# DISTANCES TO PLANETARY NEBULAE

Julie H. Lutz
Program in Astronomy
Washington State University
Pullman, WA 99164-2930
USA

ABSTRACT. Finding distances to planetary nebulae remains a frustrating undertaking, but significant progress has been made over the past several years. This review covers primarily work done on distances since 1980, with some references to earlier papers. Some interesting new methods have been tried recently and some methods that have been used for years have been refined. Missions such as the Hubble Space Telescope and Hipparcos may provide new data on distances. Advances in ground-based telescopes and instruments will make possible new studies of distances.

## 1. INTRODUCTION

Distances to planetary nebulae (PN) are a fundamental quantity but accurate methods for determining distances have remained elusive. Much progress has been made both in determining distances for individual objects and for methods that are applied to large numbers of PN. However, because PN are so diverse in terms of their physical parameters (optically thick or thin, morphology and filling factors, nebular mass, helium content, etc.), it is unlikely that there will ever be a single method for finding distances that can be applied to all PN. We will have to be content with applying appropriate methods to particular PN and remaining cognizant of the limitations and selection effects associated with each method.

The disagreement among investigators comes in the assessments of which methods are appropriate for which nebulae and the associated errors and limitations. Table 1, adapted from Gathier, Pottasch and Pel (1986), illustrates that the amount of disagreement between various distance determinations can be substantial.

*S. Torres-Peimbert (ed.), Planetary Nebulae, 65–72.*

In this review I will discuss the principles and limitations of various distance methods, particularly those that have appeared in the literature since 1980. To set the context, I will begin with a brief discussion of some earlier work and then proceed to more recent studies, grouped according to the techniques employed.

Table 1. Comparisons of Distances

| Object | Distances (Kpc) |
|---|---|
| NGC 3918 | 1.60(1); 1.77(2); 0.80(3); 0.92(4); 0.58(5); 2.24(6) |
| NGC 5315 | 2.36(1); 4.05(2); 2.80(3), 0.69(5); 2.62(6) |
| NGC 6567 | 3.49(1); 3.55(2); 1.20(3); 2.08(4); 1.48(5); 1.68(6) |

References

(1) Cahn and Kaler (1971)
(2) Milne and Aller (1975)
(3) Acker (1978)
(4) Maciel and Pottasch (1980)
(5) Daub (1982)
(6) Gathier et al. (1986)

## 2. STUDIES PRIOR TO 1980

Since the early 1970's major efforts have been made to determine distances to large numbers of PN. Cahn and Kaler (1971) used the photometric distance method to estimate distances (or upper limits to the distances) for more than 600 PN. The photometric distance method is based upon the assumptions that the mass of the nebular shell is the same for all PN and the nebulae are optically thin. The scale is calibrated by using one or more PN with distances determined by some "reliable" method such as trigonometric or spectroscopic parallaxes. Once the scale is calibrated, the only observations that are needed are the nebular H-beta flux, interstellar extinction and angular radius.

Cudworth (1974) used proper motions to determine statistical parallaxes for 62 PN. He divided the nebulae into two groups according to their classification as B ("binebulous") or C ("centric") morphologies as defined by Grieg (1971, 1972). The kinematics of the two groups came out slightly different, but the numbers of PN in each group and the errors of observation made Cudworth cautious about his general conclusions and the validity of the individual distances.

Acker (1978) combined all of the distance determinations available (both individual and statistical) into a synthetic scale that included 330 PN. Because of the heterogenity of the data, it is not particularly meaningful to compare the distances obtained by this method with those found in other studies. The paper provides a complete set of references for all of the individual and statistical distances published up to that time.

## 3. EXTINCTION DISTANCES

The first studies of extinction distances began in 1970's (Lutz 1973) and have continued with refinements to the present. The idea is that a plot can be made of interstellar extinction versus distance for the region of the PN and then the extinction of the nebula, as determined from Balmer line ratios, radio/H-beta measurements or other techniques, can be used to find the PN distance. Limitations of this method are severe. The interstellar medium may be non-uniform along the line-of-sight to the nebula and/or insufficient stars may be available in the region of the PN so that patchiness across the region becomes a problem.

