# GRAVITY DISTANCES OF PLANETARY NEBULAE

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(Received 23 December, 1996; accepted 3 June, 1997)

**Abstract.** Recent work on the PN classification scheme initially proposed by Peimbert has shown that "type I" and "non-type I" objects have markedly different properties. Type I PN have He and N enrichments, lower heights relative to the galactic plane, and lower peculiar velocities, while non-type I nebulae have normal abundances and increasing heights and peculiar velocities. This implies some mass and age differences of the different types, which can be used in order to determine distances to disk PN. In this work, the behaviour of PN of different types on the $\log g \times \log T_{eff}$ plane is explored, in view of the fact that central stars of different masses have different paths on this diagram. As a result, distances can be derived for some galactic PN, which can be compared with previous determinations. The possibility is discussed of establishing a statistical distance scale based on the population segregation of PN of different Peimbert types.

## 1. Introduction

The determination of distances to galactic planetary nebulae (PN) remains a difficult problem, despite some recent attempts in the literature both regarding individual (Hajian *et al.*, 1993; Maciel, 1995) or statistical distances (Cahn *et al.*, 1992; Zhang, 1995). It is well known that the uncertainties of most distances are very large (cf. Kwok, 1994; Terzian, 1993; Pottasch, 1992; Peimbert, 1990), so that new determinations are welcome, especially concerning individual distances.

Recent work has shown that PN of different Peimbert types have in general different properties, especially for "type I" and "non-type I" objects (Maciel, 1997; Cazetta and Maciel, 1994; Maciel and Köppen, 1994; Maciel and Dutra, 1992). These differences can be summarized as follows: Type I PN have generally higher abundances of He and N, are closer to the galactic plane, and show smaller peculiar velocities relative to the galactic rotation curve; they are considered as younger objects, with relatively massive progenitors. On the other hand, disk PN of types II and III, which in this paper are taken as "non-type I" PN, have no He and N excesses, show increasing heights and peculiar velocities, are relatively older and associated with less massive progenitor stars. These differences can be used in order to determine distances of disk PN.

Owing to the population segregation implied by the Peimbert types, an approximate range of progenitor masses can be attributed to PN of a given type. Theoretical models provide initial mass-final mass relationships, so that the central star mass can be estimated. On the other hand, relations involving the surface gravity as a function of central star temperatures can be derived, which can be used together

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*Astrophysics and Space Science* **249:** 341–352, 1997.

with the initial mass-final mass relation in order to determine the luminosities of the central stars. The distances can then be derived, for instance on the basis of the observed H$\beta$ flux and an independent scaling of the H$\beta$ luminosity, or using observed central star magnitudes.

In this work, the behaviour of PN of different types on the $\log g \times \log T_{eff}$ plane is explored, in view of the fact that central stars of different masses have different paths on this diagram (cf. Méndez *et al.*, 1988, Napiwotzki *et al.*, 1994; Rauch *et al.*, 1994). As a result, average individual distances can be derived for some galactic PN, which can be compared with previous determinations. We will apply this method (i) to the objects for which Lyman-$\alpha$ kinematic distances are known (Maciel 1995, 1997), and (ii) to the sample of 23 objects studied by Méndez *et al.* (1992), for which detailed information is available on the central stars from high resolution spectroscopy and the application of NLTE model atmospheres. The possibility is discussed of establishing a statistical distance scale based on the population segregation of PN of the different Peimbert types.

