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A NEW DETERMINATION OF THE ROTATION CURVE FROM GALACTIC DISK PLANETARY NEBULAE

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RESUMEN

La curva galáctica de rotación se determina en base a una gran muestra de nebulosas planetarias con velocidades radiales conocidas. Se adoptan cuatro escalas de distancia y se establece la curva para distancias galactocéntricas entre 4 a 14 kpc, aproximadamente, adoptando $R_0 = 8.5$ kpc para la distancia galactocéntrica de SLR. Las conclusiones principales son: (i) no existe indicación de que haya una disminución de la curva de rotación medida más allá del círculo solar; (ii) no hay diferencias importantes entre las escalas estadísticas de distancia consideradas, ya sean "cortas" o "largas", si bien las nebulosas individuales pueden tener muy diferentes distancias de acuerdo a las diferentes escalas, y (iii) las curvas derivadas son similares a la curva de rotación obtenida de las regiones H II, tomando en cuenta el hecho que las nebulosas planetarias son generalmente objetos más viejos y tienen componentes de velocidad perpendiculares al plano galáctico mayores.

ABSTRACT

The galactic rotation curve is determined on the basis of a large sample of planetary nebulae with known radial velocities. Four distance scales are adopted and the curve is established for galactocentric distances of 4 to 14 kpc, approximately, adopting $R_0 = 8.5$ kpc for the galactocentric distance of the LSR. The main conclusions are: (i) there is no indication of a measurable decrease of the rotation curve beyond the solar circle; (ii) there are no important differences among the statistical distance scales considered, irrespective of the "short" or "long" nature of the scale, even though individual nebulae can have very different distances according to the different scales, and (iii) the derived curves are similar to the rotation curve derived from H II regions, taking into account the fact that PN are generally older objects and have larger velocity components perpendicular to the galactic plane.

Key Words: **GALAXY: KINEMATICS AND DYNAMICS — PLANETARY NEBULAE**

1. INTRODUCTION

The galactic system of planetary nebulae (PN) includes objects with considerably different properties, such as ages, space distribution and kinematics. Therefore, these objects can be associated with different stellar populations, ranging from relatively young Population I nebulae in the galactic disk to the older population II objects in the halo and bulge. An example of such a variety of population types can be observed on the basis of the PN types originally proposed by Peimbert (1978), according to which Type I objects are the youngest PN, having the most massive progenitors, Type II are disk nebulae, Type III are PN showing strong metal underabundances and associated with the galactic thick disk, and type IV are halo objects. We could add Type V PN, which are bulge nebulae, frequently showing a wide range of chemical composition and central star masses (Maciel 1989; Cuisinier et al. 2000; Escudero, Costa, & Maciel 2004).

An analysis of the space and kinematical behaviour of planetary nebulae has been made by Maciel & Dutra (1992), leading to a determination of the galactic rotation curve in the galactocentric range of 6 to 12 kpc and of Oort's constants. According to these results, some flattening has been observed near the solar circle, as well as a moderate increase for larger galactocentric distances. This analysis was based on a sample of galactic nebulae studied by the IAG/USP group (see for example Faúndez-Abans & Maciel 1986; Maciel 1984), for which radial velocities were available in the catalogue of Schneider et al. (1983). Similar results have been obtained by Amaral et al. (1996) using planetary nebulae, oxygen-rich and carbon-rich AGB stars as kinematic tracers.

More recently, a new catalogue of radial velocities has become available (Durand, Acker, & Zijlstra 1998), in which a compilation of previous data and new measurements add to a total of 867 nebulae, 90% of which have uncertainties smaller than 20 km s^{-1}. As a comparison, the earlier catalogue of Schneider et al. (1983) included 524 nebulae, half of which have uncertainties smaller than 10 km s^{-1}. On the other hand, several new distance scales for galactic planetary nebulae have been published, thus contributing to solve one of the most difficult problems in the study of these objects. Some of these scales are in the "short" distance scale class, while others belong to the "long" scale class (see for example Peimbert 1990; Phillips 2001), so that they may have an effect on the space distribution and kinematic properties of the planetary nebulae in the galactic disk. Many of the nebulae are located in the galactocentric range of 4 to 14 kpc or even farther away, so that a more extended rotation curve could in principle be derived. Therefore, it is interesting to perform a reanalysis of the work by Maciel & Dutra (1992), including the new radial velocities and distance scales. In this paper, we make an attempt in this direction, by taking into account the published distance scales of Maciel (1984), Cahn, Kaler, & Stanghellini (1992), van de Steene & Zijlstra (1994), and Zhang (1995).

