

TRIGONOMETRIC PARALLAXES OF PLANETARY NEBULAE

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Abstract. The accuracy of parallaxes obtained with ground-based CCD cameras now often reaches or exceeds 0.5 milliarcseconds. This improved accuracy permits us to measure significant parallaxes and determine distances for the nearest planetary nebulae. At present, the central stars of 11 planetary nebulae have been observed as part of the USNO parallax program. We now have determined distances with accuracies better than 20 percent for four central stars and better than 50 percent for five more. This paper gives the present status of the program, a brief interpretation of the results, and future prospects.

1. Introduction

In observing stellar parallaxes, the use of cameras with CCD detectors offers three advantages over traditional photographic cameras. First, images have much higher signal/noise, limited by photon statistics rather than by grain noise. Second, the data are linear, allowing astrometry of both bright and faint stars with minimal systematic errors. Third, higher quantum efficiency allows the use of fainter reference stars which, in turn, allows a reference frame with smaller angular size less subject to distortion by Earth's atmosphere.

These advantages of astrometry with CCD cameras have resulted in a dramatic improvement in the accuracy of parallax measurements. Parallaxes can now be obtained with an accuracy of 0.5 milliarcseconds (mas) or better, based on data accurate to typically 3 mas in relative positions for a single observation (Monet *et al.* 1992 and in preparation). These results are almost an order of magnitude better than was typically achieved with photographic cameras during the 1970s and 1980s.

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Until recently, planetary nebulae have eluded successful parallax measurements. Although the Yale Parallax Catalogue (van Altena *et al.* 1995) lists 24 PNe with measured parallaxes, all but one (NGC 7293) have errors more than 8 mas, so these measurements obviously are not significant. The parallax of NGC 7293 was marginally detected in several studies, the best (according to the Yale Catalogue) with an error of 5 mas (Dahn *et al.* 1973; see Harrington & Dahn 1980). Below we obtain 4.7 ± 0.7 mas, demonstrating the improved accuracy that has been achieved. Perhaps 23 PNe or more have distances ≤ 400 pc (Terzian 1993), so we might expect to make significant distance measurements (errors $\leq 20\%$) for most of these PNe. We began this work in 1987 and gave a first report at the Innsbruck meeting (Pier *et al.* 1993). Here we present the current status of the program and plans for the future.

2. Observations

The USNO parallax program using a Texas Instruments 800x800 CCD was described by Monet *et al.* (1992). Observations of nine PNe were begun in 1987 using this camera. In 1992, observing began using a Tektronix 2048x2048 CCD. Four PNe (two in common with the TI800 program) are being observed with this camera. The much wider field of the Tek2048 CCD (11 arcminutes, compared with 3 arcminutes for the TI800 CCD), together with the greater full well of the Tek2048 pixels, allows selection of better reference stars (more stars, more distant stars, and stars with a better symmetrical distribution around the parallax star) that is important in sparse fields. Parallaxes determined with the TI800 CCD have a median error in the relative parallax of 1.0 mas, while parallaxes determined with the Tek2048 CCD at present have a median error of 0.7 mas, and the latter error is still dropping as more data are obtained. These results led us to terminate observing with the TI800 CCD in 1995. The current status of our PNe parallax data is shown in Table 1.

A correction for the finite distances of the reference stars must be applied to convert each observed relative parallax to absolute parallax. This correction is important for PNe with distances of several hundred pc, and becomes increasingly important as the error in the relative parallax drops. This correction is shown as $\Delta\pi$ in Table 1. It has been determined both from spectroscopy and photometry of the reference stars. Spectra of many reference stars taken at Kitt Peak National Observatory (4-meter telescope, 7\AA resolution) were used to measure strengths of 17 spectral features (H lines, Ca K, G and CN bands, MgH, MgI, Na D, CaI, and several Fe features). These indices were used to determine the spectral type and luminosity class of each star and to check for any peculiarities (e.g. binary star, metal-poor

star, emission lines, etc.). Second, BVI colors were measured for all stars; for red stars with $(V-I)_C > 1.1$ they allow classification as a giant or dwarf.

