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THE OUTER RING OF THE GALAXY REVEALED BY YOUNG OPEN CLUSTERS

A. M. Mel'nik[1], P. Rautiainen[2], E. V. Glushkova[1] and A. K. Dambis[1]

[1] *Sternberg Astronomical Institute, M. V. Lomonosov Moscow State University, Universitetskij pr. 13, Moscow 119899, Russia; anna@sai.msu.ru*

[2] *Department of Astronomy, University of Oulu, P.O. Box 3000, FIN-90014 Oulun yliopisto, Finland*

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Abstract. The distribution of young open clusters in the Galactic plane suggests the existence of the outer ring R_1R_2' in the Galaxy. The solar position angle $\theta_{\rm b}$ providing the best agreement between the observed and model distribution is $\theta_{\rm b} = 35 \pm 10°$. We compared the $\theta_{\rm b}$ values derived from three different catalogues of open clusters and they appear to be consistent within the errors.

Key words: Galaxy: structure – Galaxy: kinematics and dynamics – open clusters and associations

1. INTRODUCTION

Open clusters are born inside giant molecular clouds, and therefore the concentration of young open clusters in some regions suggests the presence of gas there and traces the positions of spiral arms and Galactic rings, which are often found to be regions of enhanced gas density and star formation.

Studies of Galactic spiral structure are usually based on the classical model suggested by Georgelin & Georgelin (1976), which includes four spiral arms with a pitch angle of ∼12°. The spiral arms in their schema are quite short in the azimuthal direction, winding for ∼180° around the center (Fig. 11 in Georgelin & Georgelin 1976). Since then a number of authors further developed this model (see e.g. Russeil 2003; Vallée 2008; Efremov 2011) by making the spiral structure more symmetrical, extending spiral arms over more than 360° in the azimuthal direction, and attempting to incorporate the bar. The main achievement of this model is that it can explain the distribution of H II regions in the Galactic disk. However, it is difficult to find a galaxy with the spiral structure which includes the bar, regular four-armed spiral pattern, and the arms making more than a revolution around the center (Fig. 1 in Vallée 2008).

There is extensive evidence for the bar in the Galaxy (Benjamin et al. 2005; Cabrera-Lavers et al. 2007; Churchwell et al. 2009; González-Fernández et al. 2012). The general consensus is that the major axis of the bar is oriented in the direction $\theta_{\rm b} = 15$–$45°$ in such a way that the end of the bar closest to the Sun lies in quadrant I. The semi-major axis of the Galactic bar is supposed to lie in the range $a = 3.5$–5.0 kpc. Assuming that its end is located close to its corotation radius, we can estimate the bar angular speed Ω_b, which appears to be constrained to the interval $\Omega_b = 40$–65 km s^{-1} kpc^{-1}. This means that the outer Lindblad resonance (OLR) of the bar is located in the solar vicinity: $|R_{\rm OLR} - R_0| < 1.5$ kpc.

Explaining the kinematics of young objects in the Perseus region (see its location in Fig. 1d) is a serious test for different concepts of the Galactic spiral structure. The fact that the velocities of young stars in the Perseus region are directed toward the Galactic center, if interpreted in terms of the density-wave concept (Lin, Yuan & Shu 1969), indicates that the trailing fragment of the Perseus arm must be located inside the corotation radius (CR) (Burton & Bania 1974; Mel'nik et al. 2001; Mel'nik 2003; Sitnik 2003), and hence imposes an upper limit for its pattern speed $\Omega_s < 25$ km s^{-1} kpc^{-1}, which is inconsistent with the pattern speed of the bar $\Omega_b = 40$–65 km s^{-1} kpc^{-1} mentioned above.

This contradiction disappears in the model of a two-component outer ring R_1R_2', which reproduces well the velocities of young stars in the Sagittarius and Perseus regions (Mel'nik & Rautiainen 2009; Rautiainen & Mel'nik 2010). This model can also explain the position of the Carina-Sagittarius arm with respect to the Sun and the existence of some of the so-called tangential directions connected with the maxima in the thermal radio continuum, H I and CO emission (Englmaier & Gerhard 1999; Vallée 2008), which in this case can be associated with the tangents to the outer and inner rings (Mel'nik & Rautiainen 2011).

Two main classes of outer rings and pseudorings (incomplete rings made up of spiral arms) have been identified: rings R_1 (pseudorings R_1') elongated perpendicular to the bar and rings R_2 (pseudorings R_2') elongated parallel to the bar. There is also a combined morphological type R_1R_2', which exhibits elements of both classes (Buta 1995; Buta & Combes 1996; Buta & Crocker 1991). Simulations show that outer rings are usually located near the OLR of the bar (Schwarz 1981; Byrd et al. 1994; Rautiainen & Salo 1999, 2000).

