# The Magellanic Cloud Calibration of the Galactic Planetary Nebula Distance Scale 

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#### Abstract

Galactic planetary nebula (PN) distances are derived, except in a small number of cases, through the calibration of statistical properties of PNe. Such calibrations are limited by the accuracy of individual PN distances which are obtained with several non-homogeneous methods, each carrying its own set of liabilities. In this paper we use the physical properties of the PNe in the Magellanic Clouds, and their accurately known distances, to recalibrate the Shklovsky/Daub distance technique. Our new calibration is very similar (within $1 \%$ ) of the commonly used distance scale by Cahn et al. (1992), although there are important differences. We find that neither distance scale works well for PNe with classic ("butterfly") bipolar morphology, and while the radiation bounded PN sequences in both the Galactic and the Magellanic Cloud calibration have similar slopes, the transition from optically thick to optically thin appears to occur at higher surface brightness and smaller size than that adopted by Cahn et al. The dispersion in the determination of the scale factor suggests that PN distances derived by this method are uncertain by at least $30 \%$, and that this dispersion cannot be reduced significantly by using better calibrators. We present a catalog of Galactic PN distances using our re-calibration which can be used for future applications, and compare the best individual Galactic PN distances to our new and several other distance scales, both in the literature and newly recalibrated by us, finding that our scale is the most reliable to date.


Subject headings: Planetary nebulae: general; distances

## 1. Introduction

The uncertainty associated with distances measurements of Galactic planetary nebulae (PNe) is a major obstacle to the advancement of PN research.

[^0]Only $\sim 40$ Galactic PNe have distances that have been determined individually with reasonable accuracy. Distances to Galactic PNe can be determined individually in various ways, including cluster membership (Chen et al. 2003, CHW03; Alves et al. 2000, ABL00), by measuring the rate of their expansion (e. g., Liller \& Liller 1968, LL68; Hajian
et al. 1995, HTB95), by the reddening method (e. g., Gathier et al. 1986, GPP96; Kaler \& Lutz 1985, KL85), and by measuring their spectroscopic parallax (Ciardullo et al. 1999, C99) or trigonometric parallax (Harris et al. 2007, Hea07).

For the remaining $>1800$ Galactic PNe (Acker et al. 1992) one has to rely on statistical distance scales, whose calibrations are based on the reliability of the individually known PN distances, and the validity of a general correlation that links the distance-dependent to the distance-independent physical properties of PNe. The Cahn, Kaler, \& Stanghellini (1992, CKS) distance scale of Galactic PNe is based on an attempt by Daub (1982, D82) to improve Shklovsky's distance scale (Shklovsky 1956a, 1956b) for optically thick nebulae. Shklovsky's distance scale assumes that all PNe have equal (observed) ionized mass. D82 assumed that Shklovsky's constant mass approach was still valid, but only for those PNe that are optically thin to the Lymann continuum radiation emitted by the central stars (density bounded). For the optically thick (radiation bounded) PNe, D82 based the distance scale on a calibration of an ionized mass versus surface brightness relation. CKS improved D82's calibration with the use of a larger number of calibrators (PNe with known individual distance), and calculated the statistical distances to 778 Galactic PNe.

Since its publication, distances from the CKS catalog have been used preferentially and widely in the literature. Other statistical methods that have been commonly used include those by Maciel (1984), Zhang (1995, Z95), van de Steene \& Zijlstra (1995, vdSZ), Schneider \& Buckley (1996, SB96) and Bensby \& Lundström (2001, BL01). All these distance scales rely on a set of Galactic calibrators whose distances are mostly derived from reddening or expansion properties, or from the assumption of Galactic Bulge membership, with all the consequent uncertainties. With the publication over the past decade of critical physical parameters for a large sample of Magellanic Cloud PNe (Shaw et al. 2001, 2006; Stanghellini et al. 2002, 2003), including highly accurate $\mathrm{H} \beta$ fluxes, physical dimensions, morphologies, and extinction constants, we have the opportunity to assess and improve the distance scale for Galactic PNe. In this paper we take advantage of the wealth of Magellanic Cloud PN
data to re-calibrate the CKS distance scale, as well as other distance scales for comparison. Homogeneously determined photometric radii from $H S T$ of a PN sample with low Galactic reddening are the best way to determine any relation that involves apparent diameters. Furthermore, the relatively recent publication of trigonometric and spectroscopic parallax and cluster membership distances to Galactic PNe allow us to test with unprecedented reliability our own and other distance scales.

The construction of any statistical distance scale for PNe is composed of three fundamental steps: the selection of a method that has some physical or empirical basis, the selection of a set of calibrator $P N e$, for which distances have been determined by some independent means, and an analysis of the applicability of the calibration to a wide variety of PNe. Until now it has been difficult to compare the viability various methods, since their calibrations and applications have varied so widely. In $\S 2$ we describe in detail the Shklovsky/Daub/CKS distance scale and the superiority of the Magellanic Cloud PNe as calibrators. We also derive our new calibration of this method and assess its inherent uncertainties. In $\S 3$ we discuss the physical underpinning of the CKS distance method in light of recent advances in modeling the evolution of PNe. In $\S 4$ we take a closer look at the viability of various methods for determining independent distances to Galactic PNe (i.e., the set that had previously been used as calibrators), and discuss the applicability of the Magellanic Cloud distance scale to Galactic PNe. In $\S 5$ we recalibrate the most used statistical distance methods with the Magellanic Cloud PNe, and then compare the accuracy of these methods to one another using the best independently determined distances to Galactic PNe. We conclude in $\S 6$ with our final prescription and recommendation for determining statistical distances to Galactic PNe.

## 2. The Magellanic Cloud Calibration and the New PN Distance Catalog

The CKS statistical distance scale is based on the calibration of the relation between D82's ionized mass

$$
\begin{equation*}
\mu=\left(2.266 \times 10^{-21} D^{5} \theta^{3} F\right)^{1 / 2} \tag{1}
\end{equation*}
$$

and the optical thickness parameter

$$
\begin{equation*}
\tau=\log \frac{4 \theta^{2}}{F} \tag{2}
\end{equation*}
$$

where D is the distance to the PN in parsecs, $\theta$ is the nebular radius in $\operatorname{arcsec}$, and F is the nebular flux at 5 GHz . The parameter $\mu$ increases as the ionization front expands into the nebula. Once a PN becomes density bounded, $\mu$ remains constant for the rest of the observable PN lifetime.

By calculating $\mu$ and $\tau$ for several PNe with known distances, dimensions, and fluxes, CKS derived the $\mu-\tau$ relation:

$$
\begin{align*}
\log \mu & =\tau-4, \tau<3.13  \tag{3a}\\
\log \mu & =-0.87, \tau>3.13 \tag{3b}
\end{align*}
$$

where Eq. 3a holds for PNe of high surface brightness, and Eq. 3b for PNe with low surface brightness.

The calibration of the above distance scale was based upon 19 Galactic PNe with independent distances with comparatively poor accuracy. At the time when the CKS paper was written there were hardly any Magellanic Cloud PNe with accurately measured diameters, and the distances to the Magellanic Clouds were also quite uncertain. We can now re-calibrate the distance scale using the nebular parameters relative to the LMC and SMC PNe observed by us with the Hubble Space Telescope (HST) (Shaw et al. 2001, 2006; Stanghellini et al. 2002, 2003). In order to determine $\tau$ and $\mu$ for Magellanic Cloud PNe we use a transformation between the 5 GHz and the $\mathrm{H} \beta$ fluxes (Eq. 6 in CKS), since radio fluxes are not available for Magellanic Cloud PNe. All other parameters are available in our $H S T$ paper series. Note that we use the photometric radius as the proper measure of the nebular dimension, which is defined as the radius that includes $85 \%$ of the flux in a monochromatic emission line.

We have adopted a distance to the LMC of 50.6 kpc (Freedman et al. 2001; Mould et al. 2000), which is accurate to $\sim 10 \%$ (Benedict et al. 2002). The variation in the adopted distance when applied to individual objects can be easily estimated given that the three dimensional structure of the

LMC has been well established (Freeman, Illingworth, \& Oemler 1983; van der Marel \& Cioni 2001). The LMC can be considered a flattened disk with a tilt of the LMC plane to the plane of the sky of $34^{\circ}$ (van der Marel \& Cioni 2001). Freeman, Illingworth, \& Oemler (1983) derived a scale height of 500 pc for an old disk population. The scale height of young objects is between 100 to 300 pc (Feast 1989). Using the scale height of an old disk population the 3D structure of the LMC introduces a variation in the adopted distance smaller than $1 \%$ from object to object and therefore has been neglected in the calibration.

For the SMC we have used a distance of 58.3 kpc (Westerlund 1997). The accuracy of this distance is not as well established as for the LMC. Moreover, the SMC is irregular with a large intrinsic line of sight depth (between 6 and 12 kpc : Crowl et al. 2001) which varies with the location within the galaxy. We have estimated an average line of sight depth of 5 kpc for the PNe in our sample by combining the span of the positions ( 400 pc in right ascension and 2 kpc in declination) of the PNe with respect to the optical center of the SMC with the dispersion in the distance to the SMC derived by Crowl et al. (2001) using SMC clusters positions. The distance uncertainty introduced by this depth in the SMC is roughly $9 \%$, still low to significantly affect the result but one order of magnitude larger than the one obtained for the LMC. In this respect we consider LMC PNe to be better calibrators than the SMC PN for the distance scale.

In Figure 1 we show the LMC PNe on the $\log \mu$ - $\tau$ plane. We have calculated $\tau$ and $\log \mu$ as explained above, and assumed $\mathrm{D}_{\mathrm{LMC}}=50.6 \mathrm{kpc}$. In the Figure we plot the different morphological types with different symbols, following the classification in Shaw et al. $(2001,2006)$. To guide the eye we have plotted, on the figure, the Galactic distance scale fit from CKS (solid line). The optically thick sequence of LMC PNe is very tight for $\tau<2.1$, and most LMC PNe are optically thin for $\tau>2.1$. The fitted value of the function for optically thin LMC PNe is almost identical to that of Galactic PNe if we exclude bipolar planetary nebulae. The broken line in Figure 1 corresponds to the Magellanic Cloud fit of the optically thick sequence of LMC PNe (see Eq. 4a and 4 b below). Similarly, in Figure 2 we show the same plot
of Figure 1, but for SMC PNe. The morphology and sizes of the nebulae are from Stanghellini et al. (2003). Even with the scarcity of data points, the thick PN sequence is well defined by SMC PNe, and it is identical to that of the LMC PNe.

The observed ionized masses of bipolar PNe in both Figures 1 and 2 appear mostly well above the constant ionized mass line. The parameters $\mu$ and $\tau$ have been calculated with the photometric radii of the PNe, that can be very different from the isophotal radii in the case of PNe with large lobes. Furthermore, bipolar PNe might be optically thick for most of their observed lifetime (Villaver et al. 2002a), and thus are not the ideal calibrators for the optically thin PNe branch of the $\log \mu-\tau$ relation. In deriving the distance scale based on Magellanic Cloud PNe we thus exclude PNe with bipolar morphology. This leave us with 70 Magellanic Cloud calibrators, a very large number of PNe with individual distances when compared to the 19 calibrators in CKS. In Figure 3 we show the Magellanic Cloud calibration of the PN distance scale, where open symbols are LMC PNe and filled symbols are SMC PNe, and where we exclude bipolar PNe. Note that we have assumed that the ionized mass for optically thin PNe is constant, as in D82 and CKS.

