harris, H. C., Dahn, C. C., Monet, D. G., and Pier, J. R., 1996. These Proceedings.
Hollis, J. M., Lyon, R. G., Dorband, J. F., and Feibelman, W. A., 1966, ApJ. (in press).
Kawamura, J. and Masson, C., 1996, ApJ, 461, 282.
Keeler, J. E., 1908, Publ. Lick Obs., 8, 1.
Latypov, A. A., 1957, Publ. Astro. Obs. Tashkent, 5, 31.
Liller, W., 1965, PASP, 77, 25.
Liller, M. H., Welther, B. L. and Liller, W., 1966, ApJ, 144, 280
Liller, M. H., and Liller, W., 1968, IAU Symposium 34, eds. D. Osterbrock and C. R. O'Dell (D. Rediel, London), 38.
Masson, C. R., 1986, ApJ Lett., 302, L27.
Masson, C. R., 1989, ApJ, 336, 294.
Orlova, O. N., 1973, Soviet Astron., 16, 949.
Pier, J. R., Harris, H. C., Dahn, C. C., and Monet, D. G., 1993, IAU Symposium 155, eds. R. Weinberger and A. Acker (Kluwer, Dordrecht), 175.
Pottasch, S. R., 1984, Planetary Nebulae, (Reidel:Dorchecht).
Pottasch, S. R., 1996, preprint.
Ringwalt, F. A., and Naylor, T., 1996, MNRAS, 278, 808.
Seaquist, E. R., 1991, AJ, 101, 2141.
Terzian, Y., 1980, QJRAS, 21, 82.
Terzian, Y., 1993. IAU Symposium 155, eds. R. Weinberger and A. Acker (Kluwer, Dordrecht), 109.
Van de Steene, G. C., and Zijlstra, A. A., 1994, A & A, Suppl., 108, 1994.
Xilouris, K. M., Paleologou, E. V. Papamastorakis, J., and Terzian, Y, 1996, A&A, 310, 603.