## 2. Masses of PN Central Stars

Recent work on the galactic population of PN clearly shows that the progenitor masses at the main sequence decrease as one moves along Peimbert types I, II, III and IV. However, the mass segregation of the different types is not clearcut, as shown for example by attempts to place these objects on the HR diagram (Cazetta and Maciel, 1994), or to establish a definite abundance-mass relation based on N/O abundances (Stasińska and Tylenda, 1990; Gorny *et al.*, 1996; Cazetta and Maciel, 1997). Also, observational evidences exist of an overlapping of star masses for PN of different types, especially for non-type I PN, as shown by the masses derived by Méndez *et al.* (1992). Therefore, as a first step, we decided to adopt for the different PN types the initial mass ranges shown in Table I (cf. Peimbert, 1978; Peimbert and Torres-Peimbert, 1983; Faúndez-Abans and Maciel, 1986; 1987; 1988; Maciel and Köppen, 1994; Maciel, 1989; 1992; Ortiz and Maciel, 1994; 1996).

Table I
Initial masses of central stars

| Mass ($M_\odot$) | Type I | non-Type I |
|---|---|---|
| Minimum | 2.4 | 1.0 |
| Average | 3.0 | 1.7 |
| Maximum | 6.0 | 2.4 |

Figure 1 shows some recently derived initial mass-final mass relationships, as applied to intermediate mass stars with masses $M < 8\ M_\odot$ on the main sequence. The curves are from Schönberner (1983) and Blöcker and Schönberner (1990) (curve 1); Groenewegen and de Jong (1993, curve 2); Weidemann and Koester

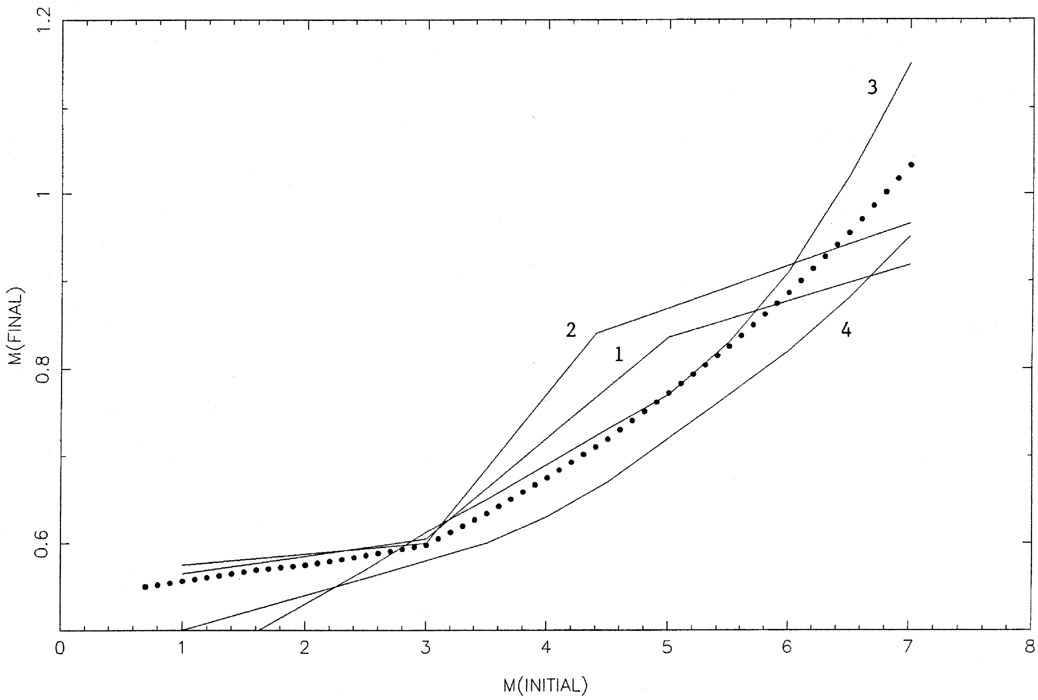


*Figure 1.* Initial mass-final mass relationships. Curve 1: Schönberner (1983) and Blöcker and Schönberner (1990); curve 2: Groenewegen and de Jong (1993); curves 3 and 4: Weidemann and Koester (1983). Dotted line: adopted relationship.