The fit to the distance scale based on the Magellanic Cloud PNe (this paper, hereafter SSV) is:

$$
\begin{gather*}
\log \mu=1.21 \tau-3.39, \tau<2.1  \tag{4a}\\
\log \mu=-0.86, \tau>2.1 \tag{4b}
\end{gather*}
$$

The solid line in Figure 3 shows this relation. The separation between optically thick and thin PNe is very obvious from the figure, and the optically thick sequence is much better defined here than in CKS, thanks to the use of the best calibrators available now. The optically thick sequence has been derived by least-square fit, and has correlation coefficient $\mathrm{R}_{\mathrm{xy}}=0.8$. The optically thin sequence is determined by the average of the log $\mu$ for $\tau>2.1$. Using another estimate of the central tendency will change the horizontal scale by less than $5 \%$, which is well within the uncertainty. Furthermore, if we were to fit the data points of Figure 3 with just one line for all $\tau$ we would have a very poor correlation $\left(R_{x y}=0.14\right)$, which reinforce the evolutionary scheme of optically thick to
thin PNe, proposed by D82 to improve Shklovsky's method.

By examining Figure 3 we infer that: (1) Our analysis allows us to confirm the CKS distance scale for optically thin PNe; (2) the optically thick sequence is very well defined by the Magellanic Cloud PNe and it is different from that of CKS; (3) the new statistical distance for optically thin PNe increases slightly the assumed ionized mass, such that distances for optically thin nebulae are tipically $1 \%$ larger compared to those computed using the CKS calibration. (4) bipolar PNe do not follow the empirical relation, and their ionized mass actually increases steadily with $\tau$, confirming that they stay in the ionization bound state for much longer than PNe with other morphological types. The probable reason why the bipolar PN relation does not flatten out for $\tau>2.1$ is because they are the progeny of the more massive stars and they are expected to remain optically thick (given a combination of the large circumstellar densities and fast evolution of the central star).

By using the SSV distance scale we calculated the statistical distances to all non-bipolar PNe in the LMC and the SMC. We obtain distributions that are nicely narrow, with mean values (and dispersions), $\mathrm{D}_{\mathrm{LMC}}=50.0 \pm 7.5 \mathrm{kpc}$ and $\mathrm{D}_{\mathrm{SMC}}=57.5 \pm 5.5 \mathrm{kpc}$, that are within $1 \%$ of the distances to the Magellanic Clouds.

We applied our new distance scale to the large sample of Galactic PNe in the original CKS catalog, and present the revised distances in Table 1. Column (1) gives the usual name as in CKS, column (2) gives the calculated $\tau$, columns (3) and (4) give the angular radius and the flux used in the calculation, and column (5) gives the distance to the PNe. Note that the fluxes in (4) are the 5 GHz fluxes from CKS when available, or their $\mathrm{H} \beta$ equivalents.

## 3. The Physics of the Statistical Distance Scale

As CKS pointed out, the assumption of constant ionized mass for optically thin PNe (or that it can be computed for optically thick PNe with a one-parameter model) would seem to be a doubtful proposition since the progenitor stars vary in mass by nearly an order of magnitude. CKS minimized the significance of the variation in ionized
mass by pointing out that distances so derived depend only on the square-root of the assumed mass. One might also expect that the ionized mass would be fairly directly correlated with the progenitor mass. However, hydrodynamical models of the co-evolving PN and central star by Villaver et al. (2002a) show that the decline of gas density with radius is generally quite steep (except within the bright inner shell of gas) over a wide range of progenitor masses and during the entire visible lifetime of the nebula. The implication is that, for optically thin nebulae, the bulk of the mass exists in the faint, low-density, outer halo. Since the volume emissivity of recombination lines is proportional to the square of the gas density, the massive nebular halo contributes very little to the observed emission. Most published values for PN masses assume a constant density for the gas, one that is only representative of the bright inner shell, leaving the bulk of the PN mass unaccounted for. In part for these reasons, ionized masses derived in this way reflect only a modest fraction of the total mass of the nebula, such that the assumption of a constant mass is sufficiently accurate to render the Shklovsky distance method useful.

We have shown that the distance method of CKS is empirically sound, and derived the scale factor for optically thin PNe to that from observations of Magellanic Cloud PNe. It is important to note the significance of the dispersion in the PN masses (expressed in the $\mu$ parameter) about the mean in the calibration shown in Figure 3. The $1-\sigma$ deviation about the mean value is 0.28 , which translates to a corresponding uncertainty in the distance of about $30 \%$. We regard this value as a rough estimate of the minimum uncertainty that may be associated with the distance to an individual PN derived using this methodology. It is important to note that the uncertainty in the distance scale cannot be reduced with improved calibrator nebulae, since the distance uncertainty is of order $10 \%$ (i.e., of order the size of the symbols in Figure 3). The scatter in the data results from genuine variations in the ionized masses of the calibrator nebulae, and quantifies the fundamental limitation in this technique.

The new PN distance scale (SSV) is very similar to that of CKS, with the exception of the transition between optically thick and optically think stages. From Eq. 4b, the definition of $\mu$, and the
relation $D=206265 R_{\mathrm{PN}} / \theta$ (where $\mathrm{R}_{\mathrm{PN}}$ is the linear nebular radius in pc ) we can determine the radius at which the PN becomes optically thin. For $\tau=2.1$ we obtain $R_{\mathrm{PN}} \sim 0.06 \mathrm{pc}$. The same calculation to determine the PN radius at which the thick to thin transition occurs by using Eq. 3b and $\tau=3.13$ gives $R_{\mathrm{PN}} \sim 0.09 \mathrm{pc}$. The uncertainty in the determination of $\tau$ at transition, and thus of $R_{P N}$, depends on the scatter of the ionized mass calibrators used in CKS. The new calibration is much more reliable.

The metallicities of the LMC and SMC are, on average, of the order of half and a quarter that of the solar mix respectively (Russell \& Bessell 1989; Russell \& Dopita 1990). The AGB wind is likely to be dust driven, therefore it has a strong dependency on metallicity. It is then expected that LMC and SMC stars with dust-driven winds lose smaller amounts of matter (Winters et al. 2000) during the AGB phase than their Galactic counterparts. The mass-loss history during the AGB determines the circumstellar density structure that will eventually constitute the PN shell (Villaver et al. 2002b). A reduced mass-loss rate during the AGB has the effect of decreasing the density of the circumstellar envelope prior of PN formation.

Furthermore, after the envelope is ejected, the remnant central star leaves the AGB and its effective temperature increases. The stellar remnant becomes a strong emitter of ionizing photons, responsible for ionizing the nebula. The mechanism that drives the wind during the central star phase (with velocities a few orders of magnitude higher than that experienced during the AGB phase) is the transfer of photon momentum to the gas through absorption by strong resonance lines (Pauldrach et al. 1988). The efficiency of this mechanism depends on metallicity, thus it is expected to be less efficient in Magellanic Cloud central stars than in the Galactic ones, with correspondingly lower escape velocities for the winds, and a decreased efficiency in shell snow-plow.

As has been shown by Villaver et al. (2002a), the propagation of the ionization front determines the density structure of the nebula early in its evolution, while the pressure provided by the hot bubble has no effect at this stage. The propagation velocity of the Strömgren radius, which ultimately determines the transition from the optically thick to the optically thin stages, depends mainly on
the ionizing flux from the star and on the density of the neutral gas. Given the dependency of the AGB mass-loss rates on metallicity, the ionization front will encounter a lower neutral density structure in Magellanic Cloud PNe than in Galactic PNe. This would tend to make the transition from optically thick to thin at a smaller radius in Magellanic Cloud PNe than in Galactic PNe. The fact that our Magellanic Cloud calibration of the CKS scale occurs at smaller radii than that derived by CKS is probably coincidence. On the other hand, if we really could determine empirically the transition radius as a function of metallicity, we would expect two different thick sequences for the SMC and the LMC PNe, given their different metallicity, and yet the sequences are almost identical (Figs. 1 and 2). That is, we do not see the effects of metallicity on our distance scale, and that is applicable to Galactic PNe as well. We discuss below (§4) how the newly derived distances match extremely well with the best individual distances to Galactic PNe independently of metallicity.

## 4. Comparison of our Distance Scale to Individual Galactic PN Distances

We have assessed that our new calibration of the PN distance scale is very similar to that of CKS, but with a revision in the transition between the radiation bounded and the density bounded stages. The comparison between the CKS and the SSV scales suffers from the fact that part of the CKS calibrators are obsolete, and that new Galactic calibrators have become available. It is worthwhile to compare the SSV scale with the best available individual distances to Galactic PNe to date before we confirm the validity of the new calibration.

In Table 2 we give the best set of individual Galactic PN distances available to date. Column (1) gives the common name; columns (2) and (3) give the best individual distance and, where available, its uncertainty; columns (4) and (5) give respectively the statistical distances for the same PNe from CKS and the SSV; columns (6) and (7) give the distance determination method (CM for cluster membership, P for parallax, E for expansion, R for reddening, see explanations below) and its reference. We have selected a sample of individual Galactic PN distances based on the lit-
erature, and whose statistical distances have been calculated by CKS and can be derived for the SSV calibration as well.

The best methods to get individual PN distances are (1) trigonometric parallax, (2) the use of a spectroscopic companion of the PN central star, which allows to derive the spectroscopic parallax, and (3) the membership of the PN in an open or globular cluster. Apart from trigonometric parallaxes, that are applicable only for nearby PNe , the distance to the PN is that of a companion or a cluster, whose uncertainties are typically much lower than those related to other methods for PN distances. In the past decade there have been two major studies of PN parallaxes. C99 used $H S T$ imaging to determine central star companions of a PN sample, obtaining ten probable associations and the relative spectroscopic parallaxes. We list all of these in Table 2, except for A 31, where only a lower limit to the distance is given, and A 33 and K 1-27, whose distances seem to be controversial in C99. Hea07 published trigonometric parallaxes of several Galactic PNe. Following the discussion in Hea07, we include all their final determinations in Table 2, including the uncertainties. Planetary nebulae whose distances have been derived through cluster membership are the PN in Ps 1, whose distances has been recalculated by ABL00, and that in the open cluster NGC 2818, whose distance has been estimated by CHW03. It is worth noting that Mermilliod et al. (2001) found that the radial velocity of the NGC 2818 PN is slightly lower than that of the cluster, making its membership marginally questionable.

Since CKS was published there have been other PNe observed in clusters, including JaFu1 and JaFu2 (Jacoby et al. 1997), and a PN in M 22 (Monaco et al. 2004), but their distances are not included in Table 2 either because their cluster membership is not definitive or because their nature is still uncertain, as described in detail in the discovery papers.