The combined data give an estimate of the reddening and distance of each reference star. Any nearby stars are then rejected from the astrometric solutions. We have from 4 to 8 reference stars in the final solutions for the PNe observed with the TI800 camera, and from 7 to 13 stars for those observed with the Tek2048 camera. Note that for fields close to the galactic plane (particularly S216, and to a lesser extent NGC 6853), reddening is large enough to make the distance of each reference star more uncertain, adding to the error in $\Delta\pi$. For all fields, Table 1 shows that the reference stars are typically at distances of 1–2 kpc. At these distances, $\Delta\pi$ is fairly small and reasonably well-determined. Therefore, for each of these PNe, the error in $\Delta\pi$ contributes only a small amount to the final error in the absolute parallax. Note that the use of *faint* reference stars is an important factor in keeping this contribution to the total error small. With *faint* reference stars, the error in the observed relative parallax dominates the total error.

TABLE 1. Observed Data

PN	Number of		Epoch	π_{rel}	$\Delta\pi$	π_{abs}
	Frames	Nights		(mas)	(mas)	(mas)
TI800 CCD Program:						
NGC 6720	230	117	88.1–95.2	0.58 ± 0.45	0.84 ± 0.32	1.42 ± 0.55
NGC 6853	146	68	88.4–95.6	2.10 ± 0.38	0.53 ± 0.20	2.63 ± 0.43
A21	66	53	87.9–95.8	1.60 ± 0.50	0.25 ± 0.10	1.85 ± 0.51
A24	18	18	88.0–95.2	2.62 ± 1.11	0.49 ± 0.17	3.11 ± 1.12
A29	26	25	89.2–95.2	1.74 ± 1.29	0.43 ± 0.19	2.18 ± 1.30
A31	22	18	88.2–93.1	3.78 ± 1.54	0.97 ± 0.48	4.75 ± 1.61
A74	53	50	88.5–94.8	0.96 ± 0.62	0.37 ± 0.12	1.33 ± 0.63
S216	103	40	89.7–94.9	6.31 ± 0.88	1.06 ± 0.47	7.37 ± 1.00
PW1	61	31	87.9–95.8	2.58 ± 0.51	0.54 ± 0.24	3.12 ± 0.56
TEK2048 CCD Program:						
NGC 7293	123	87	92.6–96.6	3.74 ± 0.65	0.96 ± 0.36	4.70 ± 0.75
S216	84	53	92.8–96.1	7.06 ± 0.50	0.71 ± 0.30	7.77 ± 0.58
PW1	119	59	92.8–96.2	1.07 ± 0.47	0.58 ± 0.19	1.65 ± 0.51
A7	35	31	93.9–96.2	-0.51 ± 0.59	0.68 ± 0.21	0.17 ± 0.63

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3. Discussion

The resulting “final” parallaxes are shown in Table 2. Obviously these results are not really final, because we are continuing to observe the four PNe on the Tek2048 program for at least one more season, and because we anticipate reobserving several (probably NGC 6853, A24, and A31) with the Tek2048 camera beginning soon. All these fields are likely to benefit from this additional observing. On the other hand, it appears that A7 is at a distance too large for us to be able to make a useful parallax measurement, and others (NGC 6720 and A74) are sufficiently distant that our data are only marginally useful.

Table 2 includes our determination of $E(B-V)$ for the central star from our observed BVI_C , assuming $(B-V)_0 = -0.38$ and $(V-I)_0 = -0.45$, and the derived M_V . The results are consistent with all stars having $M_V \sim 6.8$ except the central stars of NGC 6853 and A7, which appear to be brighter, and the central stars of A24, A29, and A31, which appear to be fainter. The latter are also the three PNe with the most uncertain distances, so their faint absolute magnitudes are only tentative.