(1983, curves 3 and 4). On the basis of these curves, we have adopted an average initial mass-final mass relation (dotted line), which was approximated by a fourth order polynomial of the form

$$M_f = a_0 + a_1 M_i + a_2 M_i^2 + a_3 M_i^3 + a_4 M_i^4 \tag{1}$$

where the masses are in solar masses, and the coefficients are:

$a_0 = 5.426 \times 10^{-1}$
$a_1 = 2.093 \times 10^{-2}$
$a_2 = -1.122 \times 10^{-2}$
$a_3 = 4.470 \times 10^{-3}$
$a_4 = -3.119 \times 10^{-4}$.

From Figure 1 and Table I it can be seen that type I PN have final star masses $M \geq 0.6 M_\odot$, while non-type I have final star masses $M \leq 0.6 M_\odot$.

### 3. The Gravity-Temperature Relation

Evolutionary trajectories on the HR diagram are known with a reasonable accuracy for intermediate mass stars (cf. Wood and Faulkner, 1986; Schönberner, 1983;

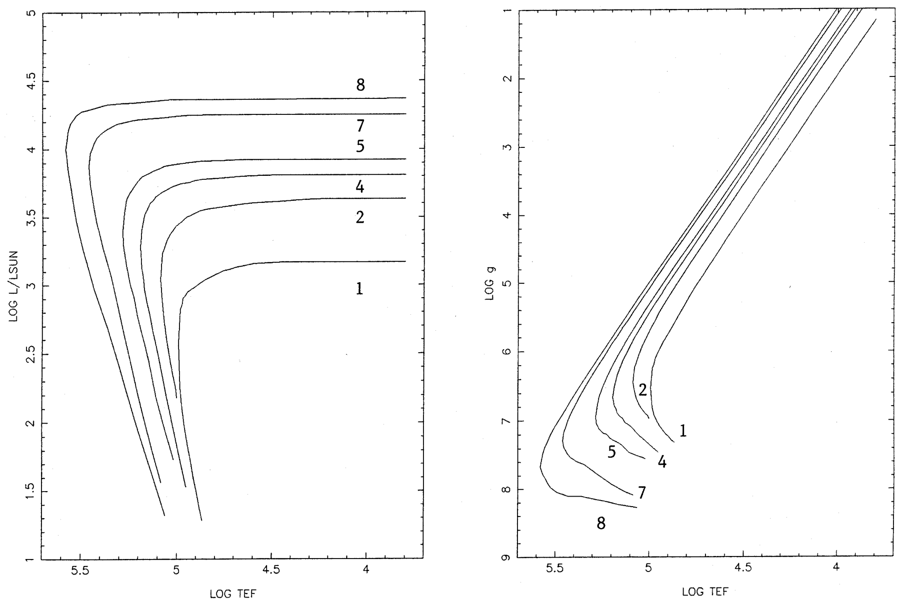


*Figure 2.* Evolutionary tracks (a): HR diagram; (b): gravity. Curves 1,2: Schönberner (1983); curves 4,7: Blöcker and Schönberner (1990); curve 5: Schönberner (1989); curve 8: Wood and Faulkner (1986).

1989; Blöcker and Schönberner, 1990). Some derived curves are listed in Table II, where we give the central star masses and original references. These curves are shown on the plane $\log L/L_\odot \times \log T_{eff}$ (Figure 2a), where we have selected curves 1, 2, 4, 5, 7, and 8, as representative of the final mass range of planetary nebula central stars.