An alternative method for PN distances is the determination of the secular PN expansion, a method that had its renaissance with the use of the accurate relative astrometry afforded by the $H S T$. In this category we found distances to several PNe by Hajian et al. (1993, 1995, 1996; HBT93, HBT95, HT96), Palen et al. (2002,

Pea02), Gomez et al. (1993, GRM93), and also the work by LL68. Among the distances determined by expansion we have only listed in Table 2 those deemed reliable by the authors listed above. In particular, in Pea02 there are several distances determined by different expansion algorithms, and if the results are very different by different methods for the same PN we have excluded them. Uncertainties in expansion distances, when available, are much higher than those of parallaxes or cluster membership, and the method is intrinsically less reliable, given the impossibility of following the PN acceleration history, and the modeling difficulty given unknown process as such as differential mass-loss.

Finally, a very rough individual distance can be derived in some cases by studying the reddening patches around the PN and then building reddening-distance plots for the known stars surrounding the PN. This method, although providing several data-points in the literature, is the most uncertain given the inhomogeneity of the Galactic ISM. GPP96 derived reddening distances for several PNe, and we used in Table 2 only the reliable ones, as deemed by the authors. We have excluded NGC 2346, since the scatter in its distancereddening plot is overly large. KL85 also published several PN distances by the same method, and we included their results in Table 2.

In Figure 4 we plot the data of Table 2 on the $\tau-\log \mu$ plane, drawing also the CKS and the SSV distance scales (note that the scales of Figures 3 and 4 are different). It is interesting to note that the best data points, those of the PNe whose distances have been determined via parallax or cluster membership, follow very well the SSV calibration, and they are less compatible with that of CKS. Naturally, the CKS calibration was based principally on reddening and expansion distances, since very few parallaxes were available at that time, and we can see that the thinning sequence determined by the data points relative to expansion or reddening distances is compatible with the CKS calibration (but these individual distances have much lower reliability than the parallaxes and cluster memberships represented by the filled symbols). While the SSV seems to be the best statistical scale to be used for Galactic PNe, its preference, for optically thick PNe, over the CKS scale is based only on one data point (the
parallax at $\tau<2.1)$. But let us recall here that the filled symbols are not the calibrators of the SSV scale, rather they are the Galactic PNe with best individual distances to date, used for comparison, while the calibration is based on $\sim 70$ data points whose errorbars would be smaller than the symbols.

In Figure 5 we show the direct comparison of the individual PN distances and those from the SSV calibration, where the correspondence of the parallax and cluster membership individual distances with the SSV distances is remarkable. It is worth noting that the two lower-left filled circles, those for which the parallax and statistical distances do not coincide within $30 \%$, are A 7 and A 31; both are very large nebulae, whose diameters are larger than the radio beam used to detect the 5 GHz flux (Milne 1979), and whose flux densities are deemed to be uncertain. In Figure 6 we show the distribution of the relative differences of the SSV and individual distances versus $\tau$ for the four methods of deriving individual distances. The thin vertical lines represent the $\tau=2.1$ and $\tau=3.1$, i.e., the thick-to-thin PN transition for the CKS and SSV scales. We could conclude that the SSV scale fails to reproduce the individual distances for PNe around the transition between thick to thin, but this failure seems to pertain only to the comparison with expansion and reddening distances, and it does not occur for the comparison with parallax and cluster membership distances.

## 5. Comparison of Statistical Distance Scales

We compare the relative merits of the new SSV scale, calibrated on Magellanic Cloud PNe, in relation to other distance scales in the literature. We compare the statistical distances from different methods to individual Galactic PN distances, by using only the best individual PN distances of Table 2, those from parallax and cluster membership. We also calculate the distances to all LMC and SMC PNe using the statistical methods, then we compare the resulting averages with the actual distances to the Clouds. It is worth recalling that all old scales have been calibrated with Galactic or Bulge PNe, thus we expect a lower reproducibility of the Magellanic Cloud distances.

For all scales we give in Table 3: in column (1) the reference, in column (2) the statistical method,
in column (3) the correlation coefficient between statistical and individual PN distances, in column (4) the mean relative difference between the statistical and individual distances, in column (5) the relative difference between the median distances to Large Magellanic Cloud PNe and the actual LMC distance, in column (6) the same relative difference, but for the SMC PNe. Statistical distance scales in the literature use in this comparison are those by CKS, vdSZ, Z95, SB96, and BL01.

The statistical scheme that best compares with the best individual distances is the SSV scale, with higher $\left(\mathrm{R}_{\mathrm{xy}}=0.99\right)$ correlation and lower median difference between statistical and individual distances than any other scale, and best reproduces the Magellanic Cloud distances. This is hardly a surprise, since for the first time it was possible to calibrate a distance scale with absolute calibrators from the Magellanic Clouds. By comparison, the correlation coefficients between the distances from the CKS, vdSZ, Z95, SB96, and BL01 scales are always lower, and the median of the relative differences are higher.

We also want to test whether PN distances derived with other distance scales, if recalibrated with the Magellanic Cloud PNe, would compare better than the SSV scale to the best individual distances of Galactic PNe. First, we consider the relation between the brightness temperature and the linear nebular radius, which vdSZ calibrated with Galactic bulge PNe. Our new calibration of the relation is

$$
\begin{equation*}
\log D\left(\mathrm{~T}_{\mathrm{b}}\right)=3.49-0.35 \log \theta-0.32 \log F \tag{5}
\end{equation*}
$$

based on a fit of the $\log \mathrm{T}_{\mathrm{b}}-\log \mathrm{R}_{\mathrm{PN}}$ relation $\left(\mathrm{R}_{\mathrm{PN}}=(\theta \mathrm{D}) / 206265\right)$. We also calibrate the log $M_{i o n}-\log R_{P N}$ relation as in Maciel \& Pottasch (1980), Z95, and BL01, and found, by assuming that the filling factor is 0.6 ,

$$
\begin{equation*}
\log D\left(\mathrm{M}_{\mathrm{ion}}\right)=3.45-0.34 \log \theta-0.33 \log F \tag{6}
\end{equation*}
$$

Finally, we also recalibrate with the Magellanic Cloud PNe the relation between the surface brightness, $\mathrm{I}=\mathrm{F} /\left(\pi \theta^{2}\right)$, and $\mathrm{R}_{\mathrm{PN}}$, as in SB96, and obtained:

$$
\begin{equation*}
\log D(I)=3.68-0.50 \log \theta-0.25 \log F \tag{7}
\end{equation*}
$$

The possibility of building a distance scale based on a $\log \mathrm{I}-\log \mathrm{R}_{\mathrm{PN}}$ calibration was mentioned by Stanghellini et al. (2002), and also used by Jacoby (2002).

All three relations used to derive the distance scales in Eqs. (5), (6), and (7) have high correlation coefficients $\left(\mathrm{R}_{\mathrm{xy}} \sim 0.8\right)$. In these relations, excluding the bipolar PNe does not change the coefficients by more than $5 \%$, thus their exclusion as calibrators is irrelevant.

Using the scales in Eqs. (5), (6), and (7) we have calculated the distances for those Galactic PNe whose individual distances are known either through a trigonometric or spectroscopic parallax, or by cluster membership. In Table 3 we give the comparison between these newly calibrated scales and the individual distances of PNe. We also give the estimates for the LMC and SMC distances, and we infer that the SSV scale is superior to all other scales here recalibrated with the Magellanic Cloud PNe as well. We then plot in Figure 7 the relative difference between the statistical and individual distances for the scales recalibrated with Magellanic Cloud PNe. The filled symbols represent the SSV scale, triangles are the distances from the $\mathrm{T}_{\mathrm{b}}-\mathrm{R}_{\mathrm{PN}}$ relation (Eq. 5), crosses represent the $\log \mathrm{M}_{\text {ion }}-\log \mathrm{R}_{\mathrm{PN}}$ scale (Eq. 6), pentagons are the distances from Eq. (7), based on the $\log \mathrm{I}$ $-\log R_{\text {PN }}$ relation. We see that the SSV scale is the best possible Galactic statistical distance scale with the calibrators and comparisons available to date. Since the $\log I-\log R_{P N}$ relation works for bipolar PNe, it might be used to determine the distance to bipolar PNe instead of the SSV scale.

## 6. Conclusion

The wealth of new data available that describe the physical parameters of Magellanic PNe has allowed us to check and re-calibrate the Shklovsky/Daub/CKS statistical distance scale, which is most commonly used in the literature, and provide distances of 645 Galactic PNe following the new distance scale calibration (Table 1). To calculate the SSV distance for other PNe, or for the same PNe but using other parameters than those in CKS, given $\theta$ and F , the 5 GHz flux, one can use the following equations:

$$
\begin{array}{r}
\log D_{\mathrm{SSV}}=3.06+0.37 \log \theta-0.68 \log F, \tau<2.1 \\
\log D_{\mathrm{SSV}}=3.79-0.6 \log \theta-0.2 \log F, \tau>2.1
\end{array}
$$

(8b).
If the 5 GHz flux is not available for the given PN, one can use Eq. (6) in CKS to derive the equivalent 5 GHz flux from the $\mathrm{H} \beta$ flux.

In this paper we have used recent data on PNe in the Magellanic Clouds to construct a set of calibrators for which the distances are known to high absolute accuracy ( $\sim 10 \%$ ), and for which the dispersion among the distances is extraordinarily small (a few percent). Furthermore, the great distance of these nebulae allows us to establish a distance scale factor that is insensitive to uncertainties in distances to Galactic PNe that are drawn from a heterogeneous, nearby (few hundred pc) sample; a local sample has generally been necessary given the limited range over which many independent distance methods (notably trigonometric and expansion parallaxes) can provide accurate distances. In addition, we use consistent and reliable means to determine angular sizes (from photometric radii), and the $\mathrm{H} \beta$ fluxes and extinction constants, derived from HST calibrations, are among the most reliable in the literature. There has never been a better set of calibrators for statistical distance determinations. For comparison, we selected Galactic PNe where the independent distances are the best available (including recently published data), and we evaluated the reliability of various independent distance methods by the degree to which they are consistent with our distance scale.

With this study we show that: (1) the distance scale as calibrated from the Magellanic Cloud PNe is very similar to that derived by CKS; (2) our revised distance scale agrees superbly with the most accurate distances measured for individual Galactic PNe. We also show that other methods of statistical distance determination generally do not yield results that are better than this statistical method; (3) the distance scale does not work for PNe with bipolar morphology, and we believe this is because progenitors of bipolars are often not fully ionized during the course of PN evolution (the $\log \mathrm{I}-\log \mathrm{R}_{\mathrm{PN}}$ relation could be used instead for these PNe); (4) with the Magellanic Cloud cali-
bration we provide a more robust physical basis for why the Shklovsky/Daub distance scale works, despite wide variations in the expected ionized mass; we also show that the recalibration of other distance scales with Magellanic Cloud PNe might not work as well as the recalibrated Shklovsky/Daub distance scale; (5) we point out that the dispersion in the distance scale is an inherent property of the method, and cannot be reduced significantly by using better calibrators; (6) the radiation-bounded sequence for Magellanic Cloud PNe may terminate at higher surface brightness than previously derived. It seems that the new sequence and the radiation bounded to density bounded transition does not depend on metallicity very much, as it is the same for the LMC and the SMC PNe; the best available data show that the Magellanic Cloud calibration of this sequence is entirely consistent with Galactic PNe.

