Tests of the Galactic planetary nebula distance scale with the initial Gaia parallax distances of their central stars

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ABSTRACT

We used the primary dataset of Gaia Data Release 1 (DR1) to search for parallax measurements of central stars (CSs) of Galactic planetary nebulae (PNe), to determine PN distances. We found that a trigonometric parallax is available for 16 CSs, seven of which with relative uncertainty below 80%. The limited comparison of these trigonometric distances to other reliable individual determinations discloses good correlation between the two sets, with the Gaia parallax distances being lower by a factor of $\sim 0.1$ dex in the logarithmic distances. We tested with the Gaia parallaxes the most popular Galactic PN distance scales, namely, the physical radius vs. surface brightness, and the ionized mass vs. inverse optical thickness scales. While the number of available calibrators may still be too low, and their relative uncertainties too high, to derive a working distance scale, we were able to assess the current sample and to reveal the very promising potential of the future Gaia releases for a recalibration of the distance scale of Galactic PNe.

Subject headings: (ISM:) planetary nebulae: general — distances — Gaia
1. Introduction

Planetary nebulae (PNe) are the dust and gas shells ejected at the late AGB stellar phases, and then ionized, partially or fully, by the radiation from the hot, evolving central stars (CSs). PNe are probes of stellar and nebular evolution and of cosmic chemical enrichment, and knowing their formation and evolution is essential in many astrophysical fields.

Galactic PNe are known by the hundreds (e.g., catalogs by Acker et al. 1992, Parker et al. 2006), but their distances have always been elusive. Reliable individual distances are known for a relatively small number of Galactic PNe (Stanghellini et al. 2008 [hereafter SSV]) if we exclude those whose distances are model-dependent (Frew et al. 2016, hereafter F16). Since the PN distance is needed to study the astrophysics of the nebulae and their central stars, scientists in the field have recurred to calibrate physical relations between distance-dependent and distance-independent astronomical parameters of the PNe. Once these relations have been calibrated for the few PNe with a credible individual distance determination, they are used as a distance scale, yielding distances to all Galactic PNe whose distance-independent parameters used in the scale can be measured.

The Galactic PN distance scales are typically derived by using a measure of the PN surface brightness (or its inverse, the optical thickness) as the independent parameter, and with the physical radius (e.g., Schneider & Buckley 1996; Shaw et al. 2001; F16) or the ionized mass (e.g., Daub 1982; Cahn et al. 1992, SSV) as distance-dependent parameter. The original idea of the statistical distance scale is due to Shklovsky (1957). It is beyond the scope of this paper to review all the literature regarding the development of distance scales, but there is purpose in reviewing the basic concepts. It is assumed that a set of several PNe whose physical parameters, including distance, have been accurately measured, offers a snapshot of PN evolution. In the first method (which we will refer to
as physical radius distance scale), it is assumed that PN surface brightness decreases with
time since PN ejection, while the physical radius increases; in the second scenario (the
ionized mass distance scale), the ionized mass increases for optically thick PNe, while it
stays approximately constant for optically thin PNe, as the PN evolves. Both scales have
their drawbacks and advantages (see a detailed discussion of the scales in SSV and F16),
but they are meaningless unless their calibrators are spot-on reliable.

Good PN distance calibrators are rare. SSV (in their Table 2) list all individual
distances of PNe that are model independent and reliable, although the distance
uncertainties may be large, and in some cases they are not available at all from the original
distance measurements, which makes the assessment of their quality hard. Of the many
calibrators that have been used to date, the most reliable are those whose distances can be
measured from cluster membership of the PNe, and from spectroscopic parallaxes, usually
determined by using stellar properties such as binarity of the CSs. Secondarily, one can
employ distances derived from the expansion of the nebulae; this method is not as accurate
as the previous ones, since it does not account for the possible acceleration of the nebular
ejecta. PN distances can be estimated also from extinction of the PN itself, and of a
selection of nearby stars, by building an extinction-to-distance relation for each PN; the
extinction method is biased by patches in the ISM extinction, which are hard to predict,
and by a mild model-dependency of the stellar distance scale.