The importance of such an analysis is twofold. First, it sheds light on the kinematics and space distribution of planetary nebulae, as offsprings of progenitor stars in a relatively wide range of masses on the main sequence, namely 0.8 to 8 $M_\odot$. Second, it may contribute to the establishment of the behaviour of the rotation curve beyond the solar circle, where a relatively small number of H II regions are observed. Therefore, the possibility of a flat or even rising rotation curve can be investigated, which bears a clear connection with the existence of dark matter in the Milky Way.

2. THE DATA

Our initial sample consists of the 867 nebulae in the catalogue of heliocentric radial velocities by Durand et al. (1998). About 90% of these objects have uncertainties smaller than 20 km s^{-1}, and those showing the largest errors are located near the direction of the galactic bulge, which will not be considered in the present work. We have adopted distances from four different statistical scales, namely: (i) the scale by Maciel (1984), which is based on a relationship between the ionized mass and radius of the nebula (Maciel & Pottasch 1980). This catalogue is still one of the largest published, and has the advantage that the adopted mass-radius relationship is totally consistent with the accepted mechanism of PN formation by the two-wind interaction theory (Kwok, Purton, & FitzGerald 1978). This scale includes a total of 663 objects, for which average distances can be attributed to 468 nebulae, and limits to the remaining 195 objects; (ii) the distances to 778 galactic PN by Cahn et al. (1992, CKS), which were determined by a modified Shklovsky method following the scheme proposed by Daub (1982); (iii) the distances by van de Steene & Zijlstra (1994, vdSZ), who have devised a method to determine statistical distances based on a correlation between the radio continuum surface brightness temperature and the nebular radius (see also van de Steene & Zijlstra 1995), and (iv) the scale developed by Zhang (1995), which averages distances to 647 nebulae obtained by a method also based on a mass-radius correlation and by another correlation between the radio continuum surface brightness temperature and the radius of the nebula. The first two scales belong to the so-called "short" distance scales, while the last two are in the category of the "long" distance scales (see for example Peimbert 1990; Phillips 2001). Therefore, these scales are adequate in order to investigate any systematic effects on the rotation curve by the adoption of scales of a different nature. In practice, the final samples are smaller, as many of the nebulae in the radial velocity catalogue do not have distances determined by these statistical methods.

In order to define a meaningful rotation curve, we have adopted some selection criteria which were applied to the four distances scales. (i) We have included only galactic disk planetary nebulae, so that halo (type IV) and bulge (type V) nebulae have been excluded. (ii) PN having extremely large peculiar radial velocities have not been considered, as these objects have a weak correlation with the galactic disk rotation curve, as can be seen for example by the work of Maciel & Dutra (1992). These objects are basically Peimbert type III nebulae, so that most of the objects in our sample could be classified as type I or II, and our curves can be directly compared with the corresponding results by Maciel & Dutra (1992). Also, (iii) objects near the direction of the galactic center have been excluded, since the expected radial velocities of these objects may show a very large variation, so that the possible errors are increased. Therefore, our sample does not include objects having galactic longitudes within 20 degrees of the galactic center. Finally, (iv) in order to make a homogeneous comparison of the four distance scales, we have considered objects in the galactocentric range of approximately 4 to 14 kpc.

Applying these selection criteria, our final samples include 259 objects for the distance scale by Maciel (1984), 240 objects with distances by Cahn et al. (1992), 164 nebulae from van de Steene and Zijlstra (1994) and 224 objects from the distance scale by Zhang (1995). The new samples are considerably larger than those considered in the earlier work of Maciel & Dutra (1992), in which only 113 nebulae of types I and II have been taken into account.

3. THE MODEL

The kinematic model adopted here assumes circular rotation and is essentially the same as in Maciel & Dutra (1992), to which the reader is referred for details. For a given nebula, let d be the heliocentric distance and l, b the galactic coordinates. The height z from the galactic plane can then be written as

$$z = d \sin b, \tag{1}$$

and the relation between the heliocentric distance of the nebulae d and the galactocentric distance R is simply

$$R^2 = R_0^2 + (d \cos b)^2 - 2R_0\, d \cos b \cos l, \tag{2}$$

where $R_0 = 8.5$ kpc, the IAU adopted galactocentric distance of the LSR. Assuming circular orbits, the rotation velocity $\theta(R)$ at the galactocentric distance R is given by

$$\theta(R) = \frac{R}{R_0}\left[\frac{V_r}{\sin l \cos b} + \theta_0\right], \tag{3}$$

where V_r is the radial velocity relative to the LSR and $\theta_0 = 220$ km s^{-1} is the adopted velocity at the LSR. Somewhat lower values of R_0 and θ_0 have been proposed in the recent literature. However, the main results of this paper are not affected by these differences, and our adopted values provide an easier comparison with earlier work on planetary nebulae (Maciel & Dutra 1992) and younger objects (see for example Clemens 1985).

