GRAVITY DISTANCES OF PLANETARY NEBULAE II. APPLICATION TO A SAMPLE OF GALACTIC OBJECTS

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1. Introduction

The main results on the difficult problem of distance determination for planetary nebulae in the last few years derive from the application of trigonometric parallaxes (Harris *et al.* 1997), radio expansion method (Hajian *et al.*, 1993, 1995) and Hipparcos distances (Pottasch and Acker 1998, see also Terzian, 1993, 1997). However, these methods are necessarily restricted to a few objects, which remain a small fraction of the known population of galactic PN, estimated as around 1800 true and possible PN (Acker 1997). Therefore, there is still a need for the development of statistical methods, which may be applicable to a larger number of objects, even though at the cost of a lower accuracy.

One such method is the so-called gravity distance method, proposed by Maciel and Cazetta (1997, hereafter referred to as Paper I). According to this method, an approximate range of progenitor masses can be attributed to the different PN types of the Peimbert classification scheme (Peimbert 1978, Peimbert and Torres-Peimbert 1983). Using theoretical initial mass-final mass relationships, the central star mass can be obtained. On the other hand, relations involving the surface gravity as a function of the central star temperature can also be derived for a given stellar mass, so that the luminosities of the central stars are obtained. The distances are then determined on the basis of the observed Hβ flux and an independent scaling of the Hβ luminosity (Maciel and Cazetta 1994). Previous work have included a few objects for which Lyman-α kinematic distances were known (Maciel 1995, 1997), and also the PN sample by Méndez *et al.* (1992), for which accurate distances have been obtained from high resolution spectroscopy and NLTE model atmospheres of the central stars. For a detailed description of the method, the reader is referred to the original work of Maciel and Cazetta (1997).

A characteristic feature of the gravity distance method is that it can be used either as an individual method, provided accurate surface gravities are independently known, or as a statistical method, if this quantity is not previously known. In the latter case, approximate distances are obtained, or sometimes a distance range. Such obvious disadvantage is partially compensated for by the fact that very

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few parameters are needed in this method, namely (i) a preliminary classification according to the Peimbert types, (ii) a determination of the stellar temperature and (iii) the nebular Hβ flux. In the present work, an application is made of the method to a large sample of galactic planetary nebulae, as a first attempt to establish a statistical distance scale based on gravity distances.

2. The Sample

The basic sample includes about two hundred nebulae belonging to the Peimbert types I, II and III, which we will consider as type I or non-type I. Detailed data on these objects including spatial and kinematical properties and chemical abundances are given in previous papers (Maciel and Dutra, 1992; Maciel and Köppen, 1994; Maciel and Chiappini, 1994; Maciel and Quireza, 1999; Cazetta and Maciel, 1994).

The final sample contains 167 objecs, and is shown in Tables I, II and III. We have generally adopted Zanstra He II temperatures (65% of the sample), as they are more representative of the stellar temperature. For the remaining nebulae, we have used temperatures derived from model atmospheres (19%), hydrogen Zanstra temperatures (10%), or Stoy temperatures (6%). A detailed discussion of the temperatures of the central stars has been given by Cazetta and Maciel (1994), to which the reader is referred. The references for the temperatures include Freitas Pacheco *et al.* (1986), Gleizes *et al.* (1989), Golovatyi (1988), Jacoby and Kaler (1989), Kaler (1983), Kaler and Jacoby (1989), Martin (1981), Méndez *et al.* (1992), Peña *et al.* (1992), Pottasch (1984), Preite-Martinez *et al.* (1989, 1991), Sabbadin (1986), Shaw and Kaler (1985, 1989), and Viadana and Freitas Pacheco (1985). The corrected Hβ fluxes have been taken from Cahn *et al.* (1992), Acker *et al.* (1991), Shaw and Kaler (1989) and Viadana and Freitas Pacheco (1985). Surface gravities, when available are taken from Méndez *et al.* (1992), Pottasch (1996, 1997), Zhang (1993) and Zhang and Kwok (1993).