Given the limited number of reliable calibrations, SSV recurred to Magellanic Cloud
PNe as calibrators. There are many dozen of such PNe observed with the HST, which
allows to measure their apparent radii with very low uncertainty (Magellanic Cloud PNe
are typically unresolved from the ground). The SSV calibration is probably the best scale
for PN distances, except for PNe that are transitioning from the optically thick to optically
thin status. The inverse surface brightness (or \( \tau \), as defined for the ionized mass scale
by Cahn et al. 1992) where the optically thick PN sequence ends, and the optically thin sequence begins, is critical to determine which of the two branches of the ionized mass scale to use, and it may be moderately dependent on metallicity, since the thinning of PNe, i.e., the time lapsed until the evolving PN becomes transparent to the ionizing radiation, is more rapid in low-metallicity environments. Even with the mismatch of the transition from thick to thin PNe, the Magellanic Cloud-based distance scale is the one that best reproduced the individual distances from spectroscopic parallaxes and cluster membership observations.

The situation of Galactic PN distances is not going to improve considerably unless we increase the number of calibrators, their quality, or if we could reduce the calibrator’s distance error bars. The first Gaia Data Release (DR1, Gaia Collaboration, Brown A., Vallenari A. et al 2016) offers the opportunity to test new directions for Galactic PN distance scales. Gaia measured the parallaxes of several CSs of nearby PNe, and we can use the few good parallax measurements of the DR1 as an initial tool to explore the PN distance scales with the physical radius and ionized mass methods.

In §2 we describe the PNe in the DR1 sample. In §3 we calculate the calibration values for the physical radius and ionized mass distance scales using DR1 parallaxes as calibrators. In §4 we discuss the results. Finally, §5 gives the conclusions of our study, and its foreseen future developments.

2. A sample of Galactic PNe with a CS parallax in DR1

2.1. Searching DR1 for PN CSs

Trigonometric parallaxes for a set of about 2 million stars, mostly brighter than 11.5 visual magnitude, are delivered by DR1 (the so called primary data set, Lindegren et al. 2016). This task has been accomplished by combining 14 months of Gaia observations with
earlier positions from the Hipparcos and Tycho-2 catalogs, thereby allowing to disentangle the component of translational motion from the parallactic one, at the same time preserving the independent and absolute nature of parallax estimations.

As detailed in Lindegren et al. (2016), the typical parallax uncertainty of DR1 stars is \( \approx 0.3 \) mas, sources having a formal parallax error smaller than 1 mas solely retained in this release. At the end of the nominal five-year mission, however, Gaia is expected to deliver an order of magnitude or more improvement for these sources, while providing parallaxes with submas precision even for fainter PNe.

We searched the DR1 dataset for stellar detection and parallax determination corresponding to the locations of Galactic PNe. We searched for all spectroscopically confirmed PNe in the Galaxy, as listed in the Strasburg-ESO catalog (Acker et al. 1992, online version Acker et al. 1994), combined with the MASH survey (Parker et al 2006), and by using the astrometric coordinates by Kerber et al. (2003), when available.

In Table 1 we list all detected PNe whose parallax measurement (of the CS) was available. In Table 1 we give, in column (1) PN G number; (2) the common name; (3) \( p \), the parallax in mas from the Gaia archive; (4) the relative uncertainty in the parallax, \( \epsilon(p) \); (5) \( D_p \), the distance expressed in parsec, and calculated from the DR1 parallax as \( 10^3/p \); (6) \( \theta \), the optical angular radius; (7) the 5 GHz flux, expressed in Jy; (8) \( \log F_\beta \), the \( H\beta \) flux; (9) \( c \), the logarithmic optical extinction. It is worth noting that \( \epsilon(D_p) = \epsilon(p) \) as well. All parameters that are not in the Gaia release have been taken from Stanghellini & Haywood (2010, hereafter SH10), with exceptions noted below. The most useful PNe for building a distance scale are those whose relative parallax uncertainties are small.