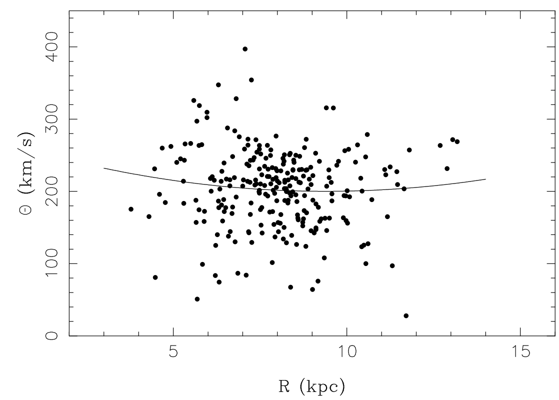

Fig. 1. Rotation curve from PN, distances by Maciel (1984).

For a given distance scale, the individual heights from the galactic plane are given by Eq. (1), and the galactocentric distances are determined from Eq. (2). The radial velocity relative to the LSR can be computed from the heliocentric velocities given in the catalogue of Durand et al. (1998) using the standard solar motion as given by Mihalas & Binney (1981) and Lang (1978). Therefore, the expected circular velocity $\theta(R)$ follows from Eq. (3). As is well known, there is a sharp increase in the number of PN in the direction of the galactic bulge, where large velocities are often observed, as can be expected from the simple model given by Eq. (3). In this work we are interested in the determination of the galactic rotation curve up to a few kpc away from the solar circle, so that the objects that are in the direction of the galactic centre (within roughly 20 degrees) have been discarded.

4. RESULTS AND DISCUSSION

The main results of this paper are shown in Figures 1 to 5 and in Table 1. Fig. 1 shows all objects in the approximate range of 4 to 14 kpc with measured radial velocities adopting distances of Maciel (1984), including limits. If we exclude those nebulae for which distance limits are given in Maciel (1984), the number of objects drops to about two hundred nebulae, but the behavior of the rotation curve is indistinguishable from Fig. 1, so that we prefer to display the full statistical sample. The solid line in Fig. 1 is a second degree polynomial fitted to the data. Following Maciel & Dutra (1992), we may write the rotation velocity in the form

$$\theta(R) = a_0 + a_1 R + a_2 R^2, \tag{4}$$

where $\theta(R)$ is in km s^{-1} and R in kpc. The coefficients are given in Table 1. Fig. 1 can be considered as representative of all four distance scales adopted in this work, since all of them present qualitatively similar results. The derived rotation curves based on the four distance scales are better seen in Figs. 2 to 5, where we show the average velocity values adopting 0.5 kpc bins in galactocentric distance and explicitely show the individual dispersion in each bin, apart from the polynomial fits. The corresponding coefficients are also given in Table 1. The largest error bars, which are generally near the largest galactocentric distances, reflect the fact that the samples do not contain many objects in these regions. This is the case of the distance scales by Maciel (1984), van de Steene & Zijlstra (1994), and Zhang (1995), for which we have adopted as error bars of the last two bins the averages of the remaining error bars for $R > 10$ kpc. Also, in the scale by Maciel (1984) there is only one object in the first bin at $R = 3.75$ kpc, so that we have in this case adopted the same error bar as in the next bin. The well known rotation curve by Clemens (1985), which is essentially based on galactic CO clouds, H I and H II regions is also shown for comparison purposes in Figs. 2 to 5 as a dashed curve.

From Figs. 2 to 5, it can be concluded that the disk PN in our sample present a reasonably well defined rotation curve, taking into account that these are evolved objects, that is, their velocity dispersions relative to an average curve are expected to be higher than in the case of young objects such as H II regions. It can be seen that all scales present similar results, in the sense that there is no indication of a decrease in the rotation curve beyond the solar circle, thus confirming the earlier result by Maciel & Dutra (1992). There is generally a relative minimum near the Sun's position, and the curves remain approximately constant beyond R_0. In some of the scales, such as those by CKS and Zhang, there seems to be a slight increase in the region beyond 13 kpc; however, the number of data points in this region is very small, and also our sample does not extend beyond $R = 14$ kpc, essentially due to the fact that the distances of far away planetary nebulae generally have the largest errors. Therefore, the conclusion about any increase beyond $R \simeq 13 - 14$ kpc cannot be presently confirmed.

