Spatial orientation of planetary nebulae in the Milky Way

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Resumen / En este trabajo, utilizamos simulaciones Monte Carlo para estudiar posibles alineaciones de una muestra de nebulosas planetarias distribuidas con el perfil de densidad de un disco delgado,l imitadas por un corte en distancia al observador. Investigamos cómo varía la señal bajo diferentes escenarios de alineación y comparamos los resultados con datos observacionales. Descubrimos que, con los datos actuales, aún no puede descartarse por completo el escenario orientado, y que un bajo grado de alineación podría ser posible.

Abstract / In this work we used Monte Carlo simulations to study the alignment signal given by a distance limited sample of planetary nebulae distributed with the density profile of a thin disk. We investigated how the signal varies under different alignment scenarios and compared the results with observational data. We discovered that, with the current data, the oriented scenario cannot yet be completely ruled out, and a low degree of aligment might yet be posible.

Keywords / planetary nebulae: general — Galaxy: structure — galaxies: individual (Milky Way)

1. Introduction

Planetary nebulae (PNe) are the remnants of intermediate-mass stars, characterized by their expanding envelopes of low-density ionized gas. Their evolution could be influenced by electromagnetic phenomena within galaxies, such as the magnetic field of the Milky Way, interactions with the interstellar medium, or interactions with charged dark matter particles. These interactions could lead to galaxy-scale alignments. Given the range of morphologies presented by PNe, often exhibiting mostly ellipsoidal shapes, this allows for the determination of an angle between their major axis and a reference point within our Galaxy.

However, studying the spatial orientation of PNe poses a significant challenge due to the inherent limitations of astronomical observations, which provide two-dimensional projections of three-dimensional shapes on the celestial sphere. Consequently, distinguishing between a truly oriented distribution and a random one is non-trivial. Moreover, there is a notable lack of consensus regarding the spatial orientation exhibited by PNe. The resulting distributions are highly sensitive to the methodologies employed, the size of the catalogs utilized, and the galactic regions observed. Consequently, various distributions with differing trends have been reported in the literature (Grinin & Zereva, 1968; Melnick & Harwit, 1975; Corradi et al., 1998; Weidmann & Díaz, 2008; Ali et al., 2012).

The main motivation of this work is not to resolve the tension regarding whether orientation exists or not, but primarily to ascertain if the physical feasibility of such orientation is distinguishable due to the effects of angle projections, no matter how weak they are.

In this study, we adopt a novel approach to investigate the issue of PNe orientations. Rather than relying solely on observational or statistical methods, we employ Monte Carlo simulations to replicate the distribution of PNe observed in the Milky Way. This approach enables us to model their positions while considering the constraints imposed by observational data. By progressively refining the complexity of the model, we gain understanding and can effectively extract valuable insights from the observational data. We start by exploring the orientations of a sample of PNe distributed according to an exponential disk profile. We examine samples exhibiting varying degrees of orientation relative to the center of the Galaxy, measuring how the signal varies across different scenarios. Our analysis aims to shed light on the relationship between simulated distributions and observational data, offering insights into the spatial orientation of PNe within the Milky Way.

In the Sec. 2, we explain the algorithm applied to simulate the PNe, the projection of their major axes and the subsequent measurement of the projected angle. In Sec. 3, we analyze the results obtained and compare those to observational data. We delve into the conclusions that can be extracted from the work.

2. Methodology

We used Monte Carlo simulations to study the orientation of a sample of PNe with different degrees of alignment towards the center of the galactic disk, whose three-dimensional spatial distribution is given by the

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exponential density profile for a thin disk:

$$\Sigma(R,z) = \Sigma_0 \exp\left(-\frac{R}{R_\mathrm{d}}\right), \quad (1)$$

where R_d represents the characteristic sizes of the Milky Way and $\Sigma_0 = \frac{M_\mathrm{MW}}{2\pi {R_\mathrm{d}}^2}$ (Mo et al., 2010). For the z-coordinate, we choose a small interval within galactic latitude of $\theta = (-30°, 30°)$.