3. Results and Discussion

The derived distances are given in Tables I, II and III. Table I includes 46 objects for which the surface gravity is independently known with a reasonable accuracy, so that individual distances are derived. For these objects, we can estimate individual error boxes in view of the assumptions of the method, which result in an average error of about 40%. Table II lists 82 nebulae for which determinations of the surface gravity are also available, but the derived distances are less accurate, and are strictly interpreted as lower/upper limits, as indicated in the table. As discussed in Paper I, depending on the position of the central star on the $\log g \times \log T_{eff}$ diagram, there is a relatively large uncertainty in the association of the surface gravity with a given track on the diagram, which may include an ambiguity in the determination of the

TABLE I
Gravity distances of PN

name	type	d (kpc)	name	type	d(kpc)
NGC 40	n-I	1.1	IC 4593	n-I	3.0
NGC 1360	n-I	2.2	IC 4637	I	2.8
NGC 1535	n-I	3.5	BD+303639	n-I	1.6
NGC 2392	n-I	2.3	Hb 4	I	5.0
NGC 2899	I	2.7	Hb 5	I	1.7
NGC 3242	n-I	1.8	He2-7	n-I	8.8
NGC 4361	n-I	2.2	He2-99	n-I	2.8
NGC 5315	I	2.8	He2-108	n-I	5.2
NGC 6153	I	5.7	He2-112	I	5.9
NGC 6210	n-I	2.2	He2-138	n-I	2.6
NGC 6369	I	1.3	He2-151	I	6.7
NGC 6445	I	3.6	He2-162	I	4.3
NGC 6563	n-I	4.8	He2-164	I	8.0
NGC 6629	n-I	1.9	He2-182	I	4.4
NGC 6751	I	6.3	H2-1	I	3.6
NGC 6803	I	7.8	M1-26	n-I	1.0
NGC 6826	n-I	1.9	M1-35	I	10.7
NGC 6891	n-I	3.0	M1-51	I	2.4
NGC 7009	n-I	1.9	M3-14	I	5.2
NGC 7293	I	0.3	M4-3	n-I	5.1
IC 418	n-I	0.8	Mz 3	I	0.9
IC 2448	n-I	4.7	PB 4	I	8.4
IC 3568	n-I	4.1	Tc 1	n-I	2.3

surface gravity. Therefore, the distances given can be affected by errors up to a factor 2, as in most statistical methods. Finally, Table III lists 39 objects for which the surface gravity is not independently known, so that only a distance range can be determined. Even in this case, however, the derived range is relatively narrow, so that in practice an average distance can always be obtained. The errors in this case are more difficult to estimate, since no calibration using the gravity was possible. However, the intrinsic uncertainty of the method is similar to the objects of Table I, namely about 40%.

An interesting example is the PN K648, located in the M15 globular cluster. Since the cluster distance $d \simeq 10\pm1$ kpc is known by independent methods (see for example Gurzadyan, 1997), this object is particularly important as a confirmation of the accuracy of the gravity distances.

