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Origin and evolution of the bulge of our Galaxy

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The modern observations of planetary nebulae (PNe) are used to recalculate the element abundances for more than 150 PNe of the Milky Way and Magellanic Clouds. Based on our data, we study the evolution of the abundance gradients for PNe in the thin disk and in the bulge. We show that abundances are similar for PNe in the bulge and PNe of Peimbert's type II whose progenitor stars belong to the population of the thin disk with the ages greater than 4–6 Gyrs. We put forward the scenario of the star formation in the thin disk and bulge. We suppose that the intense star formation both in the bulge and in the thin disk do not stop at least up to 4–6 Gyr ago.

Keywords: Galactic bulge: planetary nebulae; Magellanic Clouds: planetary nebulae

1 Introduction

The problem of the Galactic bulge formation and its connection with the formation of the thin and thick disk is one of the most intriguing in modern astronomy. The bulges of spiral galaxies can be either *true* bulges formed in S0–Sb spirals through the accumulation of the gaseous stellar component of the galaxies at their early evolution phases or *pseudobulges* formed in late-type spirals due to the instability of their disks. The bulge of our Galaxy is most likely *true* (e.g. Zoccali et al. [30], Matteucci [18]).

A review of the existing models of bulge formation is given by Minniti and Zoccali [22] and by Matteucci [18]. The bulge and the disk may have different evolutionary histories as is described for example by the disk inside-out formation model [5] or by the multiple infalls scenario [6] and we can expect these differences to be rejected on the chemical properties of each component. Elmegreen [7] has proposed a bulge formation as a result of coalescence of large clumps in primordial galaxies. These clumps are formed by gravitational instability. This model suggests a fast assembly of the bulge.

More recently Cescutti [4] compared abundance predictions from a detailed chemical evolution model for the bulge with the newest data for stellar population of the bulge. They computed several chemical evolution models by adopting different initial mass functions for the Galactic bulge stars and then compared the results

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to new data including both giants and dwarf stars in the bulge. Their model predicts that the bulge formed very quickly with the majority of stars formed inside the first 0.5 Gyr.

Investigation of the galactic PNe is a good tool to study the evolution of both the Milky Way as whole and all its subsystems, including the bulge (see e.g. [20]). The precursors of PNe are the stars of low and intermediate mass with ages from less than 10^9 years up to 13×10^9 years. It means that studying bulge PNe allows us to investigate the history of its formation up to the first ages.

2 Model and catalogue of PNe parameters

The modern observations of the planetary nebulae were used by us to recalculate the abundances of He, C, N and O in the nebulae of our Galaxy and the Magellanic Clouds. We use the stochastic model of the planetary nebulae described by Kholtygin [12, 13, 21] to take into account the temperature and density fluctuations and the real distributions of errors in the observed line intensities. These data were included into the updated electronic version of our catalogue of Galactic and Magellanic Clouds planetary nebulae parameters [15]. In this catalogue the references on the sources of the line intensities in spectra of nebulae are also given.

We compare our new He, C, N and O abundances with data of other authors, for example, given by [24]. There is a good agreement of our O abundances with obtained by Perinotto, but for C and N the differences between two set of abundances are larger. We can explain this fact by taking into account the temperature and density fluctuations for PNe in our model.

The synthetic star evolution models are used to avoid the huge calculations of full star evolution models and to describe simplified asymptotic giant branch star evolution and to predict its observed parameters. Marigo et al. [16] and Matteucci [17] calculated the synthetic evolution model of low and intermediate mass stars from AGB-stage till white dwarf phase. Our data confirms the decreasing of C/O abundance ratio in galactic PNe with increasing the initial solar metallicity from $Z = 0.004$ to $Z = 0.019$ in the model [16].