It is interesting to notice that the derived rotation curves shown in Figs. 2 to 5 do not change appreciably when different distance scales are adopted. As discussed by Phillips (2001), even though the individual distances of planetary nebulae cannot be considered reliable, a statistical analysis of many objects may in principle be used to constrain the average distances. Our results show that, concerning the average rotation curve, the differences among the adopted distance scales are not significant.

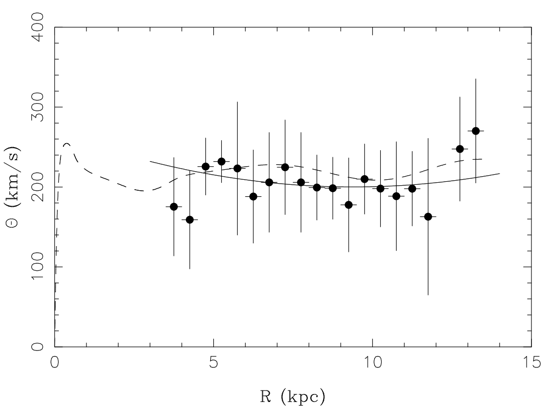

Fig. 2. Rotation curve from PN (solid line) and average velocities in 0.5 kpc bins (dots with error bars), adopting distances by Maciel (1984). Also shown is the rotation curve from H II regions by Clemens (1985, dashed line).

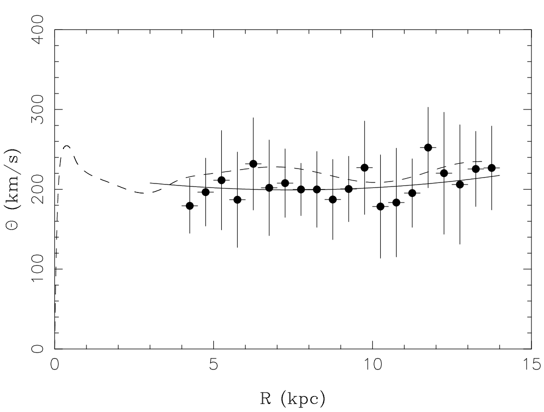

Fig. 3. The same as Fig. 2 with distances by Cahn et al. (1992).

The average rms velocity deviation σ_{PN} is in the range of 50–55 km s^{-1} for all considered distance scales. This can be compared with the corresponding value for H II regions, which is typically of about $\sigma_{H\ II} \simeq 20$ km s^{-1} (see for example Clemens 1985; Rohlfs et al. 1986; Maciel & Dutra 1992), particularly for $R > R_0$, which is the region we are mainly interested in. This larger dispersion for the planetary nebulae is totally consistent with their average height from the galactic plane, which is about $z \simeq 0.4$ kpc for the sample considered here. Therefore, our objects represent a somewhat "hotter" population, so that part of their space velocities are in the z direction, thus decreasing somewhat the rota-

TABLE 1

COEFFICIENTS OF THE POLYNOMIALS

Distance Scale	a_0	a_1	a_2
Maciel (1984)	269.2549	−14.7321	0.7847
Cahn et al. (1992)	223.3683	−6.4367	0.4293
van de Steene & Zijlstra (1994)	258.0714	−13.1068	0.7760
Zhang (1995)	197.7348	−1.4770	0.2429

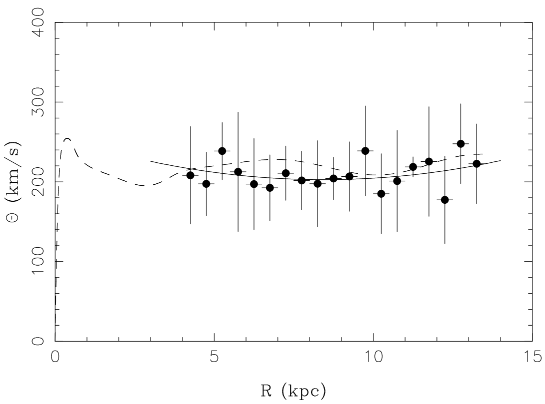

Fig. 4. The same as Fig. 2 with distances by van de Steene & Zijlstra (1994).