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TABLE 1
Catalog of Galactic PN Distances

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| NGC40 | 3.46 | 18.20 | 0.460 | 1249 |
| NGC246 | 5.31 | 112.00 | 0.248 | 475 |
| NGC650 | 5.24 | 69.20 | 0.110 | 746 |
| NGC1360 | 5.82 | 192.00 | 0.222 | 351 |
| NGC1501 | 4.08 | 25.90 | 0.224 | 1167 |
| NGC1514 | 4.59 | 50.20 | 0.262 | 760 |
| NGC1535 | 3.31 | 9.20 | 0.166 | 2305 |
| NGC2022 | 3.62 | 9.70 | 0.091 | 2518 |
| NGC2346 | 4.54 | 27.30 | 0.086 | 1369 |
| NGC2371 | 4.33 | 21.80 | 0.090 | 1554 |
| NGC2392 | 3.93 | 22.40 | 0.237 | 1259 |
| NGC2438 | 4.83 | 35.20 | 0.073 | 1215 |
| NGC2440 | 3.42 | 16.40 | 0.411 | 1359 |
| NGC2452 | 3.81 | 9.40 | 0.055 | 2838 |
| NGC2610 | 4.58 | 17.20 | 0.031 | 2215 |
| NGC2792 | 3.16 | 6.50 | 0.116 | 3050 |
| NGC2818 | 4.69 | 20.00 | 0.033 | 1998 |
| NGC2867 | 2.93 | 8.00 | 0.299 | 2228 |
| NGC2899 | 4.97 | 45.00 | 0.086 | 1014 |
| NGC3132 | 3.94 | 22.50 | 0.230 | 1263 |
| NGC3195 | 4.66 | 20.00 | 0.035 | 1975 |
| NGC3211 | 3.51 | 8.00 | 0.080 | 2901 |
| NGC3242 | 3.22 | 18.60 | 0.835 | 1094 |
| NGC3587 | 5.64 | 100.00 | 0.091 | 621 |
| NGC3699 | 4.48 | 22.40 | 0.067 | 1620 |
| NGC3918 | 2.62 | 9.40 | 0.857 | 1639 |
| NGC4071 | 5.18 | 31.50 | 0.026 | 1596 |
| NGC4361 | 4.45 | 40.50 | 0.230 | 887 |
| NGC5189 | 4.59 | 70.00 | 0.507 | 546 |
| NGC5307 | 3.22 | 6.30 | 0.095 | 3235 |
| NGC5873 | 3.08 | 3.50 | 0.041 | 5445 |
| NGC5882 | 2.77 | 7.00 | 0.334 | 2362 |
| NGC5979 | 2.74 | 4.00 | 0.117 | 4075 |
| NGC6026 | 4.72 | 16.90 | 0.022 | 2398 |
| NGC6058 | 5.03 | 13.20 | 0.007 | 3538 |
| NGC6072 | 4.43 | 35.00 | 0.181 | 1017 |
| NGC6153 | 2.98 | 12.30 | 0.632 | 1482 |
| NGC6210 | 3.01 | 8.10 | 0.256 | 2282 |
| NGC6302 | 2.77 | 22.30 | 3.403 | 741 |

TABLE 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ <br> [pc] |
| :---: | :---: | :---: | :---: | :---: |
| NGC6309 | 3.06 | 6.90 | 0.167 | 2736 |
| NGC6326 | 3.30 | 6.00 | 0.073 | 3511 |
| NGC6337 | 4.19 | 23.50 | 0.143 | 1354 |
| NGC6369 | 2.59 | 14.00 | 2.002 | 1089 |
| NGC6439 | 2.67 | 2.50 | 0.053 | 6330 |
| NGC6445 | 3.48 | 16.60 | 0.368 | 1380 |
| NGC6543 | 2.59 | 9.40 | 0.899 | 1623 |
| NGC6563 | 4.42 | 21.50 | 0.070 | 1646 |
| NGC6565 | 3.29 | 4.50 | 0.042 | 4660 |
| NGC6567 | 2.68 | 4.40 | 0.161 | 3610 |
| NGC6572 | 2.16 | 7.20 | 1.429 | 1736 |
| NGC6578 | 2.65 | 4.30 | 0.166 | 3638 |
| NGC6620 | 3.40 | 2.50 | 0.010 | 8836 |
| NGC6629 | 2.93 | 7.50 | 0.266 | 2372 |
| NGC6720 | 4.10 | 34.60 | 0.384 | 880 |
| NGC6741 | 2.49 | 3.90 | 0.197 | 3728 |
| NGC6751 | 3.85 | 10.50 | 0.063 | 2585 |
| NGC6765 | 4.91 | 19.00 | 0.018 | 2334 |
| NGC6772 | 4.74 | 32.40 | 0.076 | 1266 |
| NGC6778 | 3.66 | 7.90 | 0.055 | 3150 |
| NGC6781 | 4.54 | 53.00 | 0.323 | 706 |
| NGC6803 | 2.52 | 2.80 | 0.094 | 5273 |
| NGC6804 | 3.84 | 15.70 | 0.142 | 1726 |
| NGC6807 | 2.17 | 1.00 | 0.027 | 12550 |
| NGC6818 | 3.04 | 9.10 | 0.304 | 2055 |
| NGC6826 | 3.20 | 12.70 | 0.404 | 1590 |
| NGC6842 | 4.25 | 23.70 | 0.126 | 1380 |
| NGC6852 | 4.59 | 14.00 | 0.020 | 2736 |
| NGC6853 | 4.94 | 170.00 | 1.325 | 264 |
| NGC6879 | 3.10 | 2.50 | 0.020 | 7692 |
| NGC6881 | 2.30 | 2.50 | 0.124 | 5340 |
| NGC6884 | 2.49 | 3.80 | 0.186 | 3830 |
| NGC6886 | 2.77 | 3.80 | 0.098 | 4354 |
| NGC6891 | 3.00 | 5.10 | 0.103 | 3613 |
| NGC6894 | 4.50 | 22.00 | 0.061 | 1669 |
| NGC6905 | 4.42 | 20.20 | 0.062 | 1751 |
| NGC7008 | 4.53 | 42.80 | 0.217 | 869 |
| NGC7009 | 3.03 | 14.10 | 0.735 | 1325 |
| NGC7026 | 2.91 | 7.50 | 0.277 | 2352 |

TABLE 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| NGC7048 | 4.91 | 27.50 | 0.037 | 1613 |
| NGC7094 | 5.72 | 47.50 | 0.017 | 1358 |
| NGC7139 | 5.30 | 38.00 | 0.029 | 1396 |
| NGC7293 | 5.70 | 402.00 | 1.292 | 159 |
| NGC7354 | 2.83 | 10.00 | 0.597 | 1698 |
| NGC7662 | 2.57 | 7.70 | 0.634 | 1962 |
| IC289 | 3.81 | 18.40 | 0.212 | 1448 |
| IC351 | 3.15 | 3.50 | 0.035 | 5620 |
| IC972 | 5.51 | 23.50 | 0.007 | 2488 |
| IC1295 | 5.42 | 54.10 | 0.045 | 1034 |
| IC1297 | 2.85 | 3.50 | 0.069 | 4908 |
| IC1454 | 5.95 | 17.00 | 0.001 | 4207 |
| IC1747 | 3.12 | 6.50 | 0.128 | 2991 |
| IC2003 | 2.97 | 3.30 | 0.047 | 5489 |
| IC2120 | 4.24 | 23.50 | 0.126 | 1388 |
| IC2149 | 2.36 | 4.20 | 0.309 | 3258 |
| IC2165 | 2.50 | 4.00 | 0.202 | 3653 |
| IC2448 | 3.17 | 5.00 | 0.067 | 3985 |
| IC2553 | 2.77 | 4.50 | 0.137 | 3679 |
| IC2621 | 2.10 | 2.50 | 0.197 | 4867 |
| IC3568 | 3.64 | 9.00 | 0.075 | 2738 |
| IC4191 | 3.06 | 7.00 | 0.170 | 2703 |
| IC4406 | 3.56 | 10.00 | 0.110 | 2381 |
| IC4593 | 3.25 | 6.40 | 0.092 | 3225 |
| IC4634 | 2.76 | 4.20 | 0.122 | 3924 |
| IC4637 | 3.42 | 9.30 | 0.132 | 2396 |
| IC4642 | 3.66 | 8.30 | 0.060 | 3006 |
| IC4663 | 3.66 | 7.20 | 0.045 | 3467 |
| IC4673 | 3.56 | 7.40 | 0.060 | 3220 |
| IC4699 | 3.10 | 2.50 | 0.020 | 7692 |
| IC4732 | 2.83 | 2.50 | 0.037 | 6801 |
| IC4776 | 2.88 | 3.50 | 0.065 | 4966 |
| IC5148 | 5.71 | 60.00 | 0.028 | 1068 |
| IC5217 | 2.98 | 3.40 | 0.048 | 5369 |
| A1 | 5.55 | 23.50 | 0.006 | 2534 |
| A2 | 5.62 | 15.50 | 0.002 | 3967 |
| A3 | 6.12 | 30.00 | 0.003 | 2585 |
| A4 | 5.43 | 10.00 | 0.001 | 5621 |
| A5 | 6.80 | 63.70 | 0.003 | 1658 |