The distribution of our samples was taken so that the PNe are contained within a circle of radius 3 Kpc, centered in the observer situated at a distance of 8 kpc from the galactic disk's center. This approach allows us to consider the limit in observational distance and the Earth's position relative to the Galaxy's center, both factors influence the final projection of angles. The size of the samples was chosen to match the number of objects in the reference catalog (Weidmann & Diaz, 2008).

Each nebula was assigned a particular orientation. To do so we defined a major axis given by a realization of a vector of unitary length within an oriented spherical cone, characterized by an aperture angle Θ centered on the galactic center, which represents the range of alignment for the sample. Essentially, Θ denotes the maximum angle that the cone can encompass. When the cone aperture is 90°, we are effectively simulating random orientations. We systematically adjusted the cone's aperture angle from 10° to 90° in 10° increments, analyzing the resulting signal at each step. This approach allowed us to smoothly transition from fully oriented scenarios to random ones.

After assigning each nebula a spatial orientation, given by Θ, we projected the major axis onto the plane perpendicular to the line of sight to the nebula, as observed from Earth. The resulting angle was subsequently employed to calculate the position angle of the projected major axis, following the methodology outlined in (Weidmann & Díaz, 2008). This facilitated the replication of the angle provided in the catalog, thereby enabling a comparison of our model's outcomes with those derived from their statistical approach.

To assess the accuracy of our measurements, we used the bootstrap resampling method to estimate its variance. Finally, we compared the distributions obtained from our models with those from the reference catalog.

In order to see how the signal varied for different parts of the galaxy, we divided the samples in regions given by galactic longitude. An inner region for those PNe with $0° < b < 90°$ and $270° < b < 360°$ and an outer region for $90° < b < 270°$.The division into inner and outer regions is motivated by a desire to gain insights into how the projection effects differ between regions and their respective impacts on the observed distribution.

To determine which angular apertures could be discarded using the information from the measured data, the reduced chi-squared test was employed.

3. Results and Conclusions

In Fig. 1, we can see the projected angle ϕ for the aligned sample, the panel in the left corresponds to a high degree of alignment with $\Theta \leq 10°$, whereas the one on the right corresponds to a low alignment, with $\Theta \leq 50°$. Both of them are compared to the observations from the reference catalog. In the latter case, we can see that the presence of noise in the observations obscures any discernible trend within the sample, in order to reduce this noise a larger sample of observed nebula's must be obtained.

In Fig. 2, we used the reduced chi-squared test and found that for the outer nebulae the data is compatible with an orientation with an opening angle Θ between 40° and 90° with respect to the center of the Galaxy. For the nebulae belonging to the inner galactic disk, the opening angle can be further restricted to angles larger than 50°. These results suggest that the nebulae are not strongly oriented with respect to the galactic center.

We conclude that despite the loss of information due to projection, this effect still enables the distinction between samples. Upon comparing observations to our model, we find no compelling evidence of a strong alignment. However, a weak alignment cannot be ruled out, which could leave room for interactions, such that models of charged dark matter or galactic magnetic field effects could be restricted. Our results are consistent with those obtained by Weidmann & Díaz (2008), although we identify fewer alignment present in the inner region. To improve the study, a larger sample size is needed to yield more precise constraints. The latest generation of telescopes such as Vera Rubin Telescope, and information produced by the Gaia mission, will contribute data on new nebulae, better mapping the distribution of PNe in the Milky Way, which will be crucial for this issue, thereby increasing the number of objects available for studies like these. Furthermore, with a broader dataset, there is potential for refining our modeling techniques to better replicate their observed distribution and phenomena and to improve our understanding of how three dimensional information is lost through projection.