Kaler and Lutz (1985) redid the objects done earlier by Lutz (1973) with improved data for both the PN extinctions and the stars that comprised the extinction diagram. They revised the techniques used to fit the nebular extinction to the stellar data. From their error analysis it has become clear that a photometry system that is more refined (i.e., narrower bands, more filters) than UBV is desirable for obtaining reasonable extinction diagrams.

Maciel (1985) and Maciel, Faundez-Abans and de Olivera (1986) have measured extinction distances for He2-131, NGC 6565 and NGC 5979 by using stars within 2 degrees of the nebulae. UBV photometry was obtained for stars chosen because their spectral types were known already.

Gathier, Pottasch and Pel (1986) determined the distances to 12 PN by using extinction diagrams. They used Walraven VBLUW photometry in conjunction with model atmospheres and stellar evolution models. In addition, they made estimates of internal reddening from IRAS colors of the program nebulae. The fields around the PN were restricted to angular radii of less than 0.3 degree so the patchiness of the interstellar medium was less of a problem than in other studies. Their results showed that there are still problems with extinction distances even when the greatest care is taken to minimize the errors. Some fields showed a large amount of scatter in the extinction diagram, while other fields had an extinction diagram that allowed quite reasonable estimates of distance to be made. The estimated errors of the distance determinations ranged from 10% to 40%.

## 4. H I ABSORPTION OBSERVATIONS

Gathier, Pottasch and Goss (1986) have made H I absorption measurements at 21 cm for 24 PN with the Westerbork Synthesis Radio Telescope. They observed a background source located within 1 degree of the PN and the 21 cm emission spectrum in the direction of the PN. They used these three observations in conjunction with either a galactic rotation curve or by using data on H II regions (distances and radial velocities) to determine the galactic structure in the regions of the PN. For half of the PN, the observations could not be used to derived distances, but for the other 12, distances with accuracies of 25% to 50% were derived. The H I absorption technique was used previously to estimate a distance for NGC 7027 by Pottasch et al. (1982).

The paper of Gathier, Pottasch and Goss (1986) points out some limitations of the H I technique. In particular, a mean rotation curve is used for the analysis but it is well known that there are substantial deviations from circular motion and substantial random motions associated with particular H I clouds.

## 5. WIND DISTANCES

Kaler, Mo and Pottasch (1985) used P Cygni profiles that appear in the ultraviolet spectra of some central stars in combination with stellar atmosphere and evolution models to derive "wind distances" to 16 PN. The terminal wind velocity, which can be measured from the P Cygni profiles, is presumed to be related to the escape velocity which in turn is related to the temperature, mass and luminosity of the central star. Temperature is found from the Zanstra method. Stellar evolution provides a second relation between temperature, mass and luminosity, so all three parameters can be calculated. Distances can then be derived from apparent magnitudes.

This method depends upon the assumption that the theory derived for the winds of Population I stars can be applied to the central stars of PN. As the authors point out, Hubble Space Telescope observations would be desirable for deriving wind distances to a much larger number of PN.

## 6. METHODS INVOLVING A MASS-RADIUS RELATION

Maciel and Pottasch (1980) and Pottasch (1980) developed a method that would allow distance determinations to optically thick PN by establishing a relation between nebular ionized mass and nebular radius. This relation is calibrated by using PN of "known distance", viz. those that have trigonometric, spectroscopic or expansion parallaxes or some other type of individual distance determination. Also needed to establish the relation are electron densities, filling factors and helium abundances. Maciel and Pottasch (1980) used electron densities which were derived from forbidden line ratios. They assumed that the filling factor and the helium abundance were the same for all PN (0.65 and 0.11 respectively). They applied the mass-radius relation to and derived distances for 121 PN that had 5 GHz radio flux measurements (Milne and Aller 1975). Major uncertainties come from the electron density determinations, size measurements and assumption of a single value for the filling factor.

Maciel (1981a,b) extended this technique to 81 additional PN and used all the distances to estimate the birthrate of PN and the total number in the Galaxy. Maciel (1984) used the same method to find distances for all PN in the catalogue of Cahn and Kaler (1971).