Table II
Evolutionary tracks of central stars

| curve | mass ($M_\odot$) | reference |
|---|---|---|
| 1 | 0.546 | Schönberner (1983) |
| 2 | 0.565 | Schönberner (1983) |
| 3 | 0.598 | Schönberner (1989) |
| 4 | 0.605 | Blöcker and Schönberner (1990) |
| 5 | 0.644 | Schönberner (1989) |
| 6 | 0.760 | Wood and Faulkner (1986) |
| 7 | 0.836 | Blöcker and Schönberner (1990) |
| 8 | 0.890 | Wood and Faulkner (1986) |

From the curves given in Figure 2a, the surface gravity can be determined, and the resulting curves compared with recent determinations of the surface gravities of PN central stars (cf. Méndez *et al.*, 1992; Napiwotzki *et al.*, 1994). It can be concluded that the curves involving the surface gravities are relatively better determined, even though some uncertainties are associated with the luminosity-temperature relations. The results are presented as $\log g \times \log T_{eff}$ in Figure 2b, and show that the surface gravity-temperature relation is not very strongly dependent on the central star masses, for masses in the range $0.6 \leq M_f/M_\odot \leq 0.9$, especially for central star temperatures $\log T_{eff} \leq 5$, for which most objects fall on the linear part of the $\log g \times \log T_{eff}$ curve.

## 4. Determination of Gravity Distances of PN

In order to derive our *gravity* distances to a given PN, it must initially be classified according to the Peimbert types. This can be done as accurately as possible if a complete set of abundances is available. Other properties that may have an influence on the classification are the radial velocities, from which peculiar velocities can be derived, and morphological aspects, following the association of some of the PN types with morphological classification schemes (cf. Stanghellini *et al.*, 1993).

Once the PN type is known, an initial mass range can be obtained, according to Table I. In the present work, only type I and non-type I objects are considered, so that approximate results are to be expected. From equation (1), the final mass range is derived, which can be used with the appropriate curves of Figure 2b to determine the surface gravity. The luminosity follows from the effective temperature and surface gravity by

$$L = 4\pi\sigma G \, \frac{M_f T_{eff}^4}{g}. \tag{2}$$

In this paper, we associate the gravity-temperature diagram of fig. 2 with the $H\beta$ luminosities in order to determine gravity distances to some galactic planetary nebulae. Other possibilities include the determination of the stellar radius or a calibration based on observed central star magnitudes.

In a recent paper, Maciel and Cazetta (1994) derived an approximate relation between the H$\beta$ flux and the total luminosity of PN central stars given by

$$L = 4\pi d^2 \, K(H\beta) \, F(H\beta) \tag{3}$$

where $d$ is the distance, $F(H\beta)$ is the $H\beta$ flux corrected for interstellar extinction, and $K(H\beta)$ is a scaling, or conversion factor, which is essentially the ratio of the total luminosity to the $H\beta$ luminosity. This factor has been determined by Maciel and Cazetta (1994) as a function of the central star temperature as

$$\log K(H\beta) = 10.29 + 4.72 \times 10^{-6} T_{eff} - 1.70 \log T_{eff}. \tag{4}$$

As discussed by Maciel and Cazetta (1994), Eq. (4) can be applied to central stars for which both Zanstra HI and HeII temperatures are known, and have further

$T_z(\text{HeII}) - T_z(\text{HI}) \leq 21000$ K. That includes most central stars cooler than about $\log T_{eff} \simeq 5.0$ which are optically thick in the Lyman continuum. However, as will be seen in Section 5.2, our method can also be expected to give reasonable results even for optically thin objects, in view of the dependence of $K(H\beta)$ on the stellar temperature, as discussed by Maciel and Cazetta (1994).

From Eqs. (2)–(4) the distance can be determined if the $H\beta$ flux and extinction are known. In this way, average individual distances (or a distance range) can be determined on the basis of generally known parameters, namely the effective temperature, the $H\beta$ flux, and the extinction, apart from some previous classification according to the Peimbert types. Such a relatively small number of parameters makes the method useful to obtain distances to objects without individual distance determinations.

The present method can be used in two different ways: (i) to estimate approximate distances, or a distance range, of nebulae for which no detailed data are available, apart from the $H\beta$ flux, an estimate of the central star temperature and a preliminary classification. In this case, it is a *statistical* method, and its accuracy is similar to most statistical methods available in the literature (cf. Daub, 1982; Maciel, 1984; Cahn *et al.*, 1992); (ii) to determine better distances of nebulae for which detailed data on the abundances, kinematical properties and especially a determination of the surface gravity is available. In this case, the method can be considered as an *individual* method, and its accuracy is accordingly higher.