It is worth noting that two of PNe have negative parallax, which are only significant in a statistical sense, and can not be used to estimate individual distances. They are not included in the following study. In Table 1 we do not include three targets that were found
in this search but have been deemed to be misclassified PNe by F16: PN G050.1+03.3 is a WR ejecta, PN G288.9-00.8 an LBV ejecta, and PN G303.6+40.0 is a patch of ionized ISM.

2.2. Building the sample of PN calibrators

We matched the Gaia CS detection in DR1 against the PN images, to infer whether the Gaia detections correspond to the PN CSs. In order to do so we use optical PN images in the literature, giving preference to those in the MAST archives, not only because \textit{HST} images have the best resolution in the optical wavelengths to date, but especially since their astrometry is compatible with that of Gaia, and the comparison can be quantitative. In a complementary paper (Stanghellini et al., in preparation) we describe these techniques, and show the Gaia to \textit{HST} image correspondent to all PNe observed by Gaia in DR1 and with \textit{HST}, including those whose parallax is not measured at this time. The DR1 also provides for detections at other positions within the PNe. Stanghellini et al. (in preparation) will also explore in detail PN morphology as seen by Gaia. For all PNe used here, the CS location in the optical images corresponds to the Gaia position for the parallaxes.

In order to determine the distance scale parameters we need $F_\beta$, the $H\beta$ fluxes, their extinction corrections, the apparent angular radii, and the 5 GHz fluxes for all PNe. In some cases, where the 5 GHz fluxes are not available but the $H\beta$ fluxes are, we use the transformation by Cahn et al. (1992) to determine the former fluxes from the latter. We searched the literature for new measurements of fluxes and angular diameters of the nebulae since the work by SSV and SH10. For SuWt 2, we found a measure of the $H\alpha/H\beta$ flux ratio (Danehkar et al. 2013), which, together with the $H\alpha$ flux measured by Frew et al. (2013), gives $\log F_\beta = -12.35$, and extinction constant $c=0.64$. We use this flux to obtain an equivalent 5GHz flux of 0.007 Jy, to be used in the distance scale formulation. All other parameters are up to date in the SSV and SH10 collections.
We have at our disposal 7 PNe whose relative uncertainty on the parallax is < 0.8 and whose flux and radius are available in the literature. It is obvious that these are too few, and the uncertainties still very high, to be used in a new, reliable distance scale. Nonetheless, there is purpose to study their location on the scales to assess future developments with the foreseen Gaia releases. At the end of the nominal five-year mission, Gaia is expected to deliver an order of magnitude or more improvement for these sources, while providing parallaxes with submas precision even for fainter PNe. Therefore, the present study is devoted to test the potentiality of Gaia parallaxes in the re-calibration of PN distance scales.

2.3. Gaia parallaxes of Galactic PNe compared to other independent distances

In Fig. 1 we show the limited comparison between the distances inferred from Gaia parallaxes of Table 1 and the PN independent distances. We have selected independent distances that are from spectroscopic parallaxes, nebular expansion, and extinction distance methods. All distances used for the comparison are given on Table 2, where all targets of Table 1 are listed if at least one reliable independent distance is available. Individual PN distances that have not been considered in the comparison are those whose distances are strongly model-dependent, such as those that assume a given CS mass (Herald & Bianchi 2011), gravity (Smith 1980), SED (e.g., Vickers et al. 2015), and all other model-dependent distances. Mendez & Niemela (1981) have estimated the distance of NGC 2346 from the spectroscopic binary located at the PN center, but incompatible extinction determinations of the CS and the nebula make it unclear whether the stellar distance is really the nebular distance, thus we do not include it in the comparison. It is worth noting that there is a mild model-dependency of spectroscopic distances as well, since the binary (or multiple) CS is modeled to infer the stellar type of the bright stellar companion to the ionizing source.
Nonetheless, they are still the most reliable distances before the release of Gaia parallaxes.