We suppose that the Galaxy includes a two-component outer ring R_1R_2'. The catalogue by Buta (1995) contains several dozen galaxies with rings R_1R_2'. Here are some examples of galaxies with the R_1R_2' morphology that can be viewed as possible prototypes of the Milky Way: ESO 245-1, NGC 1079, NGC 1211, NGC 3081, NGC 5101, NGC 5701, NGC 6782, and NGC 7098. Their images can be found in the de Vaucouleurs Atlas of Galaxies (Buta, Corwin & Odewahn 2007) at `http://bama.ua.edu/~rbuta/devatlas/`.

The study of classical Cepheids from the catalogue by Berdnikov et al. (2000) revealed the existence of "the tuning-fork-like" structure in the distribution of Cepheids: at longitudes $l > 180°$, Cepheids concentrate strongly to the Carina arm, while at longitudes $l < 180°$ there are two regions of high surface density located near the Perseus and Sagittarius regions. This morphology suggests that outer rings R_1 and R_2 fuse together somewhere near the Sun. We have also found some kinematical features in the distribution of Cepheids that suggest the location of the Sun near the descending segment of the ring R_2 (Mel'nik et al. 2015a,b).

In this paper we compare the distribution of young open clusters taken from different catalogues with the model position of the outer rings.

2. RESULTS

There are several large catalogues of open clusters. For our study we have chosen the catalogue by Dias et al. (2002), which provides the most reliable estimates of distances, ages and other parameters collected from data reported by different authors. The new version (3.4) of this catalogue contains 627 young clusters with ages less than 100 Myr. To show that our results do not depend on the choice of the catalogue, we study also the samples of young open clusters from the catalogues by Loktin et al. (1994) and Kharchenko et al. (2013), which are considered to be homogeneous. Kharchenko et al. (2013) determined the parameters for more than 3000 clusters based on the stellar data from the PPMXL (Röser et al. 2010) and 2MASS (Skrutskie at al. 2006) catalogues using a special data-processing pipeline. Loktin et al. (1994) constructed their own system of parameters (ages, color excesses, distances, and heavy-element abundances) for 330 open clusters from published photoelectric UBV data.

We used the simulation code developed by H. Salo (Salo 1991; Salo & Laurikainen 2000) to construct different types of models that reproduce the kinematics of OB-associations in the Perseus and Sagittarius regions. For comparison with observation we chose model 3 from the series of models with analytical bars (Mel'nik & Rautiainen 2009). This model has a nearly flat rotation curve with $V_c = 215$ km s^{-1}, the bar semi-axes are equal to $a = 4.0$ kpc and $b = 1.3$ kpc. The positions and velocities of 5×10^4 model particles (gas+OB) are considered at time ~1 Gyr from the start of the simulation. We scaled this model and turned it with respect to the Sun to achieve the best agreement between the velocities of model particles and OB-associations in five stellar-gas complexes identified by Efremov & Sitnik (1988).

Fig. 1(a) shows the distribution of young ($\log \mathrm{age} < 8.00$) open clusters from the catalogue by Dias et al. (2002) and that of model particles in the Galactic plane. Figs. 1(b) and (c) show similar plots for the catalogues by Kharchenko et al. (2013) and by Loktin et al. (1994), respectively. Generally, all three distributions demonstrate lower surface density of clusters in quadrant III: young objects within $r < 1.5$ kpc concentrate to the Sun, while more distant objects distribute nearly randomly over a large area. The lack of distant objects in quadrant III is a crucial point for our model, because the outer rings are located mostly in three other quadrants: I, II, and IV.

Fig. 1(d) shows the distribution in the Galactic plane of young open clusters and rich OB-associations. Only OB-associations containing more than 30 members ($N_t > 30$) in the catalogue by Blaha & Humphreys (1989) are shown. The figure also indicates the positions of the Sagittarius, Scorpio, Carina, Cygnus, Local System, and Perseus stellar-gas complexes identified by Efremov & Sitnik (1988). We can see that the Sagittarius and Scorpio complexes can be associated with the ring R_1. The Perseus complex and Local System can be associated with the ring R_2. The Carina region lies in-between the two outer rings, where they seem to fuse together.

