# DISTANCES TO PLANETARY NEBULAE

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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.

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.


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