In Fig. 1 we plot trigonometric versus independent distances for all PNe where the comparison is possible. Uncertainties associated to individual distances are not always given in the original paper. In these cases we assume a relative distance uncertainty of 0.2 dex in the plots, but of course this is only indicative of their quality. In this figure we plot as filled symbols the PNe with $\epsilon(p) < 0.8$.

While the trigonometric distances correlate well with all individual distances, especially with those from spectroscopic parallaxes, where the overall linear correlation coefficient is $R_{xy}=0.996$ for $\epsilon(p) < 0.8$, we found that the parallaxes from DR1 depict a shorter distance scale than other independent methods, and this difference is $\sim 0.1$ dex, compared to spectroscopic distances. It is worth noting that Fig. 1 offers a very limited, if compelling, comparison between PN distances from Gaia parallaxes and other methods. We also like to point out that extending the comparison to $\epsilon(p) < 1$ would include the PN PC 11, with spectroscopic distance of 10,000 pc, which is located very off the 1:1 relation in the figure. We will discuss this target further below.

3. Galactic PN distance scale based on Gaia parallaxes

3.1. The physical radius - optical thickness distance scale

In Figure 2 we plot the PNe whose CSs have a parallax measurement in DR1 in the $\log R_{\text{pc}}$ vs. surface brightness plane. The physical radius, in pc, is derived from the Gaia parallaxes and the measured angular radii, and the $H\beta$ surface brightness can be expressed as $\log S_{b\beta} = \log (I_{\beta}/\pi\theta^2)$, where $I_{\beta}$ is the extinction-corrected $H\beta$ flux. The uncertainties in the logarithmic surface brightness, shown by the abscissae error bars, reflect the propagation of the component uncertainties, where available. We typically measure
uncertainties in the $H\beta$ flux and nebulae extinction constant $c$, and in the angular radii. In general, the uncertainty in the radius is so small (less than 5%) that can be reasonably eliminated in the propagation, thus the error bar in the logarithmic surface brightness becomes $\sqrt{\sigma_{\log F_{\beta}}^2 + \sigma_c^2}$. The error bar in the y-axis is the relative errors on the parallax, multiplied by 0.434 to take into account the logarithmic scale. The filled symbols in the figure represent the loci of those PNe whose Gaia parallax has $\epsilon(d_{\text{par}}) < 0.8$. Error bars are plotted only for this lower-uncertainty subsample.

The linear fit to all data points with $\epsilon(p) < 0.8$ is

$$\log R_{\text{pc}} = -0.394 \log Sb H\beta - 6.49$$

and the correlation index of this linear fit is $R_{xy} = -0.94$. While this relation can be used to determine distances to all Galactic PNe whose surface brightness is measured, it is too early to use it as a distance scale. In fact, the data points are too few, and the uncertainties too high, to be definitive about this scale. Future Gaia releases will help setting this scale, which will probably be the most useful of all scales for PN distances in the future. It is worth noting that the locus corresponding to PC 11, which has not been used as calibrator since $\epsilon(p) > 0.8$, on Fig. 2 is the open circle right on the linear fit, proving that the linear relation between surface brightness and physical radius is right on target for this Gaia detected central star.

3.2. The ionized mass-optical thickness distance scale

We show in Figure 3 the ionized mass scale derived by using the parallaxes from Gaia detections. In the figure we plot $\log \mu = \log(\sqrt{2.266 \times 10^{-21} D^5 \theta^3 F_{5\text{GHz}}})$ vs. $\tau = \log(4\theta^2/F_{5\text{GHz}})$, as in SSV. The independent variable is a traditional distance scale variable, defined proportionally to the inverse 5 GHz surface brightness, while the dependent
variable is the ionized mass of the PN. The filled symbols in Fig. 3 represent PNe whose relative parallax uncertainty is $< 0.8$. The error bars have been calculated by propagation of logarithmic uncertainties. The solid (Cahn et al. 1992) and broken (SSV) lines represent the old distance scales. It is worth noting that the extension to low ionized masses in the traditional scales of SSV and Cahn et al. (1992) only goes to $\log \mu = -2$, indicating that the Gaia set reaches lower ionized mass PNe (i.e., early evolution PNe), as expected, given that bright central stars are preferred.