3 Our sample of bulge PNe

The standard criteria for bulge PNe (e.g. Stasińska and Tylenda [27]) are: they have locations within 10° of the Galactic centre, diameters smaller than 20 arcsec, and radio fluxes at 5 GHz of less than 100 mJy. For subsequent analysis we choose slightly modified criteria to separate bulge and non-bulge PNe:

$$\begin{cases} l & \leq & 10^\circ\,, \\ b & \leq & 8^\circ\,, \\ F\,(5\,\mathrm{GHz}) & \leq & 100\,\mathrm{mJy}\,, \\ R_\mathrm{g} & \leq & 2\,\mathrm{kpc}\,. \end{cases} \tag{1}$$

Here l and b are the galactic longitude and latitude, F (5 GHz) is the total radio flux from the nebula at 5 GHz and R_g is the distance of the PN from the galactic

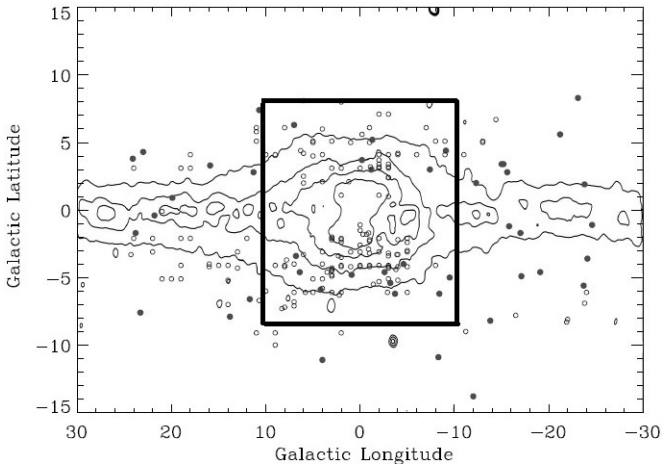


Figure 1 Selection of the bulge PNe. Thick solid lines confine the region of the bulge PNe according to the criteria (1). Thick line contours are the 2.2 μm COBE/DIRBE satellite plot [28]. Points and open circles mark PNe in the bulge direction selected by [3].

axe of rotation. The values of $R_{\rm g}$ were calculated from distances to PNe given, for example, in [1] using the standard formulae and the galactic coordinates of PNe. The last condition ($R_{\rm g} \leq 2\,{\rm kpc}$) is selected to avoid the inclusion of the PNe which are close to the Sun to the list of the bulge objects.

Figure 1 shows the region limited by the criteria (1) on the COBE/DIRBE 2.2 μm map. Using these criteria we select the 35 PNe definitely belonging to the bulge.

The distribution of selected bulge PNe in a dependence of the distance $|Z|$ from the galactic plane is shown in Fig. 2 (left panel). It is evident that there is a depletion of PNe for low values of $|Z| \leq 0.5$ kpc. This depletion is probably connected with strong interstellar absorption in the direction of the galactic center. Suppose that for $|Z| > 0.5$ kpc the Z-distribution of the bulge PNe obeys the exponential law:

$$N(|Z|)d|Z| = N_0 e^{-|Z|/Z_{\rm b}} d|Z|\,, \tag{2}$$

where $Z_{\rm b}$ is the scale of height for PNe in the bulge. For bulge PNe in our sample we find next parameters of fit (2): $N_0 = 163 \pm 1$ and $Z_{\rm b} = 0.56 \pm 0.20$ kpc. It means that the total number of bulge PNe in the region limited with the criteria (1) $N_{tot} \geq N_0 * Z_{\rm b} = 91$. The calculated value of $Z_{\rm b}$ is very close to the scale of height for the PNe in the solar vicinity: $Z_{\rm H} = 0.50\,{\rm kpc}$ [21]. The estimated value of the PNe density in the bulge center is $\approx 90\,{\rm kpc}^{-3}$.