It is impossible to obtain a general determination of the formal uncertainty of the method in both cases, as it will depend on the quality of the available data for any particular nebula, such as number of elements with known abundances, agreement of different estimates of the stellar temperature, radial velocities etc. However, from Figure 1 one can predict that the first steps leading to the determination of the final mass introduce a modest uncertainty, averaging about 50% for most PN. The main source of error lies in the determination of the luminosity, as it involves both the stellar temperature and gravity, apart from the final mass. Therefore, detailed knowledge of $T_{eff}$ and especially of the gravity $g$ will have a decisive influence on the final uncertainty. If the latter is known, e.g. from detailed model atmospheres, the previous estimate of the uncertainty will not be essentially changed, and the final uncertainty will be kept within about 50%, corresponding to our case (ii) above. On the other hand, if such detailed knowledge is lacking, an average distance within a factor of 2 or some limits for the distance can be expected, as in most statistical methods.

## 5. Results and Discussion

### 5.1. Objects with kinematic distances

Recently, individual kinematic distances of some PN have been derived from the association of the equivalent widths of interstellar Lyman-$\alpha$ lines in the direction of the nebulae with 21 cm column densities derived in the same directions (Maciel 1995, 1997). As a result, distances to NGC 7009 and BD+30°3639 were derived (cf. Maciel, 1995), followed by new determinations for NGC 2371 and NGC 2392 (Maciel 1997), as shown in Table III, along with other determinations from the literature.

The four planetary nebulae are of type II, and according to our adopted initial mass-final mass relation, their progenitor masses are expected to be around $M_i \simeq 1.7 M_\odot$. Adopting recent He II Zanstra temperatures, $H\beta$ fluxes and extinctions for NGC 7009, BD+30 3639, NGC 2371, and NGC 2392 from Méndez *et al.* (1992), Cahn *et al.* (1992) and Kaler (1983), we can determine average gravities, luminosities and distances for the PN central stars according to the procedure just described. The results given in Table III show that the present method gives reasonable distances, with average uncertainties similar to the kinematic distances. For NGC 2371, the position on the $\log g \times \log T_{eff}$ plane shows some ambiguity, which can probably be solved if a reliable estimate of the surface gravity can be made independently. A more detailed study needs to be done, especially in order to improve the determination of the progenitor masses, which play an important role in the determination of the stellar luminosity, and therefore on the distances.

### 5.2. Objects studied by Méndez *et al.* (1992)

Another test to the present method involves a direct comparison of the gravity distances with the distances of 23 planetary nebulae derived by Méndez *et al.* (1992) on the basis of detailed observations of their central stars, and the application of NLTE model atmospheres. We have used spectroscopic effective temperatures of the central stars, $H\beta$ fluxes and extinctions from Méndez *et al.* (1992) and Cahn *et al.* (1992). For these nebulae, independent surface gravities have been determined by Méndez *et al.* (1992), so that relatively accurate individual distances can be obtained. The application of the gravity distance method produces the results shown in Table IV, which can be directly compared with the distances by Méndez *et al.* (1992), as shown in Figure 3.