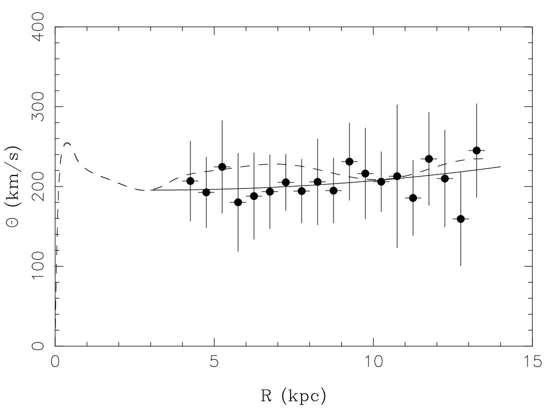

Fig. 5. The same as Fig. 2 with distances by Zhang (1995).

tion velocity. This can also be observed in Figs. 2 to 5, where we notice that the PN derived rotation velocities tend to be systematically lower than the corresponding H II region data, represented by the Clemens (1985) curve. If we take into account only the objects that belong to the thin disk population, for which we can estimate maximum values of $z \simeq 1$ kpc and $\Delta V_r \simeq 100$ km s^{-1} for the height relative to the galactic plane and the peculiar radial velocity, respectively, our derived curves do not change appreciably, but the average heights and rms velocity dispersion drop to $z \simeq 0.3$ kpc and $\sigma_{PN} \simeq 41$ km s^{-1}, respectively, irrespective of the distance scale adopted.

In view of the previous discussions, the main conclusions of this paper are the following: (i) Planetary nebulae present a relatively well defined rotation curve, which is very similar to the curve defined by the younger H II regions, although with a higher dispersion and generally somewhat lower velocities. As a comparison, our derived curves are similar to the Clemens (1985) curve, as shown in Figs. 2 to 5 and also to the more recent curve derived by Brand & Blitz (1993), which is also based on H I and H II region data. (ii) The derived rotation curves for PN do not show any decrease beyond the solar circle up to a distance of approximately 14 kpc, reinforcing the need of unobserved matter in the Galaxy, particularly for $R > R_0$. Again in this respect, our results are similar to the rotation curve by Brand & Blitz (1993). (iii) This result does not depend on the adopted statistical distance scale, and all scales considered produce similar global results, even though individual distances may be very different according to the adopted scale; also, no apparent distinction on the rotation curve arises from the adoption of the so-called “short” or “long” distance scales. In this respect, our results differ from those by Phillips (2001), who concluded that the “long” PN distance scales provide a better agreement with the H II region derived rotation curve than the “short” scales. However, Phillips analysis applies essentially to objects within the solar circle, $R < R_0$, whereas our main goal here is to establish constraints for the outer galactic disc, for which $R > R_0$. (iv) There is a clear decrease in the average velocity deviations for the nebulae located at lower distances from the galactic plane, which confirms the population spread of the PN subsystem, so that objects with younger progenitors—and possibly larger masses— are preferentially located closer to the galactic plane.

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REFERENCES

Amaral, L. H., Ortiz, R., Lépine, J. R. D., & Maciel, W. J. 1996, MNRAS, 281, 339
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Cahn, J. H., Kaler, J. B., & Stanghellini, L. 1992, A&AS, 94, 399
Clemens, D. C. 1985, ApJ, 295, 422
Daub, C.T. 1982, ApJ ,260, 612
Durand, S., Acker, A., & Zijlstra, A. 1998, A&AS, 132, 13
Cuisinier, F., Acker, A., Maciel, W. J., & Stenholm, B. 2000, A&A, 353, 543
Escudero, A. V., Costa, R. D. D., & Maciel, W. J. 2004, A&A, 414, 211
Faúndez-Abans, M., & Maciel, W. J. 1986, A&A, 158, 228
Kwok, S., Purton, C. R., & FitzGerald, P. M. 1978, ApJ, 219, L125
Lang, K. R. 1978, Astrophysical Formulae (Berlin: Springer-Verlag)
Maciel, W. J. 1984, A&AS, 55, 253
———. 1989, IAU Symp. 131, Planetary Nebulae, ed. S. Torres-Peimbert (Dordrecht: Kluwer), p. 73
Maciel, W. J., & Dutra, C. M. 1992, A&A, 262, 271
Maciel, W. J., & Pottasch, S. R. 1980, A&A, 88, 1
Mihalas, D., & Binney, J. 1981, Galactic Astronomy (San Francisco: Freeman & Co.)
Peimbert, M. 1978, IAU Symp. 76, Planetary Nebulae, ed. Y. Terzian (Dordrecht: Reidel), p. 215
———. 1990, Rep. Prog. Phys., 53, 1559
Phillips, J. P. 2001, A&A, 367, 967
Rohlfs, K., Chini, R., Wink, J. E., & Böhme, R. 1986, A&A, 158, 181
Schneider, S. E., Terzian, Y., Purgathofer, A., & Perinotto, M. 1983, ApJS, 52, 399
van de Steene, G., & Zijlstra, A. 1994, A&AS, 108, 485
———. 1995, A&A, 293, 541
Zhang, C. Y. 1995, ApJS, 98, 659

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