Milne (1982), in response to the work on the mass-radius relation, suggested an alternative way to find distances given the 5 GHz flux and the angular size of the PN. His proposed technique was a variation of the methods which assume constant luminosity during the optically thick stage.

Daub (1982) used the basic idea of a mass-radius relation, but chose to make a calibration of a quantity involving the nebular mass, temperature and filling factor versus a quantity involving the nebular angular size and the 5 GHz flux. He used the relation to derive distances for 299 PN. Phillips and Pottasch (1984) used another variant of a mass-radius relation combined with parameters observed directly or derived from observations (electron density, 5 or 14 GHz radio flux, angular diameter) to derive distances to 55 PN. Amnuel et al. (1984) calculated distances to 335 PN after calibrating the mass-radius relation by using several different considerations including individual distances, 2.7 GHz fluxes and electron densities. One of their results is that the filling factor decreases as nebular radius increases.

Kwok (1985) considered the evolution of the ionization structure of PN based upon evolutionary models of the central star. He found that the observed parameters of the nebula are a function of both the nebular evolutionary state and the central star evolution. He derived a non-linear mass-radius relation, as contrasted with the linear relation used by previous investigators. He concluded that the relationship between the radio flux density and the angular size as a result of expansion had the same form as the flux-angular size relation for PN at different distances. If his conclusion is correct, the distances for optically thick PN could not be determined uniquely from the measurements of flux (radio or optical) and angular size alone.

## 7. RECENT DIRECTIONS

Sabbadin (1986) evaluated distances that were found by various methods for 81 PN. His study included consideration of nebular morphologies (B and C nebulae).

Mendez et al. (1987) have developed a new method for finding distances that looks promising. They determine the properties of the PN central star atmosphere from high dispersion spectra and then use the derived properties (surface gravity, model atmosphere flux at 5840 A, visual magnitude, and extinction) to determine a distance. This method is similar to the "wind distances" in being limited to PN for which model atmosphere analyses are obtainable, but there is the prospect of using this method on many more PN as more high dispersion central star spectra become available.

Pottasch (1987a, b) has considered the problem of finding nebular masses for PN that have "reliable" distances. Instead of taking the PN that are usually used for such studies, he has calibrated the mass-radius relation by using PN in the galactic bulge, PN in the Magellanic Clouds and PN that have distances determined from model atmospheres (Mendez et al. 1987). He concluded at another parameter is necessary to explain the scatter in the mass-radius relation and proposed that the central star luminosity (or mass) might be the missing parameter.

## 8. PRESENT PROBLEMS AND FUTURE WORK

The work of Kwok (1985) needs a response. A great deal of effort has gone into the distance method which involves a mass-radius relation and, if the method is ambiguous in its present form, perhaps there are ways to work around the ambiguity. In addition, there are some ways in which the basic data available for distance determinations can be improved. For example, PN imaging programs can provide better information about nebular sizes and filling factors. Indeed, one thing that is bothersome about the method based upon the mass-radius calibration is that the morphology exhibited by many nebulae in the low ionization potential lines that are used for electron density determinations is very different from the morphology exhibited in the light of hydrogen. Hence, the electron densities may not be representative of the regions where hydrogen radiates and the filling factors may be very different. Another puzzling aspect of the mass-radius method is that the investigators appear to be finding that most PN are optically thick. It is difficult to understand why so many of the PN show multiple shells and faint outer structures (Jewitt, Danielson and Kupferman 1986, Balick 1987, Louise et al. 1987).

The extinction method for finding distances is showing a lot of promise and should be extended by using appropriate CCD detectors in combination with filters and detailed atmospheres/evolution analyses such as those done by Gathier, Pottasch and Pel (1986).