Table 1-Continued

| Name | $\tau$ | $\theta$ | $\mathrm{F}^{\mathrm{a}}$ | D <br> SSV |
| :--- | ---: | ---: | ---: | ---: |
|  |  | $\prime \prime$ |  | $\mathrm{pc}]$ |
|  |  |  |  |  |
| A6 | 6.45 | 93.00 | 0.012 | 967 |
| A7 | 6.28 | 382.00 | 0.305 | 218 |
| A8 | 5.15 | 30.00 | 0.026 | 1648 |
| A9 | 6.02 | 18.50 | 0.001 | 3999 |
| A10 | 5.20 | 10.00 | 0.002 | 5075 |
| A11 | 5.01 | 16.00 | 0.010 | 2901 |
| A12 | 4.58 | 18.50 | 0.036 | 2058 |
| A13 | 6.47 | 76.30 | 0.008 | 1191 |
| A14 | 5.38 | 16.40 | 0.004 | 3353 |
| A15 | 5.67 | 17.00 | 0.002 | 3691 |
| A16 | 6.59 | 70.50 | 0.005 | 1363 |
| A17 | 5.79 | 21.40 | 0.003 | 3100 |
| A18 | 5.50 | 36.60 | 0.017 | 1588 |
| A19 | 6.12 | 33.50 | 0.003 | 2310 |
| A20 | 5.78 | 33.50 | 0.007 | 1978 |
| A23 | 5.63 | 27.00 | 0.007 | 2289 |
| A24 | 6.54 | 177.40 | 0.036 | 530 |
| A26 | 5.82 | 20.00 | 0.002 | 3376 |
| A28 | 7.13 | 134.00 | 0.005 | 920 |
| A30 | 6.85 | 63.50 | 0.002 | 1702 |
| A31 | 6.97 | 486.00 | 0.102 | 235 |
| A32 | 6.05 | 67.00 | 0.016 | 1118 |
| A33 | 6.71 | 134.00 | 0.014 | 758 |
| A34 | 6.79 | 145.00 | 0.013 | 728 |
| A35 | 6.37 | 386.00 | 0.255 | 225 |
| A36 | 5.89 | 183.50 | 0.174 | 379 |
| A39 | 6.72 | 87.00 | 0.006 | 1175 |
| A40 | 5.76 | 17.00 | 0.002 | 3859 |
| A41 | 4.83 | 9.20 | 0.005 | 4644 |
| A43 | 5.76 | 40.00 | 0.011 | 1634 |
| A44 | 5.50 | 28.00 | 0.010 | 2074 |
| A46 | 5.91 | 31.70 | 0.005 | 2211 |
| A50 | 5.86 | 13.50 | 0.001 | 5091 |
| A51 | 5.19 | 33.50 | 0.029 | 1503 |
| A53 | 4.05 | 15.50 | 0.086 | 1924 |
| A54 | 6.10 | 28.00 | 0.002 | 2736 |
| A55 | 5.58 | 24.00 | 0.006 | 2519 |
| A59 | 5.61 | 43.00 | 0.018 | 1425 |
| A60 | 5.70 | 37.00 | 0.011 | 1721 |
|  |  |  |  |  |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ <br> [pc] |
| :---: | :---: | :---: | :---: | :---: |
| A62 | 4.70 | 80.50 | 0.522 | 499 |
| A65 | 6.45 | 54.00 | 0.004 | 1671 |
| A66 | 6.09 | 133.40 | 0.058 | 572 |
| A67 | 5.82 | 33.50 | 0.007 | 2011 |
| A69 | 5.01 | 11.00 | 0.005 | 4206 |
| A70 | 5.17 | 21.00 | 0.012 | 2376 |
| A71 | 5.48 | 79.00 | 0.083 | 729 |
| A72 | 6.00 | 63.70 | 0.016 | 1151 |
| A73 | 5.86 | 36.60 | 0.007 | 1875 |
| A75 | 5.28 | 28.50 | 0.017 | 1845 |
| A77 | 4.15 | 32.90 | 0.308 | 949 |
| A78 | 6.37 | 53.50 | 0.005 | 1622 |
| A79 | 5.12 | 27.10 | 0.022 | 1801 |
| A80 | 6.59 | 54.80 | 0.003 | 1752 |
| A81 | 5.92 | 16.50 | 0.001 | 4283 |
| A82 | 6.09 | 40.50 | 0.005 | 1887 |
| A84 | 6.05 | 47.50 | 0.008 | 1579 |
| AGCAR | 3.56 | 17.80 | 0.348 | 1338 |
| Ap1-11 | 4.41 | 6.00 | 0.006 | 5847 |
| Ap1-12 | 4.26 | 6.00 | 0.019 | 4610 |
| Ap2-1 | 3.53 | 16.40 | 0.320 | 1429 |
| Ap2-1 | 4.58 | 50.00 | 0.262 | 762 |
| Ba-1 | 5.05 | 19.00 | 0.013 | 2483 |
| BD +30 | 2.10 | 4.00 | 0.511 | 3034 |
| BlM | 3.10 | 2.30 | 0.017 | 8354 |
| BV-1 | 4.99 | 20.80 | 0.018 | 2211 |
| Cn1-5 | 3.05 | 3.50 | 0.044 | 5369 |
| Cn2-1 | 2.35 | 1.70 | 0.052 | 8008 |
| Cn3-1 | 2.57 | 2.50 | 0.067 | 6040 |
| CRL618 | 3.33 | 6.00 | 0.067 | 3572 |
| DdDm-1 | 2.22 | 0.50 | 0.006 | 25700 |
| Fg-1 | 3.67 | 8.00 | 0.055 | 3127 |
| Ha1-1 | 3.14 | 1.20 | 0.004 | 16400 |
| Ha1-3 | 2.79 | 7.90 | 0.405 | 2113 |
| Ha1-8 | 2.57 | 1.70 | 0.031 | 8881 |
| Ha1-11 | 3.44 | 3.00 | 0.013 | 7515 |
| Ha1-14 | 3.30 | 3.30 | 0.022 | 6389 |
| Ha1-15 | 3.17 | 2.20 | 0.013 | 9052 |
| Ha1-17 | 2.13 | 0.50 | 0.006 | 25700 |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ <br> [pc] |
| :---: | :---: | :---: | :---: | :---: |
| Ha1-20 | 2.56 | 2.00 | 0.044 | 7514 |
| Ha1-23 | 2.35 | 1.40 | 0.035 | 9750 |
| Ha1-24 | 3.70 | 4.30 | 0.015 | 5892 |
| Ha1-27 | 3.18 | 2.60 | 0.018 | 7673 |
| Ha1-33 | 2.82 | 1.40 | 0.012 | 12060 |
| Ha1-39 | 2.37 | 0.90 | 0.014 | 15290 |
| Ha1-40 | 2.36 | 1.90 | 0.063 | 7200 |
| Ha1-41 | 3.86 | 4.80 | 0.013 | 5686 |
| Ha1-42 | 2.92 | 2.90 | 0.040 | 6126 |
| Ha1-43 | 3.18 | 1.50 | 0.006 | 13300 |
| Ha1-54 | 2.13 | 1.00 | 0.029 | 12340 |
| Ha1-59 | 3.94 | 3.00 | 0.004 | 9421 |
| Ha1-60 | 3.11 | 1.90 | 0.011 | 10170 |
| Ha1-65 | 3.21 | 2.60 | 0.017 | 7780 |
| Ha1-66 | 3.86 | 3.30 | 0.006 | 8284 |
| Ha1-67 | 3.51 | 3.00 | 0.011 | 7770 |
| Ha2-1 | 2.68 | 2.80 | 0.065 | 5677 |
| На2-7 | 3.29 | 2.10 | 0.009 | 10020 |
| Ha2-10 | 2.30 | 1.00 | 0.020 | 13330 |
| Ha2-10 | 2.42 | 1.00 | 0.015 | 14060 |
| Ha2-15 | 3.76 | 1.70 | 0.002 | 15360 |
| Ha2-16 | 4.91 | 8.40 | 0.003 | 5268 |
| Ha2-17 | 3.10 | 1.80 | 0.010 | 10720 |
| Ha2-20 | 2.95 | 1.90 | 0.016 | 9447 |
| Ha2-24 | 3.21 | 2.30 | 0.013 | 8814 |
| Ha2-25 | 3.68 | 2.20 | 0.004 | 11460 |
| Ha2-33 | 4.11 | 4.00 | 0.005 | 7655 |
| Ha2-41 | 4.26 | 3.80 | 0.003 | 8632 |
| Ha2-43 | 3.49 | 4.50 | 0.026 | 5114 |
| Ha3-29 | 3.90 | 6.00 | 0.018 | 4646 |
| На4-1 | 3.83 | 1.50 | 0.001 | 18050 |
| Hb-4 | 2.18 | 2.50 | 0.166 | 5037 |
| $\mathrm{Hb}-5$ | 2.81 | 10.00 | 0.620 | 1685 |
| Hb-7 | 2.73 | 2.00 | 0.030 | 8109 |
| Hb-8 | 3.49 | 2.50 | 0.008 | 9239 |
| He1-5 | 5.39 | 18.00 | 0.005 | 3081 |
| He1-6 | 4.39 | 11.20 | 0.020 | 3119 |
| He2-5 | 2.49 | 1.50 | 0.029 | 9702 |
| He2-7 | 4.63 | 22.30 | 0.047 | 1744 |

TABLE 1-Continued

| Name | $\tau$ | $\theta$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ [pc] |
| :---: | :---: | :---: | :---: | :---: |
| He2-11 | 3.98 | 32.50 | 0.445 | 888 |
| He2-15 | 3.73 | 11.90 | 0.105 | 2165 |
| He2-21 | 2.56 | 1.20 | 0.016 | 12490 |
| He2-26 | 4.56 | 19.00 | 0.040 | 1983 |
| He2-28 | 3.70 | 5.00 | 0.020 | 5075 |
| He2-29 | 3.91 | 7.00 | 0.024 | 3999 |
| He2-35 | 3.02 | 2.50 | 0.024 | 7416 |
| He2-36 | 3.81 | 11.00 | 0.075 | 2427 |
| He2-37 | 4.37 | 11.50 | 0.023 | 3004 |
| He2-50 | 4.09 | 5.90 | 0.011 | 5151 |
| He2-51 | 3.15 | 4.50 | 0.057 | 4384 |
| He2-63 | 2.88 | 1.50 | 0.012 | 11570 |
| He2-73 | 2.32 | 2.00 | 0.076 | 6733 |
| He2-85 | 2.97 | 5.10 | 0.112 | 3555 |
| He2-99 | 4.21 | 8.50 | 0.018 | 3770 |
| He2-102 | 3.39 | 4.50 | 0.033 | 4891 |
| He2-103 | 4.35 | 10.00 | 0.018 | 3419 |
| He2-105 | 4.84 | 15.50 | 0.014 | 2764 |
| He2-107 | 3.19 | 5.00 | 0.065 | 4009 |
| He2-108 | 3.56 | 5.50 | 0.033 | 4336 |
| He2-109 | 3.54 | 3.70 | 0.016 | 6373 |
| He2-111 | 3.30 | 6.00 | 0.073 | 3511 |
| He2-112 | 3.41 | 7.30 | 0.082 | 3050 |
| He2-114 | 5.09 | 18.30 | 0.011 | 2626 |
| He2-116 | 5.58 | 25.50 | 0.007 | 2369 |
| He2-119 | 4.47 | 26.40 | 0.094 | 1372 |
| He2-120 | 4.45 | 13.50 | 0.026 | 2653 |
| He2-123 | 2.28 | 2.30 | 0.110 | 5750 |
| He2-125 | 2.65 | 1.50 | 0.020 | 10410 |
| He2-132 | 4.10 | 8.90 | 0.025 | 3434 |
| He2-138 | 2.81 | 3.50 | 0.076 | 4813 |
| He2-141 | 3.57 | 6.90 | 0.051 | 3469 |
| He2-142 | 2.30 | 1.80 | 0.065 | 7400 |
| He2-143 | 2.35 | 2.60 | 0.120 | 5250 |
| He2-146 | 3.42 | 11.00 | 0.186 | 2024 |
| He2-149 | 3.12 | 1.50 | 0.007 | 12970 |
| He2-152 | 2.79 | 5.50 | 0.196 | 3036 |
| He2-153 | 5.17 | 6.50 | 0.001 | 7744 |
| He2-155 | 3.48 | 7.30 | 0.070 | 3148 |