TABLE 2. Results

PN	π_{abs} (mas)	Distance (pc)	V	$E(B-V)$	M_V (1σ Range)	Note
NGC 6720	1.42 ± 0.55	704	15.75	0.08	6.26 (5.20–6.97)	
NGC 6853	2.63 ± 0.43	380	14.05	0.09	5.87 (5.48–6.19)	1
NGC 7293	4.70 ± 0.75	213	13.52	0.03	6.79 (6.41–7.11)	2
A7	0.17 ± 0.63	≥ 700	15.48	0.10	≤ 6.0	2
A21	1.85 ± 0.51	541	15.96	0.08	7.05 (6.35–7.58)	
A24	3.11 ± 1.12	322:	17.37	0.07	9.62 (8.65–10.29)	1,3
A29	2.18 ± 1.30	459:	18.31	0.14	9.57 (7.60–10.59)	3
A31	4.75 ± 1.61	211:	15.52	0.07	8.69 (7.79–9.32)	1,3
A74	1.33 ± 0.63	752	17.05	0.12	7.29 (5.90–8.14)	
S216	7.67 ± 0.50	130	12.62	0.08	6.79 (6.65–6.93)	
PW1	2.31 ± 0.38	433	15.53	0.14	6.91 (6.52–7.24)	2

1. Reobserve with Tek2048 CCD.
2. Will improve with more data.
3. Insufficient data, preliminary result.

In Table 3, a comparison is made between the distances determined here and those from several other recent discussions of PNe distances. In general, the agreement is about what might be expected given the known uncertainties of PNe distances. We find somewhat larger distances for A7

and PW1 than have been determined in other studies, and a somewhat smaller distance for A24. Note that A24, A29, and A31 are preliminary results based on fewer data than is desirable. For the remaining objects, the distances determined here tend to be on the large end of the range found in previous studies. For example, we have observed eight of the 11 stars listed by Terzian (1993, his Table 3) as having distances < 300 pc. We find only three of these eight stars to be within 300 pc.

TABLE 3. Comparison with Other Studies

PN	Distance in pc:					
	This Paper	CKS ¹ 1992	Terzian 1993	VZ ² 1994	NS ³ 1995	Pottasch 1996
NGC 6720	704	872	≥500	1000	990	500
NGC 6853	380	262	270	400	550	360
NGC 7293	213	157	160	400	...	280
A7	≥700	216	220	...	...	550
A21	541	...	270	...	600	500
A24	322:	525	≥500	...	...	600
A29	459:	...	410	...	...	...
A31	211:	233	240	...	...	400
A74	752	...	230	...	750	850
S216	130	...	40	...	110	130
PW1	433	141	240	...	470	300

¹Cahn *et al.* 1992

²Van de Steene & Zijlstra 1994

³Napiwotzki & Schönberner 1995

4. Future Improvements

Beside the parallax program at the Naval Observatory, Anguita, Gutierrez-Moreno, and Moreno are observing A29, YM 29, and He2-11 (Anguita 1996, private communication) and expect to get results in 1997. The Hipparcos Input Catalogue (Turon *et al.* 1992) includes the central stars of 14 PNe. Most of these have distance estimates from the literature of ~1 kpc, and of course most have magnitudes near the faint limit for Hipparcos. Therefore, unfortunately, probably only three or four PNe will have significant parallax measurements made by Hipparcos.

Several other PNe are likely to be at distances where useful parallax measurements can be made now from the ground. As well as repeating a couple of the PNe in Table 2, we hope to add NGC 3242, DHW5, HW6,

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Ton 320, PG0108+101, and RE1738+665 to the Tek2048 program soon. In addition, we hope to observe A35, LT5, and BD+28 4211 with a new camera including a 5^m neutral density filter (necessary for these bright central stars), beginning next year. We hope other researchers will include some of these objects in their studies to compare distances determined with other methods. If other PNe are of particular importance and are likely to be at a distance closer than 500 pc, please contact us to request their addition to the program.

At present, we believe systematic errors in the absolute parallaxes are still smaller than the random observational errors. If so, the errors should continue to improve to ≤ 0.5 mas for all objects as sufficient data accumulate. Judging by present results and estimated distances for new objects, it is possible that we will have 10 PNe or more with parallaxes giving distances determined to better than 20% by the time of the next meeting in this series. More importantly, the expanded sample will give a more definite indication of the systematic distance scale and space density for nearby PNe.

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