Figure 2 (right panel) shows the distribution of the bulge PNe radial velocities as a function of the Galactic longitude. The radial velocity gradient for bulge PNe is $d(V_{\rm lsr})/l \approx 25\,{\rm km\,s^{-1}\,deg^{-1}}$. Recently Howard et al. [10] reported results from BRAVA, a large-scale radial velocity survey of the Galactic bulge, using M giant stars selected from the 2 MASS catalogue. They investigated the radial velocities for stars at the edge of the Galactic bulge at latitudes $b = -8^\circ$ and compared to the radial velocities at $b = -4^\circ$. They found that the rotation curve $V(r)$ is the same

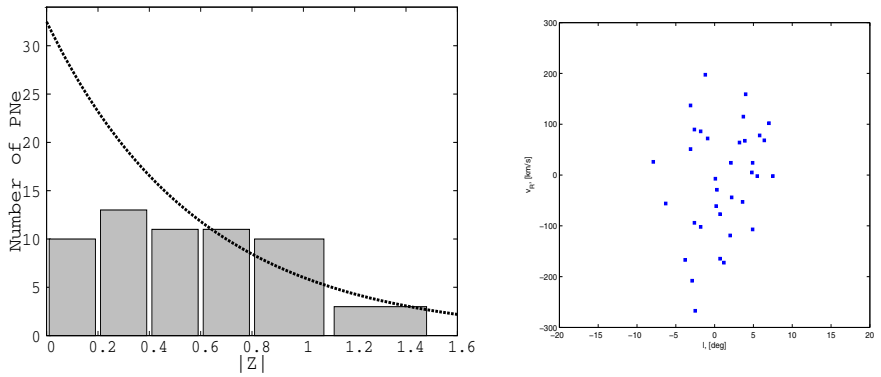


Figure 2 **Left**: Z-distribution of PNe in bulge. Dashed line is an approximation (2) for $N(|Z|)$. **Right**: distribution of bulge PNe in a radial velocity (corrected for the solar motion) versus Galactic longitude.

both at $b = -8°$ and at $b = -4°$. That means that the Galactic boxy bulge rotates cylindrically, as do the boxy bulges of other galaxies.

The maximal amplitude of the stellar radial velocities in their review at $l = \pm 10°$ are $\pm 100\,\mathrm{km/s}$. It means that the slope of radial velocity curve for M giants PNe is $\approx 100\,\mathrm{km\,s^{-1}\,degree^{-1}}$ and is much smaller than the value obtained by us for bulge PNe. The reason for such strong discordance remains unclear. It is possible that the kinematics of the M giant stars and the central stars of the bulge PNe are strongly different. In support of this hypothesis it should be noted that Chiappini et al. [5] obtained almost the same velocity gradient for bulge PNe as ours.

Table 1 Mean distances $\overline{|z|}$ to the Galactic plane for different types of PNe

Type of PNe	$\overline{\lvert z\rvert}$, kpc	Galactic subsystem
I	0.12	ultrathin disk
IIa	0.37	thin disk
IIb	0.74	thin disk
III	0.92	thick disk
IV	2.57	halo
V	0.58	bulge

We also calculated the mean distances of different types of PNe determined by Quireza et al. [25]. We used the distances to the galactic PNe in [1, 26] and suppose that the *best value* of the distance to the Galactic center is $R_0^{(\mathrm{b})} = 7.9 \pm 0.2$ kpc as it was derived from a set of recent determinations of high accuracy [23]. Obtained values of the mean distances are given in Table 1. In column 3 of this table we point out to which Galactic subsystem the PNe of given type belongs.

We see that the mean distances $\overline{|z|}$ for bulge PNe to the Galactic plane $\overline{|z|} = 0.58$ kpc. This value is close to the value obtained by us for the scale of heights for bulge PNe $Z_{\mathrm{b}} = 0.56$ kpc. The value of $\overline{|z|}$ for bulge PNe is sandwiched between

two distances to the Galactic plane for PNe of types IIa and IIb. This fact can demonstrate the possible similarity of the nature of the bulge and thin disk PNe, which is discussed in the next section.