TABLE 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & { }_{\prime \prime} \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| He2-157 | 2.48 | 1.50 | 0.030 | 9637 |
| He2-158 | 3.17 | 1.00 | 0.003 | 19890 |
| He2-159 | 3.60 | 5.00 | 0.025 | 4853 |
| He2-161 | 3.80 | 5.00 | 0.016 | 5313 |
| He2-163 | 5.07 | 10.00 | 0.003 | 4772 |
| He2-164 | 3.42 | 8.00 | 0.097 | 2791 |
| He2-165 | 5.20 | 25.00 | 0.016 | 2023 |
| He2-169 | 3.74 | 10.90 | 0.086 | 2374 |
| He2-175 | 3.21 | 3.30 | 0.027 | 6141 |
| He2-180 | 2.23 | 0.90 | 0.019 | 14350 |
| He2-186 | 2.63 | 1.50 | 0.021 | 10350 |
| He2-262 | 2.60 | 1.60 | 0.026 | 9540 |
| He2-429 | 2.41 | 2.10 | 0.069 | 6659 |
| He2-432 | 2.17 | 1.10 | 0.033 | 11420 |
| He2-433 | 3.66 | 4.00 | 0.014 | 6231 |
| He2-435 | 3.19 | 2.40 | 0.015 | 8349 |
| He2-453 | 4.52 | 11.20 | 0.015 | 3313 |
| Hf2-1 | 3.99 | 4.70 | 0.009 | 6165 |
| Hu1-1 | 3.03 | 2.50 | 0.023 | 7460 |
| J320 | 3.39 | 3.60 | 0.021 | 6120 |
| J900 | 2.51 | 3.00 | 0.110 | 4903 |
| Jn-1 | 7.05 | 166.00 | 0.010 | 716 |
| K1-1 | 5.22 | 21.70 | 0.011 | 2362 |
| K1-3 | 3.88 | 46.00 | 1.117 | 599 |
| K1-4 | 4.93 | 23.00 | 0.025 | 1943 |
| K1-7 | 5.76 | 17.00 | 0.002 | 3859 |
| K1-8 | 5.02 | 39.50 | 0.059 | 1183 |
| K1-12 | 5.14 | 18.50 | 0.010 | 2659 |
| K1-13 | 5.67 | 83.00 | 0.059 | 758 |
| K1-14 | 6.20 | 23.50 | 0.001 | 3413 |
| K1-16 | 5.07 | 47.00 | 0.076 | 1013 |
| K1-20 | 5.95 | 17.00 | 0.001 | 4207 |
| K1-21 | 5.23 | 14.50 | 0.005 | 3535 |
| K1-22 | 6.45 | 90.50 | 0.012 | 997 |
| K1-32 | 6.00 | 29.50 | 0.003 | 2479 |
| K2-1 | 5.92 | 66.00 | 0.021 | 1071 |
| K2-2 | 6.50 | 207.00 | 0.054 | 446 |
| K2-4 | 6.37 | 343.00 | 0.202 | 253 |
| K2-5 | 4.88 | 12.30 | 0.008 | 3561 |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| K3-1 | 3.70 | 2.50 | 0.005 | 10150 |
| K3-2 | 2.41 | 1.40 | 0.031 | 9991 |
| K3-3 | 3.47 | 5.50 | 0.041 | 4144 |
| K3-4 | 4.10 | 8.10 | 0.021 | 3762 |
| K3-5 | 4.52 | 5.00 | 0.003 | 7416 |
| K3-7 | 3.14 | 3.20 | 0.030 | 6116 |
| K3-9 | 3.89 | 3.80 | 0.007 | 7280 |
| K3-11 | 2.72 | 1.50 | 0.017 | 10800 |
| K3-13 | 2.63 | 1.90 | 0.034 | 8156 |
| K3-14 | 2.32 | 0.50 | 0.005 | 26880 |
| K3-16 | 3.37 | 2.00 | 0.007 | 10910 |
| K3-17 | 2.74 | 7.40 | 0.398 | 2205 |
| K3-18 | 3.09 | 2.00 | 0.013 | 9600 |
| K3-23 | 3.03 | 1.50 | 0.008 | 12460 |
| K3-24 | 3.17 | 3.10 | 0.026 | 6405 |
| K3-27 | 4.63 | 8.20 | 0.006 | 4752 |
| K3-30 | 2.70 | 1.70 | 0.023 | 9427 |
| K3-37 | 2.60 | 1.30 | 0.017 | 11760 |
| K3-38 | 2.52 | 1.50 | 0.025 | 9978 |
| K3-40 | 2.90 | 2.00 | 0.020 | 8794 |
| K3-41 | 2.17 | 0.25 | 0.002 | 50140 |
| K3-48 | 3.02 | 3.00 | 0.034 | 6201 |
| K3-55 | 2.87 | 4.10 | 0.090 | 4231 |
| K3-57 | 2.83 | 3.20 | 0.060 | 5325 |
| K3-58 | 2.87 | 2.40 | 0.031 | 7221 |
| K3-61 | 3.41 | 3.00 | 0.014 | 7405 |
| K3-63 | 3.23 | 3.50 | 0.029 | 5836 |
| K3-65 | 3.80 | 2.50 | 0.004 | 10610 |
| K3-66 | 2.43 | 1.10 | 0.018 | 12860 |
| K3-67 | 3.73 | 7.50 | 0.042 | 3430 |
| K3-68 | 4.46 | 6.00 | 0.005 | 6002 |
| K3-70 | 2.63 | 0.80 | 0.006 | 19390 |
| K3-72 | 5.55 | 11.50 | 0.001 | 5168 |
| K3-77 | 3.32 | 3.80 | 0.027 | 5618 |
| K3-78 | 3.05 | 2.20 | 0.017 | 8540 |
| K3-82 | 4.32 | 12.50 | 0.030 | 2700 |
| K3-83 | 3.59 | 2.50 | 0.006 | 9631 |
| K3-87 | 3.90 | 3.00 | 0.004 | 9291 |
| K3-90 | 3.77 | 4.50 | 0.014 | 5814 |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: |
| K3-91 | 4.82 | 5.00 | 0.001 | 8519 |
| K3-92 | 4.93 | 6.50 | 0.002 | 6871 |
| K3-94 | 4.26 | 5.00 | 0.005 | 6570 |
| K4-16 | 3.48 | 1.50 | 0.003 | 15270 |
| K4-30 | 2.51 | 1.30 | 0.021 | 11280 |
| K4-39 | 2.65 | 1.00 | 0.009 | 15640 |
| K4-41 | 2.78 | 1.50 | 0.015 | 11070 |
| K4-45 | 3.25 | 4.50 | 0.046 | 4576 |
| K4-47 | 4.31 | 3.90 | 0.003 | 8609 |
| K4-48 | 2.54 | 1.10 | 0.014 | 13520 |
| K4-58 | 4.30 | 5.00 | 0.005 | 6696 |
| K4-60 | 2.85 | 10.00 | 0.560 | 1719 |
| LoTr5 | 4.29 | 5.30 | 0.006 | 6321 |
| M1-1 | 3.58 | 3.00 | 0.009 | 8002 |
| M1-4 | 2.28 | 2.00 | 0.084 | 6600 |
| M1-7 | 3.77 | 4.40 | 0.013 | 5963 |
| M1-8 | 4.17 | 9.20 | 0.023 | 3423 |
| M1-9 | 2.20 | 1.10 | 0.030 | 11580 |
| M1-13 | 3.82 | 5.00 | 0.015 | 5375 |
| M1-14 | 2.61 | 2.40 | 0.056 | 6416 |
| M1-16 | 2.51 | 1.50 | 0.028 | 9770 |
| M1-17 | 2.72 | 1.50 | 0.017 | 10800 |
| M1-18 | 5.82 | 15.20 | 0.001 | 4433 |
| M1-19 | 2.42 | 1.30 | 0.026 | 10810 |
| M1-22 | 4.01 | 3.00 | 0.003 | 9770 |
| M1-25 | 2.59 | 2.30 | 0.055 | 6605 |
| M1-27 | 3.01 | 4.00 | 0.063 | 4612 |
| M1-28 | 4.04 | 7.40 | 0.020 | 4011 |
| M1-29 | 2.82 | 4.10 | 0.102 | 4127 |
| M1-31 | 2.93 | 3.50 | 0.057 | 5098 |
| M1-32 | 2.96 | 3.80 | 0.064 | 4741 |
| M1-33 | 2.38 | 1.90 | 0.060 | 7280 |
| M1-34 | 3.93 | 5.60 | 0.015 | 5042 |
| M1-35 | 2.68 | 2.60 | 0.057 | 6093 |
| M1-39 | 2.20 | 2.00 | 0.100 | 6374 |
| M1-41 | 4.22 | 38.00 | 0.350 | 848 |
| M1-42 | 3.45 | 4.10 | 0.024 | 5512 |
| M1-44 | 3.25 | 2.00 | 0.009 | 10320 |
| M1-46 | 3.15 | 5.50 | 0.086 | 3580 |