Ionized mass increases as the ionization front moves outward and the nebula expands. Initially, for $\tau < \tau_{\text{crit}}$, the PN is optically thick. At $\tau = \tau_{\text{crit}}$ the nebula is completely ionized. After that, the nebular ionized mass is assumed to be constant. The figure shows that it is hard to determine a $\tau_{\text{crit}}$ from the data points, even when we consider only those with $\epsilon(D_p) < 0.8$ (filled symbols). It appears that several of the data points from Gaia PNe are optically thick, and their ionized masses are spread over a range of values, defining a sequence that is different, albeit parallel, to those of the older scales. The upper limit of the ionized mass is consistent with that of the old scales.

The optically-thick sequences on Fig 3 is very interesting, and it looks like that the final ionization is reached at a later time (higher $\tau$) for the Gaia parallax set than indicated in the old scales, supporting the perception that there is more than one optically-thick evolutionary track in this plane as suggested by SSV (see Fig. 3 therein). This may signify that there is a delay in the thinning of the ejecta. Further data is needed to disclose the reasons for a different thinning sequence, and future Gaia data releases may disclose some interesting developments in this direction.
4. Discussion

The Gaia parallaxes for Galactic PN CSs available in DR1 depict a shorter distance scale than individual measurements of distances in the literature, with an offset that appear to be $\sim 0.1$ dex. While there are still too few calibrators, and their uncertainties remain relatively high, the relation between physical radius and surface brightness is well defined (see Fig. 2) at all surface brightness in our range. We should note that there is a cluster of PN radii at larger surface brightness that are above the fit, and all of these have $\epsilon(D_p) > 0.8$. At this time, we can say that their uncertainties are too high to be included in the fit for the scale.

To better illustrate the discrepancies between the distances from Gaia parallaxes and those of individual PNe, in Fig. 4 we apply the physical radius scale based on Gaia parallaxes to calculate statistical distances ($D_{\text{scale}}$) for all PNe whose individual distances have been derived with reliable methods. We use for the comparison the data base of the PNe listed in Table 2 of SSV, and also added the average LMC and SMC distances derived from PNe. The fit between the independent and statistical distances is $\log D_{\text{scale}} = 0.783 \log D_{\text{ind}} + 0.377$, and the linear correlation coefficient is 0.86. In this comparison the fit diverges at large distances. We studied the residuals between the physical radius scale distances and the individual distances, and found no clear correlation with distance, and average residuals of 0.49 (excluding here the SMC and LMC data averages). There are no other clear correlations between the residuals and the physical parameters in the scale, such as $H\beta$ fluxes, extinction, angular diameters.

In order to improve the scale we should consider future data releases from Gaia, which will provide parallaxes of stars with $V<15$ with a precision of 0.03 mas (Lindegren et al. 2016). From Acker et al. (1992) we found that there are $\sim 50$ Galactic PNe whose central star magnitude $V<15$ and whose statistical distance is estimated (by mean of the SSV
scale) to be smaller than 3000 pc. For this group of PNe, Gaia will provide final parallaxes to better than 10% relative uncertainty; for another \(\sim 40\) PNe the estimated parallax relative uncertainty will be of the order of 20%. This wealth of new data will definitely constraint the scale. The present work is preliminary to set the stage for these future data sets.

5. Conclusions

This paper presented an initial study of the Gaia parallaxes of central stars of Galactic PNe, those available in the DR1 release. We studied all PNe with available trigonometric distance from Gaia, collecting all the necessary physical parameters to infer their location on two major distance scales, the physical radius and the ionized mass scales. In all, we have at our disposal 16 potential data points for constraining the scale, of which only 7 have relative parallax uncertainty < 0.8 and the necessary observational parameters to build the distance scale.

