The spatial structure of the Galaxy subsystems as it looks from an analysis of the system of galactic planetary nebulae

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Abstract. We recalculate the distance to 554 galactic Planetary Nebulae (PNe) using the relation between the ionized mass of the nebula μ and the optical thickness parameter τ obtained by Akimkin et al. [1]. We classified these nebulae according to the Peimbert [9] types modified by Quireza et al. [11]. The obtained by us distances to galactic PNe were used to obtain the scale heights h for different subsystem of the Milky Way. Next values if h were estimated: h = 208 ± 10 pc for thin disk objects, h = 600 ± 54 pc for thick disk ones, and h = 1378 ± 180 pc for halo PNe.

1. Introduction
Planetary Nebulae (PNe) are the descendants of the stars with initial masses on main sequence in a range from 0.8 to 8 M☉. PNe are located in different Galaxy subsystems and they have a wide variety of spatial and kinematic properties, chemical composition, and morphology.

Studying of the spatial distribution of galactic PNe is often used test the different models of the Galactic evolution [3]. In the present time there is no agreement in the understanding of the structure of Galactic disk. Bovy et al. [4] claim that there is no clear separation between the thin and thick disks and they have the common scale height. On the other hand Girardi et al. [5] conclude that there are different scale heights both for thin and thick disks. An analyzing of the vertical distribution of PNe can help us to clarify its structure.

Unfortunately the distances to PNe which can help us to solve this problem are badly known. More or less exact distances to selected PNe which are found from the trigonometric parallaxes of their central stars are known only for nearly 40 objects. For the great majority of galactic PNe one has to use the distances based mainly on the Shklovsky/Daub statistical scale [6] which can be very unreliable. The individual statistical distances to PNe obtained by various methods are often strongly different.

In the present work, we used a new calibration of the existing distance scales for Galactic disk PNe obtained by Akimkin et al. [1]. They used the spatially-kinematic modeling of the galactic PNe ensemble proposed by Nikiforov and Bobrova [2]. Then we reclassified PNe according to the Peimbert types using the modified classification by Quireza et al. [11] based on Bayesian posterior probability estimations. Finally we recalculated the distance to 554 galactic PNe and obtained the estimations for scale heights for thin disk, thick disks, and halo.
2. Distances to PNe

Different statistical distance scales are based on the calibration of the relation between ionized mass $\mu = (2.266 \times 10^{-21} D^5 \theta^3 F)^{1/2}$ and the optical thickness parameter $\tau = \log (4 \theta / F)$ of the PNe. Here $D$ is the distance to the PN in parsecs, $\theta$ is the nebular radius in arcsec, and $F$ is the nebular flux at 5 GHz in janskys.

Akimkin et al. (1) recalibrated the known distance scales to PNe basing on the kinematic model of the galactic PNe by Nikiforov and Bobrova [2] and the high-precision determination of the distance to the center of the Galaxy. Using the corrected distances to disk PNe the obtained the refined relation between $\mu$ and $\tau$:

$$\log \mu = \begin{cases} 
0.08\tau - 1.04, & \tau \leq 2.89, \\
0.69\tau - 2.80, & \tau > 2.89.
\end{cases}$$

(1)

This relation together with the observational data on the angular sizes of the nebulae and their radio fluxes we used to obtain the precise distances to 554 PN which are in the catalogue by Stanghellini et al. [7] (SSV).

Received distances were compared in Fig. 1 with those taken from the catalogue by Stanghellini et al. [7] (SSV). These authors used the distances to the Magellanic Clouds PNe for the calibration. However, the exactness of the distances to the Magellanic Clouds themselves is not very high [8]. Moreover the properties of the PNe in the Magellanic Clouds can strongly differ from those for galactic PNe.

**Figure 1.** A comparison of distances $D$ to PNe (in kpc) derived in the present paper and determined by Stanghellini et al. [7]. The solid line shows the mean ratio of the scales and the dotted one marks one standard deviation $\sigma$.

**Figure 2.** Distribution of PNe in the (X,Z) plane.

The mean ratio of the SSV distances to those obtained by us is $0.927 \pm 0.007$. It means that our scale of the galactic PNe distances appeared to be a bit longer than that given by SSV.

In Fig. 2 we plot the projection of the galactic PNe with obtained by us distances into the galactic plane $(X,Z)$, where axis $Z$ is directed from the center of the Galaxy to the north pope and the axis $X$ is directed from the galactic center to the Sun.