The adopted Peimbert types are given in column 2 of Table IV (cf. Maciel and Köppen, 1994), and the question marks indicate that a complete set of abundances is not available, so that for these objects the Peimbert types cannot be established with certainty. We will comment on these PN later on this section. The effective temperatures, observed $H\beta$ fluxes and extinctions are given in columns 3, 4, and 5, respectively. The last two columns give the model atmosphere distances by Méndez *et al.* (1992) and the gravity distances, respectively. It can be seen from Table IV and Figure 3 that the agreement of the gravity distances with the model atmosphere results is quite reasonable, considering that we have used average masses, according to the discussion in Section 2. These results can be considered as very encouraging, especially in view of the fact that most objects in the sample of Méndez *et al.* (1992) are considered as optically thin for radiation in the H Lyman

Table III
Distances of some galactic PN (kpc)

| Reference | Method | NGC 7009 | BD +30°3639 | NGC 2371 | NGC 2392 |
|---|---|---|---|---|---|
| Cahn & Kaler (1971) | Shklovsky-H$\beta$ | 1.3 | 2.7 | 1.5 | 1.1 |
| Cahn & Kaler (1971) | Shklovsky-red | 1.6 | 2.0 | 1.7 | |
| Cudworth (1974) | proper motion | 1.9 | 1.1 | 2.5 | 2.0 |
| Milne & Aller (1975) | Shklovsky-radio | 1.3 | | | 1.2 |
| Acker (1978) | synthetic | 0.9 | 0.7 | 1.2 | 0.9 |
| Pottasch (1980) | expansion/extinction | 0.6 | 0.8 | 0.5 | 0.7 |
| Daub (1982) | radio flux | 0.8 | 0.7 | 1.4 | 1.2 |
| Amnuel *et al.* (1984) | radio flux-diameter | 0.6 | 0.7 | 1.3 | 0.9 |
| Maciel (1984) | mass-radius relation | 0.9 | $> 0.6$ | 1.5 | 1.1 |
| Kaler *et al.* (1985) | wind | 0.8 | 0.2 | 1.6 | |
| Barlow (1987) | H$\beta$ flux | 2.3 | | | |
| Gathier (1987) | expansion | 0.6 | | | |
| Weidemann (1989) | central star mass | $> 1.6$ | | | |
| Méndez *et al.* (1992) | model atmosphere | 2.1 | | | 2.0 |
| Cahn *et al.* (1992) | modified Shklovsky | 1.2 | 1.2 | 1.5 | 1.2 |
| Kingsburgh & Barlow (1992) | electron density | 2.3 | | | 2.0 |
| Zhang (1993) | mass-gravity | 1.0 | 2.6 | 3.5 | 0.5 |
| Hajian *et al.* (1993) | expansion | | 2.7 | | |
| Zhang (1995) | mass-radius relation | 1.1 | 1.9 | 2.1 | 1.4 |
| Maciel (1995,1997) | UV-radio kinematic | 1.6 | 0.8 | 1.4 | 1.9 |
| This work | gravity | 1.9 | 1.6 | $<$5.0 | 2.3 |

continuum. In fact, several of these objects present a large Zanstra discrepancy, as shown by Figure 1 of Méndez *et al.* (1992). Since we have used spectroscopic effective temperatures, this effect was partly corrected for. However, our equation (4) is expected to produce better results for optically thick nebulae, which places some limits to the expected agreement of the gravity distances and the distances by Méndez *et al.* (1992). This is confirmed by Figure 4, where we plot the luminosities relative to the sun from Méndez *et al.* (1992) as a function of the the luminosities given by equation (3), using our adopted distances. The abscissa is equivalent to the quantity '$\log(161 L_\beta)$' used as the abscissa of Figure 6 of Méndez *et al.* (1992), except that we have replaced the constant scaling factor $c \sim 161$ from Gathier and Pottasch (1989) by our parameter $K(H\beta)$, which is a function of the effective temperature. The agreement shown in fig. 4 is then much better than in Figure 6 of Méndez *et al.* (1992), showing that our expression is very good for optically thick objects, and reasonably good even for optically thin nebulae, at least for those objects that have independently derived gravities, as in case (ii) above.