We determined the PN distances from the parallaxes, and their relative errors from the parallax uncertainties. By comparing the trigonometric distances from Gaia with reliable individual distances in the literature we find a good linear correlation between the two sets, with the trigonometric distances being lower by about 0.1 dex (see Fig. 1). The comparative set for this experiment is limited.

By building the physical radius distance scale calibrated with Gaia distances, we find a very tight linear correlation between the physical radius and the \(H_{\text{rmb}}\) surface brightness, with a linear correlation coefficient of -0.94 if we consider only relative parallax errors below 80% (see Fig. 2). To gain insight on the DR1 parallaxes, we used this correlation to calculate the distance of all PNe with known individual distances. The relation of the
preliminary Gaia distance scale to individual distances is very encouraging (Fig. 4), with better match at the lower distance end.

By studying the ionized mass distance scale for the Gaia sample (Fig. 3) we realize that there are too few data constraining the scale, and that conclusions on this scale are premature. There are indications that the optically thin sequence is analogous to those of the older scales (e.g., Cahn et al. 1992), and there seem to be more than one optically thick scale in the early PN evolution.

We are looking forward to future data releases from Gaia to greatly increase the data sample, and lower the relative uncertainties of the Galactic CS parallaxes, and we expect to produce a statistical distance scale calibrated with Gaia parallaxes in the future.

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Fig. 1.— Comparison between individual vs. trigonometric distances. Circles: Spectroscopic parallax distances; squares: Expansion distances; triangles: reddening distances. Filled symbols: $\epsilon(D_p) < 0.8$. Error bars are plotted for filled symbols only. The thick line is the 1:1 correlation.
Fig. 2.— The physical radius- surface brightness relation. Filled symbols: $\epsilon(D_p) < 0.8$. The linear fit to these relative low-uncertainty points is defined by the straight line.
Fig. 3.— The ionized mass–inverse surface brightness relation. Filled symbols: $\epsilon(D_p) < 0.8$. The solid line is the Cahn et al.’s (1992) distance scale, while the broken line is the SSV scale calibrated on Magellanic Cloud PNe. Error bars are calculated wherever possible given the input data, and they are formal, conservative error bars.
Fig. 4.— Distances derived from the tentative scale from Fig. 2, against individual distances. Circles: spectroscopic distances; squares: expansion distances; triangles: reddening distances. The starred symbols represent the location of the average SMC and LMC distances derived by applying the Gaia statistical distance scale to all LMC and SMC PNe whose radius is measured from the HST images, and whose flux is available in the literature. We draw the 1:1 line as a solid line, and the least squares fit between independent and parallax distances, including the Magellanic Cloud points, as a broken line.
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Table 1. trigonometric parallaxes, distances, and other physical parameters of the DR1 PNe