4 Abundances for the Galactic bulge PNe and the nature of the bulge

The nature of the Galactic bulge is not clearly understood up to now. Many details of the bulge formation and its connection with various Galactic subsystems, in particular, the thin and thick disks, remain unclear. Analysis of the elemental abundances in these Galactic subsystems can illuminate this question. For all PNe of our sample the abundances were determined by the same way as it was described by Milanova and Kholtygin [21]. The mean abundances obtained by us for different types of PNe in a classification by Quireza et al. [25] are given in Table 2.

Table 2 Mean element abundances for different types of PNe

Type	$\overline{[\mathrm{He}]}$	$\overline{[\mathrm{C}]}$	$\overline{[\mathrm{N}]}$	$\overline{[\mathrm{O}]}$	$\overline{[\mathrm{Ne}]}$	$\overline{[\mathrm{S}]}$	$\overline{[\mathrm{Ar}]}$	$\overline{[\mathrm{Cl}]}$	$\overline{[\mathrm{Fe}]}$
All PNe	11.02	8.65	8.02	8.50	7.86	6.70	6.33	5.24	5.72
I	11.19	7.80	8.49	8.45	7.95	6.89	6.41	-	5.88
IIa	11.04	8.78	8.23	8.59	7.93	6.80	6.37	5.20	5.84
IIb	11.00	8.60	7.77	8.56	7.88	6.54	6.25	5.13	5.65
III	10.92	8.50	7.58	8.43	7.75	6.54	6.18	5.03	5.51
IV	11.00	8.57	7.67	8.37	7.66	6.54	6.07	4.86	5.51
V	10.99	8.71	8.07	8.50	7.88	6.73	6.44	5.56	5.72
Solar [2]	10.93	8.39	7.78	8.66	7.84	7.14	6.18	5.50	7.45

Of special interest are the Fe abundances for PNe. The values given in Table 2 are more than an order of magnitude smaller than the mean solar Fe abundances [2] given in the last row of Table 2. These abundances are also much smaller than those for red giant, as it is clearly seen in Fig. 4 (Left panel) where we plot the ratio of abundances $[\mathrm{Fe/H}]=\log[N(\mathrm{Fe})/N(\mathrm{H})]-[N(\mathrm{Fe})/N(\mathrm{H})]_{\odot}$ versus the metallicity [Fe/H], where $[\mathrm{Fe/H}]=\log[N(\mathrm{Fe})/N(\mathrm{H})]+12$. The solar abundances $[\mathrm{Fe}]_{\odot}$ are taken from [2]. We see a huge discordance of Fe abundances between bulge PNe and bulge red giants.

However, if we take into account the effect of condensation of gas phase iron into dust grains according to Zhang et al. [29] (≈ 1.25 dex), this discordance disappears, as we can see in Fig. 4 (right panel). It means that there are no significant differences in metallicity between stars and PNe. The high [O/Fe] ratios measured for bulge stars suggest that most formed before Type Ia SNe had time to contribute to the ISM enrichment in the bulge environment. It provides evidence that the bulge was formed on a short timescale [5].

Melendez et al. [19] determined the C, N, O, and Fe abundances in the atmospheres of red giants in the Galactic disk and bulge and concluded that the abundances of these elements are similar in bulge and thick disk objects.