TABLE II

Gravity distances of PN: estimates

name	type	d(kpc)	name	type	d(kpc)
NGC 650	I	< 3.8	IC 2165	n-I	> 3.6
NGC 2022	n-I	> 4.9	IC 2501	n-I	> 2.5
NGC 2346	I	< 0.7	IC 2621	n-I	> 3.8
NGC 2371	n-I	< 5.0	IC 4634	n-I	> 3.6
NGC 2438	n-I	< 5.6	IC 4673	I	> 9.7
NGC 2440	I	< 4.4	IC 4776	n-I	> 1.6
NGC 2792	n-I	> 3.6	IC 4846	n-I	> 5.8
NGC 2818	I	< 10.3	IC 4997	n-I	> 1.1
NGC 2867	n-I	> 2.9	IC 5117	n-I	> 2.5
NGC 3195	n-I	> 3.6	IC 5217	n-I	> 6.6
NGC 3211	n-I	> 5.4	Cn 3-1	n-I	> 3.9
NGC 3918	n-I	> 1.8	H 1-54	n-I	> 5.8
NGC 5307	n-I	> 6.2	Hb 12	n-I	> 1.3
NGC 5873	n-I	> 7.0	He2-5	n-I	> 7.9
NGC 5882	n-I	> 2.5	He2-15	I	< 2.4
NGC 5979	n-I	> 8.1	He2-86	I	> 2.7
NGC 6302	I	< 2.2	He2-115	n-I	> 2.0
NGC 6309	n-I	> 4.2	He2-117	I	$<' 1.2$
NGC 6439	n-I	> 3.1	He2-119	I	< 7.0
NGC 6565	n-I	< 4.1	He2-123	n-I	> 3.1
NGC 6567	n-I	< 2.1	He2-131	n-I	> 1.8
NGC 6572	n-I	> 1.2	He2-140	n-I	> 3.7
NGC 6578	n-I	> 2.5	Hu2-1	n-I	> 3.5
NGC 6620	I	< 8.6	J 320	n-I	> 8.0
NGC 6644	n-I	> 5.2	J 900	n-I	> 4.9
NGC 6720	n-I	< 1.7	M1-25	n-I	> 4.0
NGC 6741	I	< 3.0	M1-38	n-I	> 5.7
NGC 6778	I	> 7.8	M1-40	I	< 2.0
NGC 6790	n-I	> 2.7	M1-57	n-I	> 4.8
NGC 6818	n-I	> 2.9	M1-74	n-I	> 5.7
NGC 6853	I	< 0.9	M2-9	n-I	> 2.8
NGC 6884	n-I	> 3.6	M2-10	n-I	> 5.5
NGC 6886	n-I	> 3.8	M2-23	n-I	> 7.2
NGC 6905	n-I	> 2.0	M3-1	n-I	> 9.1
NGC 7026	n-I	> 3.4	M3-5	I	< 9.5
NGC 7354	I	> 4.9	M3-6	n-I	> 2.7
NGC 7662	n-I	> 0.7	Me2-1	n-I	> 9.6
IC 351	n-I	> 8.5	PC 14	n-I	> 8.8
IC 1747	n-I	> 5.5	SwSt 1	n-I	> 2.5
IC 2003	n-I	> 6.7	Vy 2-2	I	> 3.8
IC 2149	n-I	> 2.9	Ym 29	I	< 2.8

TABLE III
Gravity distances of PN: limits

name	type	Δd(kpc)	name	type	Δd(kpc)
NGC 246	n-I	1.5 – 4.2	Fg 1	n-I	5.4 – 7.7
NGC 1514	n-I	1.5 – 2.1	Hb 6	I	2.0 – 2.3
NGC 2610	n-I	2.8 – 11.0	He2-9	n-I	1.5 – 2.1
NGC 3132	I	3.5 – 7.8	He2-111	I	1.7 – 3.8
NGC 3587	n-I	0.9 – 3.8	He2-157	n-I	3.0 – 4.2
NGC 6537	I	0.3 – 3.1	Hu1-1	n-I	2.5 – 9.1
NGC 6543	n-I	0.9 – 1.3	K 648	n-I	10.1 – 14.0
NGC 6781	I	3.3 – 3.9	K3-67	n-I	0.7 – 1.0
NGC 6804	I	4.0 – 4.7	M1-4	n-I	2.2 – 3.1
NGC 6807	n-I	4.4 – 12.7	M1-13	I	3.9 – 8.5
NGC 6879	n-I	6.5 – 9.2	M1-50	n-I	2.3 – 6.1
NGC 6833	n-I	5.6 – 7.9	M1-54	n-I	1.6 – 5.4
NGC 6894	n-I	1.5 – 4.3	M1-78	n-I	1.6 – 2.3
NGC 7008	I	0.3 – 2.6	M2-2	n-I	1.7 – 5.4
NGC 7027	n-I	2.3 – 2.9	M2-6	n-I	7.3 – 10.4
IC 1297	n-I	1.9 – 5.4	M2-55	I	0.7 – 7.0
IC 4406	I	0.9 – 4.9	M3-29	n-I	7.5 – 10.6
IC 4732	n-I	7.2 – 10.3	Me1-1	I	4.5 – 5.3
Cn2-1	n-I	5.5 – 7.8	Vy1-2	n-I	2.8 – 13.1
DdDm 1	n-I	7.6 – 10.7			

TABLE IV
Comparison with recent individual distances

name	method	d (Pottasch 1997)	d (this work)
NGC 3242	expansion	0.5	1.8
NGC 6210	expansion	1.6	2.2
NGC 6302	expansion	1.6	<2.2
NGC 6572	expansion	1.2	>1.2
NGC 6720	parallax	0.7	<1.7
NGC 6853	parallax	0.4	<0.9
NGC 7009	expansion	0.6	1.9
NGC 7293	parallax	0.2	0.3
NGC 7662	expansion	0.8	>0.7
BD+303639	expansion	1.5	1.6