Two methods from the past should be tried again. Expansion parallaxes (Liller, Welther and Liller 1966) are an excellent concept but in the past the measurements have been unreliable because of the uncertainties in measuring the positions of nebular features. Given modern CCD detectors and data reduction software, "first epoch" images should be obtained for a project on nebular expansions. In addition, the advent of multifiber feeds for spectroscopy should make it possible to get a good expansion velocity for particular nebular features. However, care must be taken to assure that real matter rather than expanding ionization fronts are being observed. Statistical parallaxes for PN derived from proper motions and radial velocities should be redone and the numbers of nebulae included in such studies increased. Cudworth (1974) mentions the desirability of doing such a study "in another decade" and 1984 has gone by already. It would be interesting to rework the statistical parallax studies by including more recent studies of nebular morphologies to divide PN into categories.

Two space missions have the possibility of giving considerable additional information on PN distances. Hipparcos will be launched in the late 1980's and has among its many targets some central stars of PN. The Hubble Space Telescope could provide us with excellent data (fluxes, sizes, terminal wind velocities) that can be used in a variety of distance determinations, (including "wind" and "stellar atmospheres" distances), as well as for ionization models and central star atmosphere and evolutionary models. In addition, the Magellanic Cloud PN that we struggle to observe with ground-based techniques will be easy to study. Instead of observing only the brighter part of the distribution of the Magellanic Cloud PN, observers will be able to study the properties (such as nebular mass) of even faint PN. However, since these missions will be spending only a small amount of observing time on PN, the major hope for improving distances remains with ground-based optical, radio and infrared studies.

## REFERENCES

Acker, A. 1978, Astr. Ap. Suppl., 33, 367.
Amnuel, P. R., Guseinov, O. H., Novruzova, H. I., and Rustamov, Yu. S. 1984, Ap. Space Sci., 107, 19.
Balick, B. 1987, A. J., 94, 671.
Cahn, J. H., and Kaler, J. B. 1971, Ap. J. Suppl., 22, 319.
Cudworth, K. M. 1974, A. J., 79, 1384.
Daub, C. T. 1982, Ap. J., 260, 612.
Gathier, R., Pottasch, S. R., and Goss, W. M. 1986, Astr, Ap., 157, 191.
Gathier, R. Pottasch, S. R., and Pel, J. W. 1986, Astr. Ap., 157, 171.
Grieg, W. E. 1971, Astr. Ap., 10, 161.
________. 1972, Astr. Ap., 18, 70.
Jewitt, D. C., Danielson, G. E., and Kupferman, P. N. 1986, Ap. J., 302, 727.
Kaler, J. B., and Lutz, J. H. 1985, Pub. A.S.P., 97, 700.
Kaler, J. B., Mo, J. E., and Pottasch, S. R. 1985, Ap. J., 288, 305.
Kwok, S. 1985, Ap. J., 290, 568.
Liller, M. H., Welther, B. L., and Liller, W. 1966, Ap. J., 144, 280.
Louise, R., Macron, A., Pascoli, G. and Maurice, E. 1987, Astr. Ap. Suppl., 70, 201.
Lutz, J. H. 1973, Ap. J., 181, 135.
Maciel, W. J. 1981a, Astr. Ap., 98, 406.
________. 1981b, Astr. Ap. Suppl. 44, 123.
________. 1984, Astr. Ap. Suppl., 55, 253.
________. 1985, Rev. Mexicana Astr. Ap., 10, 199.
Maciel, W. J., Faundez-Abans, M., and de Olivera, M. 1986, Rev. Mexicana Astr. Ap., 12, 233.
Maciel, W. J., and Pottasch, S. R. 1980, Astr. Ap., 88, 1.
Mendez, R. H., Kudritzki, R. P., Herrero, A., Husfeld, D., and Groth, H. G. 1987, Astr. Ap., in press.
Milne, D. K. 1982, M.N.R.A.S., 200, 51P.
Milne, D. K., and Aller, L. H. 1975, Astr. Ap., 38, 183.
Phillips, J. P., and Pottasch, S. R. 1984, Astr. Ap., 130, 91.
Pottasch, S. R. 1980, Astr. Ap., 89, 336.
________. 1987a, ESO Workshop, in press.
________. 1987b, Torino Workshop, in press.
Pottasch, S. R., Goss, W. M., Arnal, E. M., and Gathier, R. 1982, Astr. Ap., 106, 229.
Sabbadin, F. 1986, Astr. Ap. Suppl., 64, 579.