We compile the catalog of the calculated distances and other parameters of all 554 galactic PNe. A small part of the catalogue is given in table 1. In the fist column we present the name of
PNe, parameters $\tau$, $\theta$ and $F$ are given in columns 2-4. The obtained by us distances are printed in the 5th column. In the last 2 columns the distances $z$ of PNe to the galactic plane and the distances to the center of the Galaxy $R_g$ are given.

Table 1. First 6 line in our catalog of the galactic PNe distances

| Name       | $\tau$ | $\theta$ | $F$ | $D$  | $z$  | $R_g$ |
|------------|--------|----------|-----|------|------|-------|
| NGC 40     | 3.46   | 18.2     | 0.460 | 1.365 | 0.232 | 8.651 |
| NGC 246    | 5.31   | 112.0    | 0.248 | 0.595 | -0.574 | 7.976 |
| NGC 650-1  | 5.24   | 69.2     | 0.110 | 0.930 | -0.171 | 8.526 |
| NGC 1360   | 5.82   | 192.0    | 0.222 | 0.457 | -0.370 | 8.107 |
| NGC 1501   | 4.08   | 25.9     | 0.224 | 1.335 | 0.151  | 9.013 |
| NGC 1514   | 4.59   | 50.2     | 0.262 | 0.903 | -0.238 | 8.746 |

3. Results and discussion

3.1. Classification of PNe

PNe in the Galaxy have a wide variety of spatial and kinematic properties, chemical composition, and morphology. So it is important to understand what the galactic subsystems belongs any PNe in our catalogue. Peimbert [9] divided all galactic PNe into four types, from the type I with the most massive progenitors to type IV which includes the PNe in halo. Later was defined type V which includes the bulge objects [10]. Each of these types correspond to the stellar population of the Galaxy belonging to different subsystems. PNe of types I and IIa are objects of thin disk. Types IIb and III includes the objects of thick disk and finally all halo PNe belong to type IV.

Due to some uncertainties in Peimbert’s classification it was extended and modified by Quiresa et al. [11]. Using modified criteria by Quiresa et al. [11] we determine that in our catalogue 36 objects belong to type I and 193 PNe belongs to type IIa. Type IIb in the catalogue is presented by 58 objects, whereas 119 PNe are the type III objects. 58 PNe appeared to be the halo objects (type IV), other 90 PNe are bulge objects. Our classification was based on distances $z$ of the PNe to the galactic plane and their radial velocities. We also used the statistical package R$^1$.

3.2. Scale heights

The observed distribution of PNe along the $z$ coordinate axis can be described by an exponential density law:

$$N(z) = N_0 \exp\left(-\frac{|z|}{h}\right),$$

where $N(z)$ is the number of PNe in the layer $z - \Delta Z/2, z + \Delta Z/2$, $N_0$ is the normalization coefficient, and $h$ is the scale height for the considered class of objects. The value of $\Delta Z$ were variable. The scale height is different for different types of object and generally have to increases with the age of the object.

Using this formula we obtained the scale heights for thin disk, thick disk and halo. The dependences of values $\log N(z)$ on $z$ are shown in figures 3, 4, 5, respectively. At large galactic heights ($z > 5$ kpc), the number of nebulae is very small. It explains the large deviation of the $N(Z)$ value from the exponential law at $z > 10$ kpc in figure 5.

1 http://www.r-project.org/
Figure 3. $N(z)$ dependence for thin disk objects. Figure 4. $N(z)$ dependence for thick disk PNe. Figure 5. $N(z)$ dependence for halo nebulae.

Table 2. Estimations of scale height, pc. Asterisk marks the results obtained in this work.

|        | Thin disk | Thick disk | Halo     |
|--------|-----------|------------|----------|
| $h$    | 208 ± 10* | 600 ± 54*  | 1378 ± 180* |
| $h$    | 197 ± 10  | 640 ± 32   | 1350 ± 0 |

Results of our determination of the scale heights for different galactic subsystems and a comparison with the same values obtained by other authors are presented in table 2. We can see good agreement of our scale heights $h$ (1st column) with those obtained by Bobylev & Baikova [12] for thin disk PNe which used PNe within distance of 2 kpc from the the Sun only.

Du et al. [13] analyzed a sample of over 1400 main sequence stars. An agreement of their value of $h$ with ours (column 2) let us to conclude that the $z$ distribution of the PNe progenitors weakly changes during evolution of this stars. Milanova & Kholtygin [14] also investigated the galactic PNe distribution for different Peimbert types. Their scale heights for halo objects is in good agreement with our determination.

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