Table 1-Continued

| Name | $\tau$ | $\theta$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ <br> [pc] |
| :---: | :---: | :---: | :---: | :---: |
| M1-47 | 3.35 | 2.80 | 0.014 | 7718 |
| M1-48 | 3.58 | 2.40 | 0.006 | 10030 |
| M1-50 | 2.80 | 2.80 | 0.050 | 5983 |
| M1-51 | 2.85 | 7.50 | 0.319 | 2287 |
| M1-52 | 3.90 | 4.00 | 0.008 | 6969 |
| M1-53 | 2.83 | 3.00 | 0.053 | 5674 |
| M1-54 | 3.65 | 6.50 | 0.038 | 3813 |
| M1-57 | 3.01 | 4.20 | 0.069 | 4398 |
| M1-58 | 2.83 | 3.20 | 0.060 | 5325 |
| M1-59 | 2.16 | 2.30 | 0.148 | 5419 |
| M1-60 | 2.11 | 1.30 | 0.052 | 9407 |
| M1-63 | 3.24 | 2.10 | 0.010 | 9771 |
| M1-64 | 5.08 | 8.50 | 0.002 | 5640 |
| M1-65 | 2.77 | 1.80 | 0.022 | 9191 |
| M1-66 | 2.12 | 1.40 | 0.059 | 8773 |
| M1-67 | 4.76 | 60.20 | 0.250 | 688 |
| M1-73 | 2.76 | 2.50 | 0.043 | 6600 |
| M1-75 | 3.87 | 7.00 | 0.026 | 3929 |
| M1-77 | 3.41 | 4.00 | 0.025 | 5549 |
| M1-79 | 4.68 | 15.00 | 0.019 | 2652 |
| M1-80 | 3.41 | 4.00 | 0.025 | 5549 |
| M2-2 | 2.96 | 3.50 | 0.054 | 5153 |
| M2-7 | 3.96 | 4.00 | 0.007 | 7157 |
| M2-8 | 2.90 | 1.90 | 0.018 | 9262 |
| M2-9 | 4.64 | 23.00 | 0.048 | 1705 |
| M2-11 | 2.56 | 1.40 | 0.021 | 10750 |
| M2-13 | 2.29 | 0.80 | 0.013 | 16610 |
| M2-15 | 3.40 | 2.90 | 0.013 | 7623 |
| M2-16 | 3.07 | 2.70 | 0.025 | 7035 |
| M2-17 | 3.81 | 4.00 | 0.010 | 6664 |
| M2-18 | 2.18 | 0.80 | 0.017 | 15740 |
| M2-19 | 3.25 | 2.50 | 0.014 | 8261 |
| M2-21 | 2.59 | 1.50 | 0.023 | 10160 |
| M2-22 | 3.41 | 2.60 | 0.010 | 8546 |
| M2-23 | 3.04 | 4.40 | 0.070 | 4262 |
| M2-24 | 4.19 | 3.40 | 0.003 | 9347 |
| M2-26 | 3.99 | 3.50 | 0.005 | 8294 |
| M2-27 | 2.14 | 1.00 | 0.029 | 12400 |
| M2-28 | 3.29 | 2.20 | 0.010 | 9540 |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & { }_{\prime \prime} \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ [pc] |
| :---: | :---: | :---: | :---: | :---: |
| M2-29 | 3.59 | 2.80 | 0.008 | 8632 |
| M2-30 | 3.06 | 2.00 | 0.014 | 9444 |
| M2-33 | 2.87 | 2.00 | 0.021 | 8668 |
| M2-36 | 3.27 | 3.40 | 0.025 | 6117 |
| M2-38 | 3.90 | 4.00 | 0.008 | 6969 |
| M2-39 | 3.11 | 1.60 | 0.008 | 12080 |
| M2-40 | 2.87 | 2.50 | 0.033 | 6942 |
| M2-42 | 3.06 | 2.00 | 0.014 | 9444 |
| M2-44 | 3.07 | 4.00 | 0.054 | 4756 |
| M2-45 | 2.47 | 3.20 | 0.139 | 4502 |
| M2-46 | 3.81 | 2.20 | 0.003 | 12140 |
| M2-47 | 3.14 | 4.10 | 0.049 | 4788 |
| M2-48 | 2.73 | 1.60 | 0.019 | 10160 |
| M2-50 | 3.51 | 2.30 | 0.006 | 10120 |
| M2-51 | 4.58 | 19.60 | 0.041 | 1941 |
| M2-52 | 4.15 | 7.00 | 0.014 | 4454 |
| M2-53 | 4.56 | 10.00 | 0.011 | 3773 |
| M2-54 | 2.10 | 0.50 | 0.008 | 24270 |
| M2-55 | 4.93 | 20.00 | 0.019 | 2232 |
| M3-1 | 3.72 | 5.60 | 0.024 | 4571 |
| M3-2 | 4.32 | 3.80 | 0.003 | 8930 |
| M3-3 | 4.42 | 6.10 | 0.006 | 5810 |
| M3-4 | 4.90 | 6.90 | 0.002 | 6392 |
| M3-5 | 3.62 | 3.40 | 0.011 | 7208 |
| M3-6 | 2.87 | 4.10 | 0.091 | 4222 |
| M3-7 | 3.14 | 3.10 | 0.028 | 6320 |
| M3-8 | 3.12 | 2.70 | 0.022 | 7206 |
| M3-9 | 3.91 | 8.40 | 0.035 | 3324 |
| M3-10 | 2.55 | 1.60 | 0.029 | 9334 |
| M3-11 | 3.67 | 3.60 | 0.011 | 6965 |
| M3-12 | 3.29 | 2.70 | 0.015 | 7780 |
| M3-14 | 3.24 | 3.60 | 0.030 | 5699 |
| M3-16 | 3.41 | 3.30 | 0.017 | 6727 |
| M3-17 | 2.88 | 1.50 | 0.012 | 11570 |
| M3-19 | 3.88 | 3.50 | 0.006 | 7870 |
| M3-20 | 2.60 | 2.00 | 0.040 | 7655 |
| M3-22 | 3.64 | 3.20 | 0.009 | 7714 |
| M3-23 | 3.71 | 6.00 | 0.028 | 4253 |
| M3-26 | 3.79 | 3.50 | 0.008 | 7550 |

TABLE 1—Continued

| Name | $\tau$ | $\theta$ | $\mathrm{F}^{\mathrm{a}}$ | D <br> SSV <br> $[\mathrm{pc}]$ |
| :--- | ---: | ---: | ---: | ---: |
|  |  |  |  |  |
| M3-28 | 3.40 | 4.50 | 0.033 | 4903 |
| M3-29 | 3.55 | 4.10 | 0.019 | 5794 |
| M3-30 | 4.61 | 8.60 | 0.007 | 4484 |
| M3-32 | 3.68 | 3.80 | 0.012 | 6627 |
| M3-33 | 3.68 | 3.00 | 0.007 | 8389 |
| M3-34 | 3.03 | 2.80 | 0.029 | 6649 |
| M3-36 | 3.47 | 1.60 | 0.003 | 14250 |
| M3-37 | 2.99 | 1.10 | 0.005 | 16610 |
| M3-38 | 2.19 | 0.90 | 0.021 | 14060 |
| M3-39 | 3.06 | 9.00 | 0.284 | 2098 |
| M3-40 | 2.57 | 1.30 | 0.018 | 11630 |
| M3-41 | 2.37 | 2.10 | 0.075 | 6556 |
| M3-42 | 4.14 | 4.50 | 0.006 | 6901 |
| M3-43 | 2.73 | 1.90 | 0.027 | 8528 |
| M3-52 | 4.68 | 6.00 | 0.003 | 6648 |
| M3-54 | 3.59 | 2.80 | 0.008 | 8632 |
| M4-1 | 2.72 | 2.20 | 0.037 | 7344 |
| M4-2 | 3.28 | 3.00 | 0.019 | 6966 |
| M4-7 | 3.01 | 2.90 | 0.033 | 6366 |
| M4-9 | 4.67 | 22.10 | 0.042 | 1794 |
| M4-14 | 3.67 | 3.70 | 0.012 | 6756 |
| M4-18 | 2.87 | 1.90 | 0.019 | 9133 |
| Me1-1 | 2.73 | 2.40 | 0.043 | 6757 |
| Me2-1 | 3.18 | 3.00 | 0.024 | 6665 |
| My60 | 2.98 | 3.80 | 0.060 | 4803 |
| MyCn18 | 3.18 | 6.30 | 0.106 | 3165 |
| Mz1 | 4.04 | 12.90 | 0.061 | 2299 |
| Mz2 | 3.85 | 11.50 | 0.075 | 2364 |
| Mz3 | 3.00 | 12.70 | 0.649 | 1446 |
| NA1 | 3.37 | 4.00 | 0.027 | 5464 |
| PB2 | 2.35 | 1.50 | 0.040 | 9098 |
| PC12 | 2.23 | 0.90 | 0.019 | 14350 |
| PB3 | 2.85 | 3.50 | 0.070 | 4893 |
| PB4 | 3.25 | 5.60 | 0.071 | 3680 |
| PB6 | 3.61 | 5.50 | 0.030 | 4419 |
| PB8 | 2.98 | 2.50 | 0.026 | 7299 |
| PB9 | 3.31 | 4.50 | 0.040 | 4706 |
| 3.50 | 0.030 | 5796 |  |  |
|  |  |  |  |  |

Table 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ <br> [pc] |
| :---: | :---: | :---: | :---: | :---: |
| PC17 | 3.23 | 2.50 | 0.015 | 8180 |
| PC19 | 2.49 | 1.40 | 0.025 | 10390 |
| PC23 | 2.43 | 1.10 | 0.018 | 12860 |
| PC24 | 3.14 | 2.50 | 0.018 | 7856 |
| Pe1-5 | 2.71 | 5.50 | 0.233 | 2932 |
| Pe1-6 | 3.11 | 3.60 | 0.040 | 5380 |
| Pe1-11 | 4.01 | 4.50 | 0.008 | 6493 |
| Pe1-12 | 4.63 | 6.00 | 0.003 | 6484 |
| Pe1-13 | 4.21 | 3.50 | 0.003 | 9186 |
| Pe1-15 | 3.25 | 2.50 | 0.014 | 8249 |
| Pe1-17 | 3.91 | 3.50 | 0.006 | 7997 |
| Pe1-19 | 3.51 | 2.20 | 0.006 | 10570 |
| Pe1-20 | 3.14 | 3.20 | 0.029 | 6141 |
| Pe1-21 | 3.39 | 4.30 | 0.030 | 5123 |
| Pe2-12 | 4.10 | 2.50 | 0.002 | 12190 |
| Pe2-15 | 2.88 | 1.30 | 0.009 | 13360 |
| PHL932 | 6.92 | 135.00 | 0.009 | 828 |
| Ps1 | 2.93 | 1.80 | 0.014 | 10000 |
| Pu-1 | 5.80 | 33.00 | 0.007 | 2024 |
| PW1 | 7.83 | 200.00 | 0.085 | 416 |
| Sa1-8 | 3.46 | 2.80 | 0.011 | 8099 |
| Sa2-21 | 5.82 | 20.00 | 0.002 | 3376 |
| Sa2-22 | 4.15 | 4.00 | 0.004 | 7818 |
| Sh1-89 | 4.53 | 19.00 | 0.043 | 1959 |
| Sh1-118 | 5.80 | 57.50 | 0.021 | 1161 |
| Sh2-71 | 5.18 | 49.80 | 0.066 | 1006 |
| Sh2-207 | 5.12 | 100.00 | 0.300 | 489 |
| Sh2-266 | 4.49 | 33.50 | 0.145 | 1091 |
| Sn1 | 3.11 | 1.50 | 0.007 | 12890 |
| Sp1 | 4.84 | 36.00 | 0.075 | 1192 |
| Sp3 | 4.32 | 17.80 | 0.061 | 1895 |
| Tc1 | 3.18 | 7.50 | 0.147 | 2669 |
| Th2-A | 3.95 | 11.50 | 0.060 | 2471 |
| Th3-10 | 2.13 | 1.00 | 0.029 | 12330 |
| Th3-19 | 2.98 | 1.00 | 0.004 | 18210 |
| Th3-25 | 2.26 | 0.90 | 0.018 | 14500 |
| Th3-26 | 3.64 | 3.30 | 0.010 | 7480 |
| Th4-5 | 3.49 | 3.50 | 0.016 | 6573 |
| VV-47 | 6.88 | 190.00 | 0.019 | 578 |

TABLE 1-Continued

| Name | $\tau$ | $\begin{aligned} & \theta \\ & \prime \prime \end{aligned}$ | $\mathrm{F}^{\text {a }}$ | $\mathrm{D}_{\mathrm{SSV}}$ [pc] |
| :---: | :---: | :---: | :---: | :---: |
| VV1-2 | 5.41 | 130.00 | 0.265 | 428 |
| VV1-4 | 4.46 | 63.20 | 0.553 | 570 |
| VV1-5 | 5.02 | 162.00 | 1.002 | 288 |
| VV1-7 | 6.03 | 124.00 | 0.057 | 600 |
| VV1-8 | 4.72 | 45.00 | 0.156 | 901 |
| VV3-4 | 2.38 | 0.60 | 0.006 | 23040 |
| Vy1-1 | 3.12 | 3.10 | 0.029 | 6281 |
| Vy1-2 | 3.26 | 2.30 | 0.012 | 9002 |
| Vy1-4 | 3.20 | 2.00 | 0.010 | 10100 |
| Vy2-1 | 2.59 | 1.90 | 0.038 | 7997 |
| Vy2-3 | 3.85 | 2.30 | 0.003 | 11820 |
| We-1 | 5.38 | 9.50 | 0.001 | 5796 |
| We-2 | 3.63 | 46.00 | 2.000 | 534 |
| We-6 | 6.68 | 31.00 | 0.001 | 3233 |
| We2-5 | 6.18 | 97.00 | 0.025 | 820 |
| We2-262 | 6.80 | 65.00 | 0.003 | 1625 |
| YM29 | 6.06 | 307.50 | 0.327 | 245 |

${ }^{\text {a }}$ This is the 5 GHz flux when available, otherwise equivalent 5 GHz flux from $\mathrm{H} \beta$.