However the analysis of Figs. 2 and 3 from Melendez et al. [19] with the dependences of the [O/Fe] and [C+N/Fe] abundance ratios on metallicity [Fe/H] does not

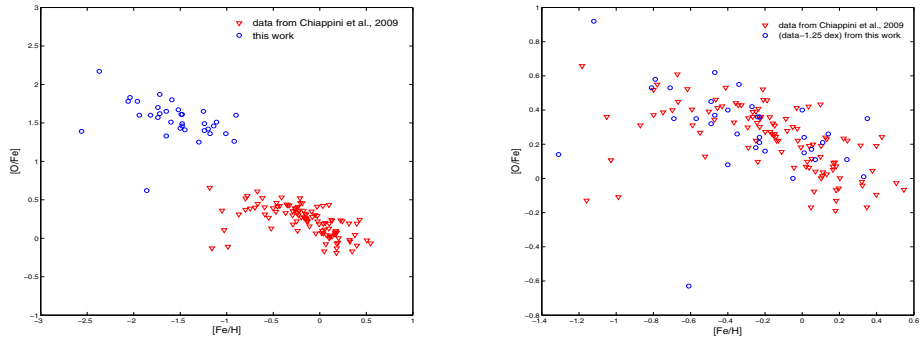


Figure 3 **Left**: a comparison of abundance ratio [O/Fe] vs. [Fe/H] for bulge PNe (our data, squares) and for red giants of the Galactic bulge ([5],triangles). **Right**: the same as in the Left panel, but after a correction of our [Fe/H] abundance ratios for the condensation of gas phase iron into dust grains.

allow one to conclude that the difference between these ratios for thin and thick disk objects is statistically significant. Based only on the data of [19] we can conclude both about the similarity of the bulge and thin disk objects and the bulge and thick disk objects with equal probabilities.

Gutenkunst et al. [9] concluded that the O, Ne, Ar, and S abundances in the bulge and thin-disk PNe differ significantly. This conclusion contradicts our analysis of the mean elemental abundances presented in Table 2.

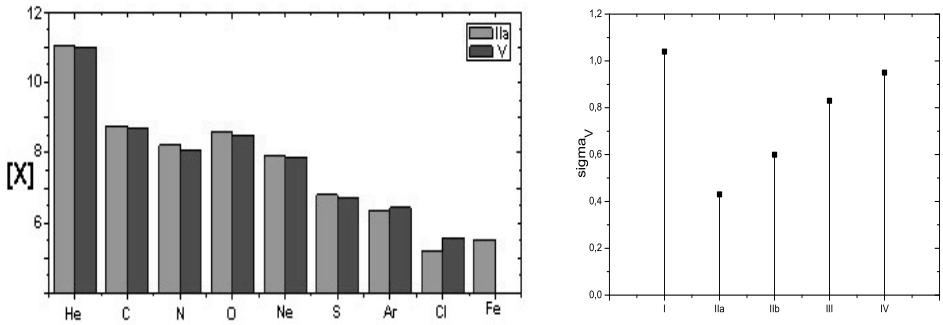


Figure 4 **Left**: a comparison of abundances for bulge PNe (dark grey columns) and for the nebulae of type IIa (light grey columns). **Right**: a parameter $\sigma_{\rm V}$ for different Galactic subsystems.

The conclusion in [9] is based on an analysis of *all* disk nebulae, while the elemental abundances depend on the age of the progenitor stars of PNe. To ascertain which PNe belonging to the Galactic disk are similar to bulge objects, we compared the abundance pattern of He, C, N, O, Ne, S, Cl, Ar and Fe abundances for bulge and disk nebulae. Our analysis shows that the abundances of bulge PNe are most similar to the abundances of type II (subtype IIa) PNe as is illustrated in Fig. 3 (left panel).

The rms deviations $\sigma_{\rm V}$ of mean relative abundances $[{\rm X/H}]_V$ for PNe in the bulge

and the values $[\mathrm{X/H}]_{\mathrm{type}}$ for all remain Galactic subsystems, where X=He, C, N, O, Ne, S, Cl, Ar an Fe can be described by the following expression:

$$\sigma_{\mathrm{V}} = \sqrt{\sum_{\mathrm{type}} ([\mathrm{X/H}]_V - [\mathrm{X/H}]_{\mathrm{type}})^2}\,, \tag{3}$$

where we sum over all types of PNe. In Fig. 3 (right panel) we plot the value of σ_{V} as a function of a type of PNe. The minimal value of σ_{V} is achieved for PNe of type II, and more exactly for subtype IIa.