| G       | Name    | $p$  | $\epsilon(p)$ | $D_p$ | $\theta$ | $F_{5\text{GHz}}$ | $\log F_\beta$ | $c$   |
|---------|---------|------|---------------|-------|----------|-------------------|----------------|-------|
| [mas]   | [pc]    | [arcsec] | [Jy] | [erg cm$^{-2}$ s$^{-1}$] |
| 038.2+12.0 | Cn 3-1  | 1.932 | 0.339 | 518 | 2.25 | 0.067 | -10.94±0.02 | 0.42±0.03 |
| 064.7+05.0 | BD+303639 | 0.279 | 1.550 | 3579 | 3.80 | 0.511 | -10.03±0.01 | 0.46±0.03 |
| 089.3-02.2 | M 1-77  | 1.072 | 0.333 | 932 | 3.50 | 0.025 | -11.90 | 1.34 |
| 104.8-06.7b | M2 -54  | -0.331 | 1.046 | ... | 0.50 | 0.008 | -12±0.07 | 0.85±0.29 |
| 165.5-15.2 | NGC 1514 | 2.286 | 0.104 | 437 | 66.0 | 0.262 | -10.98±0.03 | 0.96±0.4 |
| 166.1+10.4 | IC 2149  | 0.250 | 1.590 | 4000 | 4.25 | 0.177a | -10.55±0.01 | 0.25±0.01 |
| 215.6+03.6 | NGC 2346 | 0.778 | 0.346 | 1285 | 26.0 | 0.086 | -11.26±0.02 | 0.89 |
| 272.1+12.3 | NGC 3132 | 1.524 | 0.239 | 656 | 22.5 | 0.23 | -10.45±0.06 | 0.16±0.03 |
| 311.0+02.4 | SuWt 2   | 0.655 | 0.423 | 1527 | 32.5 | 0.007a | -12.35 | 0.64 |
| 315.1-13.0 | He 2-131 | 0.095 | 3.71 | 10530 | 3.00 | 0.335 | -10.16±0.01 | 0.19 |
| 316.1+08.4b | He 2-108 | -0.007 | 134 | ... | 5.50 | 0.033 | -11.43±0.01 | 0.55±0.1 |
| 321.0+03.9 | He 2-113 | 0.359 | 1.714 | 2785 | 0.75 | 0.115 | -11.82±0.02 | 1.32 |
| 331.1-05.7 | PC 11    | 0.741 | 0.920 | 1349 | 2.50 | 0.011 | -11.48±0.02 | 0.89 |
| 332.9-09.9 | He 3-1333 | 0.190 | 3.426 | 5259 | 3.50 | 0.026 | -12.02 | 0.93 |
| 334.8-07.4 | SaSt 2-12 | 0.310 | 0.783 | 3223 | 0.44 | 0.082a | -11.19 | 0.55 |
| 345.2-08.8 | Tc 1     | 0.219 | 2.237 | 4575 | 7.50 | 0.134 | -10.73±0.05 | 0.28±0.01 |
\textsuperscript{a} $F_{5\text{GHz}}$ derived from $F_{\beta}$.

\textsuperscript{b} Note the negative parallax, see text.
Table 2. Independent distances of PNe with measured Gaia parallax

| G       | $D_{\text{spec}}$ | $\epsilon(D_{\text{spec}})$ | $D_{\exp}$ | $\epsilon(D_{\exp})$ | $D_{\text{ext}}$ | $\epsilon(D_{\text{ext}})$ | Ref. |
|---------|-------------------|-----------------------------|------------|------------------------|----------------|-----------------------------|------|
|         | [pc]              | [pc]                        | [pc]       |                        | [pc]            |                             |      |
| 064.7+05.0 | ...               | ...                         | 2680       | 0.3                    | ...            | ...                         | SSV  |
| 089.3–02.2 | ...               | ...                         | ...        | ...                    | 2500           | 0.4                         | ...  |
| 165.5–15.2 | 550               | 0.32                        | ...        | ...                    | ...            | ...                         | AM15 |
| 215.6+03.6 | ...               | ...                         | ...        | ...                    | 1060           | 0.32                        | G86  |
| 272.1+12.3 | 770               | ...                         | ...        | ...                    | 540            | 0.26                        | C99, G86 |
| 311.0+02.4 | 2300              | 0.09                        | ...        | ...                    | ...            | ...                         | E10  |
| 315.1–13.0 | ...               | ...                         | ...        | ...                    | 590            | 0.31                        | G86  |
| 331.1–05.7 | 10000             | 0.06                        | ...        | ...                    | ...            | ...                         | P10  |
| 334.8–07.4 | 4400              | ...                         | ...        | ...                    | ...            | ...                         | P04  |

References: AM15: Aller et al. 2015; C99: Ciardullo et al. 1999; E10: Exter et al. 2010; G86: Gathier et al. 1986; P04: Pereira 2004; P10: Pereira et al. 2010.