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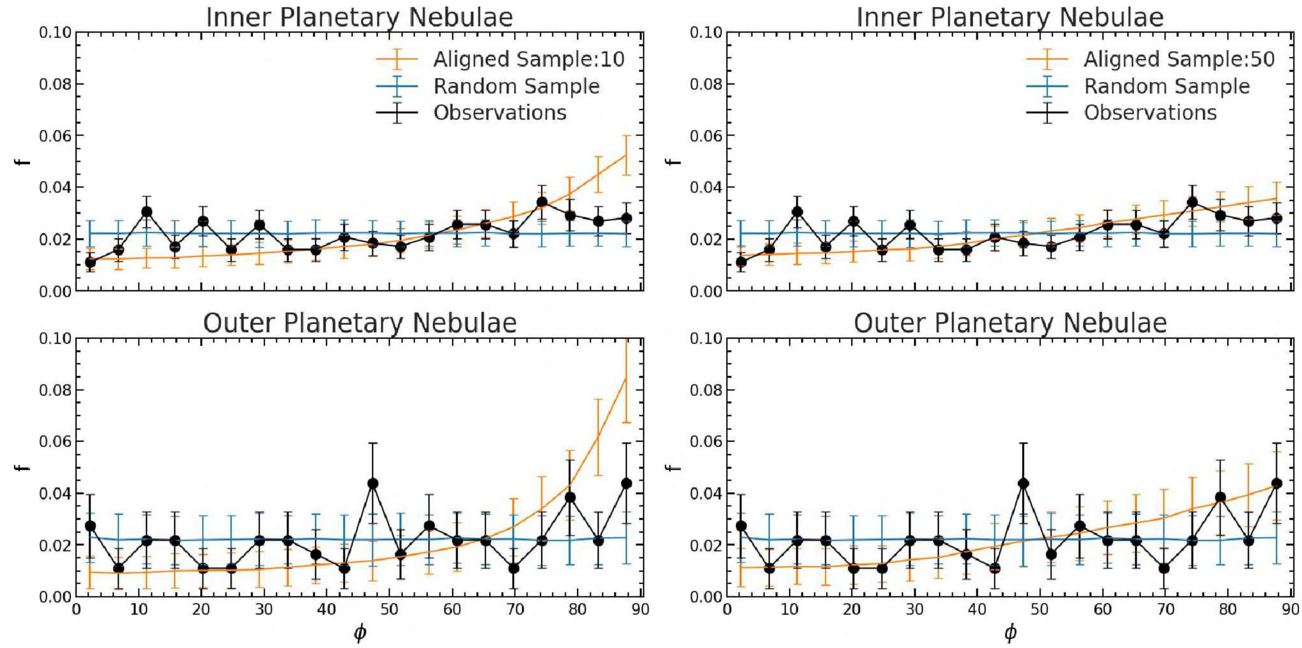

Fig. 1. Distributions of the relative frequency for the measured projected angle ϕ between the Galactic North Pole and the semi-major axis of the PNe. Blue one corresponds to the random sample, orange to the aligned one, black is for the observations from the reference catalog. *Left panel*: corresponds to an aligned sample with an aperture angle $\Theta \leq 10°$. *Right panel*: aligned sample with an aperture angle of $\Theta \leq 50°$.

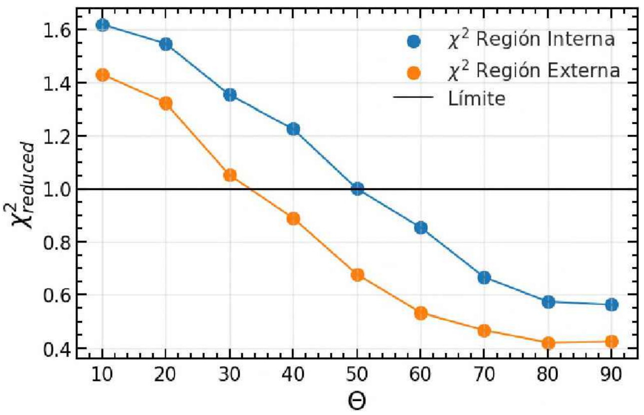

Fig. 2. The reduced chi-squared test applied to the inner and outer PNe distributions.The limit corresponds to the reduced chi-squared for one degree of freedom and a 68 % level of confidence. This test rejects alignments of up to 50° and 35° with respect to the center of the Galaxy, for PNe in the inner and outer galaxy disc, respectively.