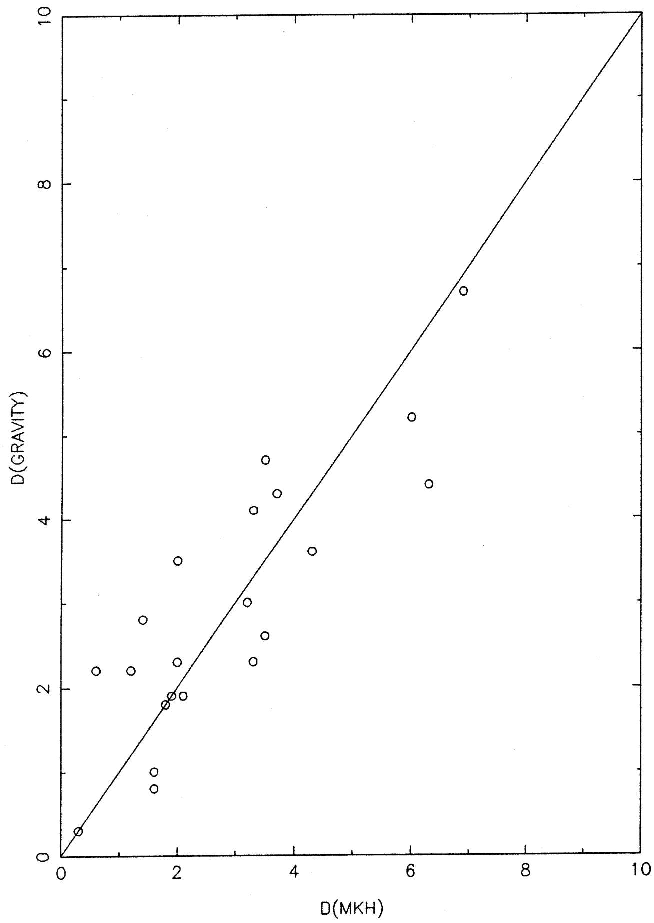


*Figure 3.* Comparison of gravity distances with distances by Méndez *et al.* (1992)

The objects with a question mark in Table IV happen to be all of type I, according to our preliminary classification. The number of such objects and the increased distance uncertainties are not large, so that they do not affect the main conclusions of this paper. However, it is interesting that they correspond to the larger mass progenitor stars, and two explanations could be found for this fact. First, the nebulae could actually be of type I, which corresponds to almost half of the analysed objects. Second, they could mean that our adopted initial mass-final mass relation needs some revision, in the sense that the implied masses are too small, so that we are artificially placing these objects in the large mass class. Much work needs to be done on these aspects, both for these objects and the remaining sample of PN with detailed observations of their central stars.

Table IV
Gravity distances to selected PN (kpc)

| name | type | $T_{eff}$ | log $F_{\rm o}(H\beta)$ | $c_{ext}$ | $d$(MKH) | $d$(grav) |
|---|---|---|---|---|---|---|
| He2-151 | I? | 25000 | −11.97 | 0.70 | 6.9 | 6.7 |
| He2-162 | I? | 27000 | −12.04 | 1.20 | 3.7 | 4.3 |
| He2-138 | IIa | 27000 | −10.68 | 0.15 | 3.5 | 2.6 |
| H2-1 | I? | 33000 | −11.46 | 0.90 | 4.3 | 3.6 |
| M1-26 | III | 33000 | −11.16 | 1.60 | 1.6 | 1.0 |
| Tc 1 | III | 33000 | −10.66 | 0.36 | 3.3 | 2.3 |
| He2-108 | III | 33000 | −11.41 | 0.40 | 6.0 | 5.2 |
| He2-182 | I? | 36000 | −10.95 | 0.26 | 6.3 | 4.4 |
| IC 418 | IIb | 36000 | −9.62 | 0.32 | 1.6 | 0.8 |
| IC 4593 | III | 40000 | −10.55 | 0.12 | 3.2 | 3.0 |
| NGC 6629 | IIb | 47000 | −10.97 | 1.00 | 2.1 | 1.9 |
| NGC 2392 | IIa | 47000 | −10.29 | 0.16 | 2.0 | 2.3 |
| IC 3568 | IIb | 50000 | −10.77 | 0.18 | 3.3 | 4.1 |
| IC 4637 | I? | 50000 | −11.24 | 1.10 | 1.4 | 2.8 |
| NGC 6826 | IIb | 50000 | −9.97 | 0.04 | 1.9 | 1.9 |
| NGC 6891 | IIb | 50000 | −10.62 | 0.30 | 3.2 | 3.0 |
| IC 2448 | IIa | 65000 | −10.85 | 0.15 | 3.5 | 4.7 |
| NGC 1535 | IIb | 70000 | −10.44 | 0.13 | 2.0 | 3.5 |
| NGC 3242 | IIb | 75000 | −9.80 | 0.09 | 1.8 | 1.8 |
| NGC 1360 | III | 80000 | −10.20 | 0.00 | 0.6 | 2.2 |
| NGC 4361 | III | 82000 | −10.53 | 0.10 | 1.2 | 2.2 |
| NGC 7009 | IIa | 82000 | −9.80 | 0.09 | 2.1 | 1.9 |
| NGC 7293 | I | 90000 | −9.37 | 0.04 | 0.3 | 0.3 |