TABLE 2
Individual Distances of Galactic PNe

| Name | $\begin{aligned} & \mathrm{D}_{\text {ind }} \\ & {[\mathrm{pc}]} \end{aligned}$ | $\begin{gathered} \sigma_{\mathrm{D}} \\ {[\mathrm{pc}]} \end{gathered}$ | $\tau$ | $\mathrm{D}_{\mathrm{CKS}}$ [pc] | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ | Method ${ }^{\text {a }}$ | Ref ${ }^{\text {b }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| A 7 | 676 | ${ }_{-150}^{+267}$ | 6.28 | 216 | 218 | P | Hea07 |
| A 24 | 521 | ${ }_{-79}^{+112}$ | 6.54 | 525 | 530 | P | Hea07 |
| A 31 | 568 | ${ }_{-90}^{+131}$ | 6.97 | 233 | 235 | P | Hea07 |
| BD+30 | 2680 | 810 | 2.1 | 1162 | 3034 | E | HTB93 |
| IC 289 | 2190 | 1630 | 3.81 | 1434 | 1448 | R | KL85 |
| IC 1747 | 2450 | 1150 | 3.12 | 2937 | 2991 | R | KL85 |
| IC 2448 | 1410 | 640 | 3.17 | 3947 | 3984 | E | Pea02 |
| HE 2-131 | 590 | 180 | 2.03 | 1413 | 3666 | P | C99 |
| K 1-14 | 3000 |  | 6.2 | 3378 | 3413 | P | C99 |
| K 1-22 | 1330 |  | 6.45 | 988 | 997 | P | C99 |
| Mz 2 | 2160 |  | 3.85 | 2341 | 2363 | P | C99 |
| NGC 2392 | 1600 | 130 | 3.93 | 1247 | 1258 | E | LL68 |
| NGC 2452 | 3570 | 560 | 3.81 | 2811 | 2838 | R | GPP86 |
| NGC 2792 | 1910 | 220 | 3.16 | 3021 | 3050 | R | GPP86 |
| NGC 2818 | 1855 | 200 | 4.69 | 1979 | 1998 | CM | CHW03 |
| NGC 3132 | 770 |  | 3.94 | 1251 | 1263 | P | C99 |
| NGC 3211 | 1910 | 500 | 3.51 | 2873 | 2901 | R | GPP86 |
| NGC 3242 | 420 | 160 | 3.22 | 1083 | 1094 | E | HTB95 |
| NGC 3918 | 2240 | 840 | 2.62 | 1010 | 1639 | R | GPP86 |
| NGC 5189 | 1730 | 530 | 4.59 | 540 | 546 | R | GPP86 |
| NGC 5315 | 2620 | 1030 | 1.94 | 1242 | 3177 | R | GPP86 |
| NGC 6210 | 1570 | 400 | 3.01 | 2025 | 2281 | E | HTB95 |
| NGC 6302 | 1600 | 600 | 2.77 | 525 | 741 | E | GRM93 |
| NGC 6565 | 1000 | 440 | 3.29 | 4616 | 4660 | R | GPP86 |
| NGC 6567 | 1680 | 170 | 2.68 | 2367 | 3610 | R | GPP86 |
| NGC 6572 | 703 | 95 | 2.16 | 705 | 1736 | E | HTB95 |
| NGC 6720 | 704 | ${ }_{-196}^{+445}$ | 4.1 | 872 | 880 | P | Hea07 |
| NGC 6741 | 1540 | 770 | 2.49 | 2047 | 3727 | R | KL85 |
| NGC 6853 | 379 | ${ }_{-42}^{+54}$ | 4.94 | 262 | 264 | P | Hea07 |
| NGC 6894 | 1090 | 110 | 4.5 | 1653 | 1669 | R | KL85 |
| NGC 7009 | 1400 | ... | 3.03 | 1201 | 1325 | E | Sea04 |
| NGC 7026 | 1450 | 840 | 2.91 | 1902 | 2352 | R | KL85 |
| NGC 7027 | 790 | . | 1.46 | 273 | 632 | P | HTB95 |
| NGC 7293 | 219 | ${ }_{-21}^{+27}$ | 5.7 | 157 | 159 | P | Hea07 |
| NGC 7354 | 2460 | 1440 | 2.83 | 1271 | 1697 | R | KL85 |
| NGC 7662 | 790 | 750 | 2.57 | 1163 | 1962 | E | HT96 |
| PS 1 | $1.23 \mathrm{e}+4$ | 600 | 2.93 | 8380 | 1.0e+4 | CM | ABL00 |
| Pw We 1 | 365 | ${ }_{+}^{+47}$ | 7.83 | 141 | 416 | P | Hea07 |
| Sp 3 | 2380 | $\ldots$ | 4.32 | 1877 | 1895 | P | C99 |

TABLE 2-Continued

| Name | $\begin{aligned} & \mathrm{D}_{\text {ind }} \\ & {[\mathrm{pc}]} \end{aligned}$ | $\begin{gathered} \sigma_{\mathrm{D}} \\ {[\mathrm{pc}]} \end{gathered}$ | $\tau$ | $\mathrm{D}_{\mathrm{CKS}}$ [pc] | $\begin{aligned} & \mathrm{D}_{\mathrm{SSV}} \\ & {[\mathrm{pc}]} \end{aligned}$ | Method ${ }^{\text {a }}$ | Ref ${ }^{\text {b }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |

${ }^{\text {a }} \mathrm{P}$ : parallax; CM: cluster membership; E: expansion; R: reddening.
${ }^{\text {b }}$ ABL00: Alves et al. 2000; CHW03: Chen et al. 2003; C99: Ciardullo et al. 1999; GPP86: Gathier et al. 1996; GRM93: Gomez et al. 1993; HTB93: Hajian et al. 1993; HTB95: Hajian et al. 1995; HT96: Hajian \& Terzian 1996; Hea07: Harris et al. 2007; KL85: Kaler \& Lutz 1985; LL68: Liller \& Liller 1968; Pea02: Palen et al. 2002: Sea04: Sabbadin et al. 2004.

Table 3
Comparison of Statistical and Individual Distances

| Ref. | Method | $\mathrm{R}_{\mathrm{xy}}$ | $<\frac{\delta \mathrm{D}}{\mathrm{D}}>_{\text {Gal }}$ | $\frac{\left\langle D_{\text {stat }}>-D_{\mathrm{LMC}}\right.}{D_{\mathrm{LMC}}}$ | $\frac{\left\langle D_{\mathrm{stat}}>-D_{\mathrm{SMC}}\right.}{D_{\mathrm{SMC}}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| SSV | $\mu \tau$ | 0.99 | 0.26 | 0.01 | 0.01 |
| Old scales |  |  |  |  |  |
| CKS | $\mu \tau$ | 0.97 | 0.32 | 0.04 | 0.05 |
| vdSZ | $\log \mathrm{T}_{\mathrm{b}}-\log \mathrm{R}_{\mathrm{PN}}$ | 0.74 | 0.86 | 0.13 | 0.12 |
| Z95 | $\log \mathrm{M}_{\text {ion }}-\log \mathrm{R}_{\text {PN }}$ | 0.70 | 1.10 | 0.19 | 0.22 |
| BL01 | $\log \mathrm{M}_{\text {ion }}-\log \mathrm{R}_{\text {PN }}$ | 0.61 | 1.35 | 0.12 | 0.12 |
| SB96 | $\log \mathrm{I}-\log \mathrm{R}_{\mathrm{PN}}$ | 0.95 | 0.46 | 0.02 | 0.02 |
| LMC/SMC calibrations |  |  |  |  |  |
| this paper | $\log \mathrm{T}_{\mathrm{b}}-\log \mathrm{R}_{\mathrm{PN}}$ | 0.82 | 0.74 | 0.07 | 0.02 |
| this paper | $\log \mathrm{M}_{\text {ion }}-\log \mathrm{R}_{\text {PN }}$ | 0.80 | 0.72 | 0.11 | 0.08 |
| this paper | $\log \mathrm{I}-\log \mathrm{R}_{\mathrm{PN}}$ | 0.96 | 0.36 | 0.03 | 0.02 |



Fig. 1.- Plotted are $\log \mu$ versus $\tau$ for the sample of LMC PNe observed with the HST. Symbols indicate morphology types: Round (open circles), Elliptical (asterisks), Bipolar core (triangles) and Bipolar (squares). The thinning sequence is clearly defined for $\tau<2.1$. The solid line reflect CKS calibration, the broken line is the new calibration (SSV).


Fig. 2.- Same as in Figure 1, but for the SMC PNe.


Fig. 3.- LMC (open symbols) and SMC (filled symbols) PN, all morphologies except bipolar PN are plotted. Solid line: our new calibration for the Magellanic Cloud PNe.


Fig. 4.- The Galactic PNe of known distances plotted on the $\tau-\log \mu$ plane. Lines as in Figure 3. Symbols denote the method used for individual distance determination. Filled circles: P; filled squares: CM; open circles: R; open triangles: E.


Fig. 5.- Comparison of statistical distances form our new calibration (SSV) with individual distances of Table 2. Symbols represent the individual distance determination method, as in Fig. 5. Solid line: 1:1. Broken lines represent the $30 \%$ differences between statistical and individual distances.


Fig. 6.- Relative differences between SSV statistical and individual PN distances, as a function of $\tau$, separated in the panels by individual distance method. Symbols as in Fig. 6. Vertical lines denotes the $\tau$ of the thick to thin transition for the CKS and the SSV scales.


Fig. 7.- Relative differences between statistical and individual PN distances, plotted against the individual distances, for the Magellanic Cloud PNcalibrated scales of CKS (filled symbols), vdSZ (triangles), BL01 (crosses) and SB96 (pentagons).


[^0]:    ${ }^{1}$ Affiliated with the Hubble Space Telescope Division of the European Space Agency