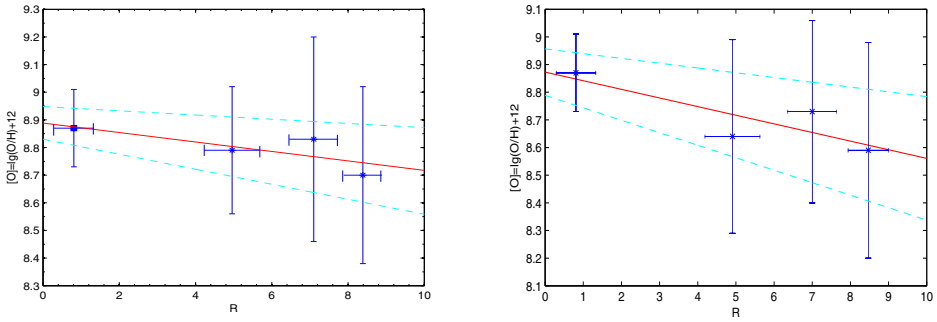


Figure 5 **Left**: averaged oxygen abundances in type IIa (asterisks) and bulge (filled squares) nebulae vs. their mean galactocentric distance according to [21]. The solid line gives a linear fit to this dependence, the dotted lines show one standard deviation from the fit. **Right**: The same as in the left panel, but for all type II nebulae.

The type IIa nebulae are thin disk objects and correspond to an intermediate age of their progenitor stars equal to 4–6 Gyr from the present epoch [25]. The similarity of bulge and thin disk PNe suggests that intense star formation in the bulge, as in the thin disk, took place at least before an epoch no more than 4–6 Gyr away from the present time.

In this case the elemental abundances for bulge PNe should continue the dependence of the abundances for thin disk PNe versus the galactocentric distance R_{g}. To test this assumption, we analyzed the R_{g} dependence of the O abundance. Since the O abundance is almost constant during the evolution of intermediate-mass stars, its value in PNe reflects the primordial O abundance in their progenitor stars determined by the abundance of oxygen in the interstellar medium at the moment of their formation.

In [21] we represented the Galactic disk by a system of five nested rings with the width $\Delta R = 2\,\mathrm{kpc}$ from the Galactic center to $R_{\mathrm{g}} = 10\,\mathrm{kpc}$. All objects within the first ring with Galactocentric distances less than 2 kpc are considered as objects of the bulge in accordance with the criteria (1).

The status of the objects whose galactocentric distances are within the ring: $2\,\mathrm{kpc} < R_{\mathrm{g}} < 4\,\mathrm{kpc}$ may be uncertain. They can belong both to the bulge and to the disk, so we excluded them from the samples of both thin disk and bulge PNe. All nebulae of type II, which are located at Galactocentric distances $R \geq 4\,\mathrm{kpc}$ are considered as objects of the thin disk.

For all of the bulge or disk nebulae with Galactocentric distances within the ring, we determined the mean O abundances and the corresponding standard deviations. These abundances referred to the distances averaged over the ensemble of all PNe in a given ring.

Figure 5 presents the dependences of the oxygen abundance in bulge and thin disk PNe on their mean galactocentric distance. The samples of thin disk nebulae in Figs. 5 (left panel and right panel) include only the type IIa and all type II nebulae, respectively. The oxygen abundance gradient $d[\mathrm{O/H}]/dR$ in the case when only the type IIa nebulae are included in the sample is $-0.017 \pm 0.01\,\mathrm{dex\,kpc^{-1}}$, which is slightly higher than a value $d[\mathrm{O/H}]/dR = -0.012\,\mathrm{dex\,kpc^{-1}}$ obtained by Kholtygin and Milanova [14] by analyzing the O abundance in all of the Galactic PNe belonging to the Galactic disk.