In view of the results shown in Tables III and IV, it can be concluded that gravity distances constitute a valid alternative to the determination of individual distances of galactic planetary nebulae. The method is relatively straightforward, and can be easily updated, for example by the use of improved $\log g \times \log T_{eff}$ relationships, or a different initial mass-final mass relationship. Its simplicity makes it suitable for the determination of distances to large numbers of objects for which no detailed analyses of the central stars have been made, even though its accuracy is then comparatively lower. In this case, some kind of approximation could be made regarding the final mass range, as suggested in Section 2, so that a consistent statistical distance scale could be derived.

## Acknowledgements

We thank an anonymous referee for some comments on an earlier version of this paper. This work was partially supported by FAPESP and CNPq.

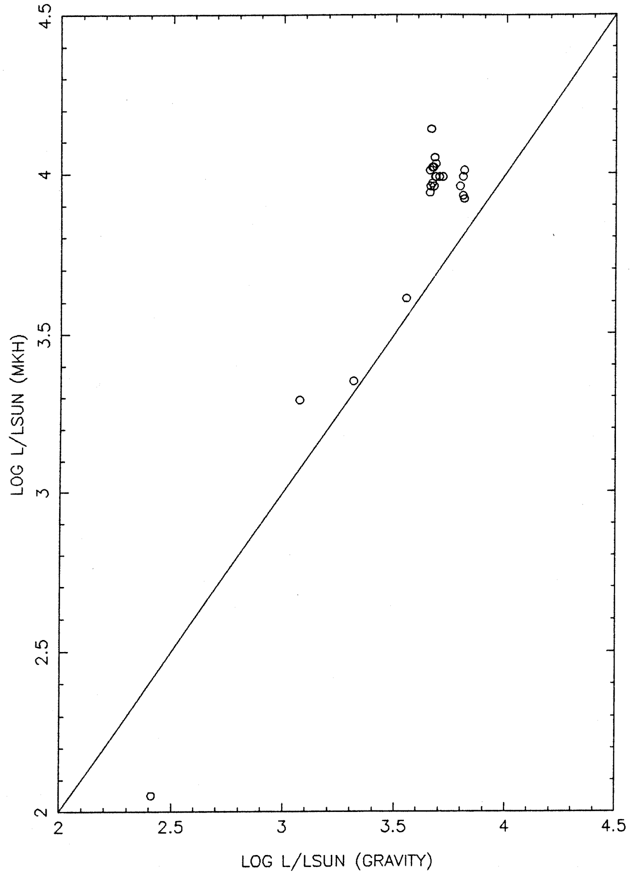


*Figure 4.* Luminosities from Eq. (3) compared with results by Méndez *et al.* (1992)

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