For some of the objects in our sample there are recent determinations of individual distances, basically from trigonometric parallaxes and radio expansion distances. These methods are independent of any assumptions on the nebulae and their central stars, so that these distances are in principle very reliable. A group of such objects has been recently discussed by Pottasch (1997) and is shown in Table IV, along with our results as given in Tables I and II. It can be seen that the agreement is generally good, so that individual gravity distances are comparable with those obtained by the most accurate methods available. In fact, the main differences are due to the adopted surface gravities. As discussed by Pottasch (1997), uncertainties in this quantity reflect directly on the derived distances.

A direct comparison of the gravity distances and the spectroscopic distances by Méndez *et al.* (1992) was included in Figure 3 of Paper I (Maciel and Cazetta, 1997). Figure 1a shows the gravity distances of Table I as a function of the distances by Méndez *et al.* (1992, MKH) for the objects in common. We have considered only the objects closer than 6.0 kpc, for which both distances are more accurate, so that the comparison is meaningful. We obtain a linear correlation of the form $d_g \simeq 0.99\, d_{MKH}$, with a standard deviation $\sigma \simeq 0.07$ and a correlation coefficient $r \simeq 0.96$, as shown by the broken line of Figure 1a. Another comparison is shown in Figure 1b, where we plot our distances against the calibration distances by Cahn *et al.* (1992, CKS). The result is $d_g \simeq 0.82\, d_{CKS}$ with $\sigma \simeq 0.07$ and $r \simeq 0.94$, and is also plotted in Figure 1b. The agreement is also good, which is especially interesting since the distances to these objects as given by Cahn *et al.* (1992) are considered as reliable, and have in fact been used as calibrators of their distance scale. The fact that the slopes of Figures 1a,b are close to unity shows that our distances are correct in average.

A comparison of the present results with statistical distances in the literature can also be useful, as it provides an immediate idea of the considered scale. This is particularly interesting, since most statistical distance scales are based on assumptions that are not readily understood. As an example, Figure 1c shows the gravity distances as a function of the statistical distances by Cahn *et al.* (1992, CKS). These distances have been obtained using the Shklovsky method according to the scheme used by Daub (1982). It can be seen that the scattering is much larger compared with Figures 1a and 1b, as is usual regarding statistical distances. On the other hand, an average slope of 1.22 ($\sigma \simeq 0.10$, $r \simeq 0.90$) can be derived, as shown by the broken line. Although the absolute value of the slope gives only a crude information on the relation between the distance scales, it is interesting that it is higher than unity, that is, our scale is longer than that of Cahn *et al.* (1992). In fact, similar results can be derived using other distance scales, such as those developed by Zhang (1993, 1995). The distances by Zhang (1993) [slope $\simeq$ 1.21] are based on the stellar mass and surface gravity (method A). In this case, the distances are given as a function of the core mass, the monochromatic emergent flux at λ5480 A, the surface gravity and the reddening-free visual magnitude, as in Méndez *et al.* (1988). The statistical distances by Zhang (1995) [slope $\simeq$ 1.15] are based both