For all PNe of type II the abundance gradient $d[\mathrm{O/H}]/dR = -0.031 \pm 0.014\,\mathrm{dex\,kpc^{-1}}$. This value is close to the oxygen abundance gradient for PNe in the galaxy M31 [8]. It can mean that ensembles of the PNe in our Galaxy and M31 are similar.

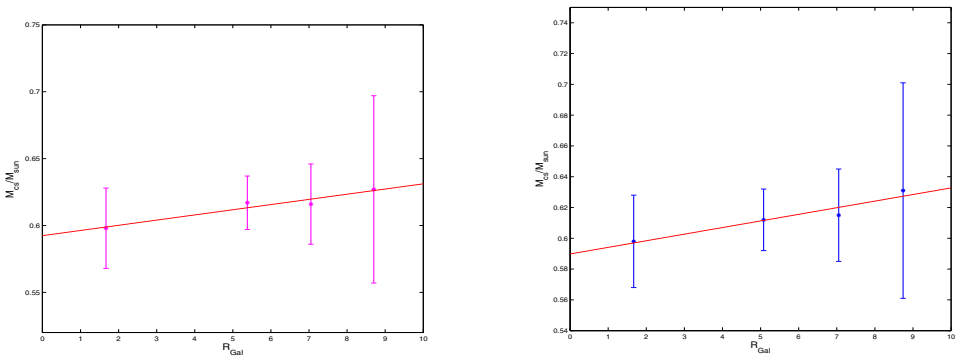


Figure 6 **Left**: averaged masses in type IIa (asterisks) and bulge (filled squares) nebulae vs. their mean Galactocentric distance. The solid line gives a linear fit to this dependence, the dotted lines shows one standard deviation from the fit. **Right**: The same as for left panel, but for all type II nebulae.

We also consider the dependence of the mean mass of the central stars of PNe versus R_g in the same way as it is made for the abundances ratio [O/H]. This dependence is shown in Fig 6. We see the regular enhancement of the mean masses with distances to the Galactic center. The mean mass of central stars of bulge PNe is $\overline{M_\mathrm{CS}} = 0.598\,M_\odot$, whereas for PNe at $R \approx 9\,\mathrm{kpc}$ $\overline{M_\mathrm{CS}} = 0.627\,M_\odot$.

Analysis of Figs. 5 and 6 shows that the bulge objects continue the oxygen abundance vs. galactocentric distance R_g and mean mass of PNe vs. R_g relations for the thin disk nebulae. The following scenario can be suggested to explain these dependences. The Galactic bulge in accordance with the model by Immeli et al. [11] is formed during the early evolutionary phases of the Galaxy. After the bulge formation the thin disk is formed first of all from regions close to the bulge. Then star formation continues in regions farther from the Galactic center. Intense stellar formation both in the bulge and in the thin disk continues at least until an epoch no later than $(4\text{–}6)\times10^9\,\mathrm{yr}$ from the present time.

5 Summary and conclusion

In conclusion we report the result concerning PNe and the chemical evolution of the Galaxy. We present the analysis of the chemical abundances of a PNe sample located in the Galactic bulge. New chemical abundances for the bulge PNe were derived.

The catalogue of element abundances and other parameters of PNe is created. We use this catalogue as a tool for the study of the evolution of different galactic subsystems.

The He, C, N, O, Ne, S, Ar and Fe abundances for the bulge PNe and the ones of Peimbert's type IIa PNe are very close. The oxygen abundances in the bulge PNe continue the dependence of [O/H] vs. Galactocentric distance $R_{\rm g}$ for thin disk PNe of type IIa.

We can propose that the bulge is formed in the early stage of the evolution of the Galaxy in accordance with the Immeli (2004) scenario. After that, the second infall occurs at 4–6 Gyr before the modern era. This infall forms the thin disk finally. The intense enrichment of ISM in the bulge probably continues up to the present day.

Acknowledgements

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