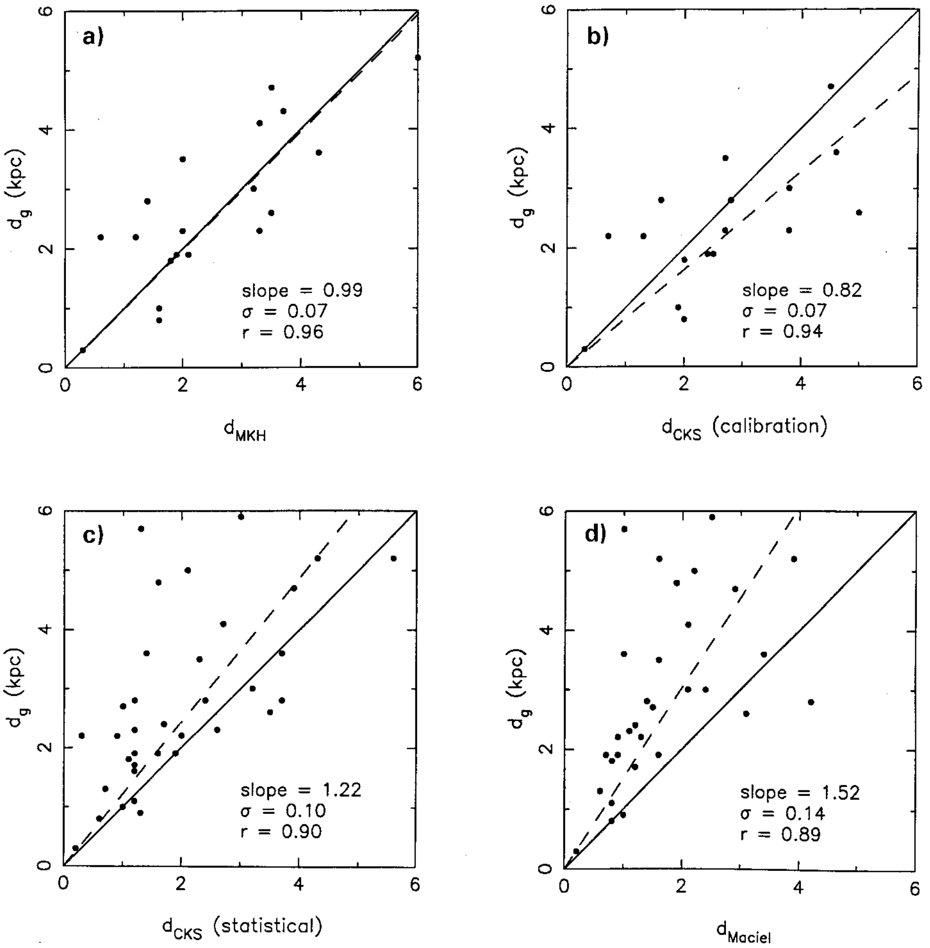

Figure 1. Comparison of gravity distances with (a) individual distances by Méndez *et al.* (1992), (b) calibration distances by Cahn *et al.* (1992), (c) statistical distances by Cahn *et al.* (1992), and (d) statistical distances by Maciel (1984).

on a correlation between the ionized mass and radius and a correlation between the radio continuum surface brightness temperature and the nebular radius. Since these distances agree very well with the scale developed by van de Steene and Zijlstra (1994), the same slope can be expected from a comparison of the latter with the distances given in this paper. Comparison with the longer scale by Kingsburgh and Barlow (1992) and Kingsburgh and English (1992) gives a smaller average slope of 0.87. These distances have been derived for a sample of galactic nebulae from electron densities using Magellanic Cloud PN as calibrators, and are generally longer than the others, although not as complete.

Another comparison with the distances by Maciel (1984), which are based on a mass-radius relationship (see also Maciel and Pottasch, 1980), is shown in Figure

1d. It produces a slope of 1.52 ($\sigma \simeq 0.14$, $r \simeq 0.89$), so that our distances are roughly about 50% as large as those by Maciel (1984). As a conclusion, the present scale ranks among the so-called "long distance scales", and is comparable with other scales in the literature such as those by Cudworth (1974), Mallik and Peimbert (1988) and the distances derived from spectroscopic analyses of PN central stars (Méndez *et al.* 1992). As discussed by Peimbert (1990a, b), such long distance scales are favoured on the basis of an analysis of the PN and white dwarf birth rates in the Galaxy.

Finally, it is worth mentioning that the problem of finding accurate distances of galactic PN remains largely unsolved, although some advances have been made as our previous comparisons have shown. New distances for 167 objects have been obtained with our method, which is certainly not a negligible sample. Unfortunately, only a relatively small number of nebulae have accurate individual distances to compare with, as shown in Table IV. On the other hand, the adopted classification system was initially defined basically in terms of relative abundances (cf. Peimbert, 1978), so that the attribution of progenitor masses to a given type is still subject to uncertainties. However, recent work on (i) the location of the PN central stars on the HR diagram (Cazetta and Maciel, 1994), (ii) morphological correlations (Stanghellini, 1999) and (iii) theoretical models of AGB stars (Marigo, 1998 and private communication) are beginning to shed some light on the nature of these objects, so that we can expect a better understanding of the relation between the stellar mass and the observed nebular properties in the near future.

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