The simulated distribution can be fitted by two ellipses oriented perpendicular to each other. The outer ring R_1 can be represented by the ellipse with the semi-axes $a_1 = 6.3$ and $b_1 = 5.8$ kpc, while the outer ring R_2 fits well the ellipse with $a_2 = 8.5$ and $b_2 = 7.6$ kpc. These values correspond to the solar Galactocentric distance $R_0 = 7.5$ kpc. The ring R_1 is stretched perpendicular to the bar and the ring R_2 is aligned with the bar, and therefore the position of the sample of open clusters with respect to the rings is determined by the position angle θ_b of the Sun with respect to the major axis of the bar. We now try to find the optimum angle θ_b providing the best agreement between the positions of the open clusters and

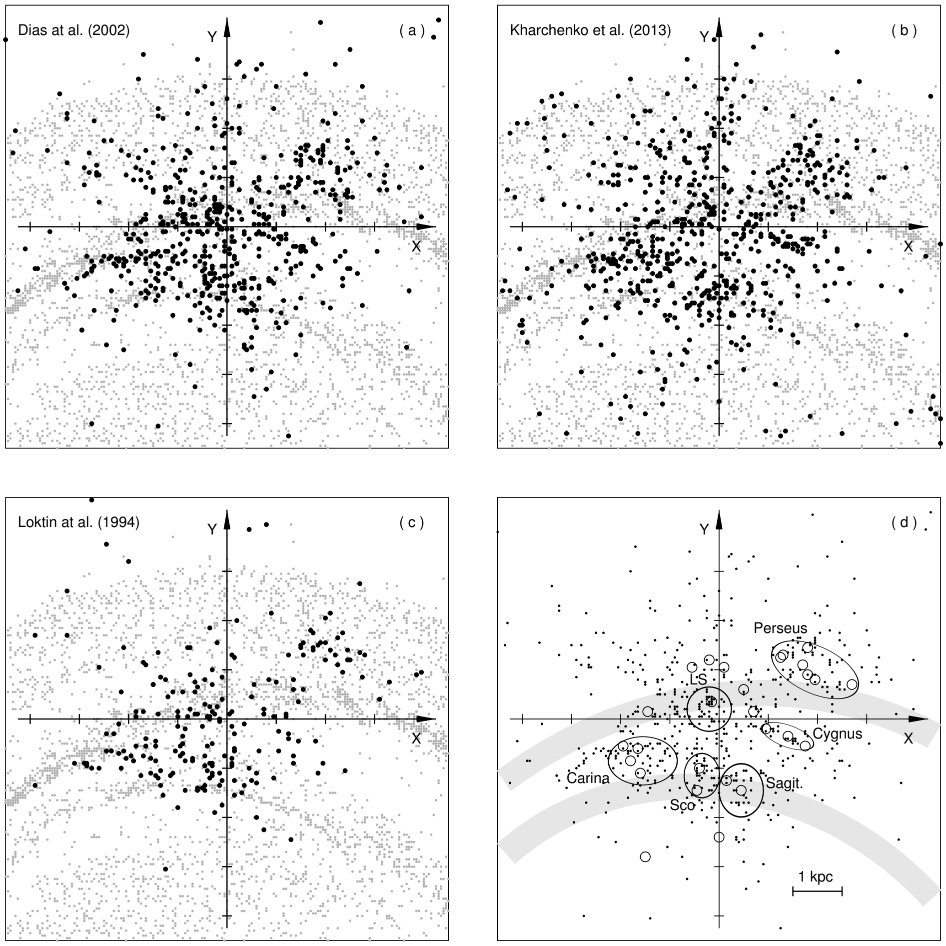

Fig. 1. (a) Distribution of young (log age < 8.00) open clusters (black circles) from the catalogue by Dias et al. (2002) and model particles (grey dots) in the Galactic plane. (b, c) Cluster parameters are adopted from the catalogues by Kharchenko et al. (2013) and Loktin et al. (1994), respectively. (d) The distribution of young open clusters from the catalogue by Dias et al. (2002) (black dots) and rich OB-associations (open circles) in the Galactic plane. The locations of the outer rings R_1 and R_2 are indicated by the gray arches. The positions of the Sagittarius, Scorpio, Carina, Cygnus, Local System (LS), and Perseus stellar-gas complexes are drawn by ellipses. The Sagittarius and Scorpio complexes can be associated with the ring R_1. The Perseus complex and Local System are associated with the ring R_2. The Carina region lies in-between the two outer rings, where they seem to fuse together. The Sun is at the origin. The positions of model particles are drawn for $\theta_b = 45°$. The X-axis points in the direction of the Galactic rotation and the Y-axis is directed away from the Galactic center.

the orientation of the outer rings.

Fig. 2 shows the χ^2 functions – the sums of normalized squared deviations of open clusters from the outer rings – calculated for different values of the angle θ_b. For each cluster we determined the minimum distance to each of the outer

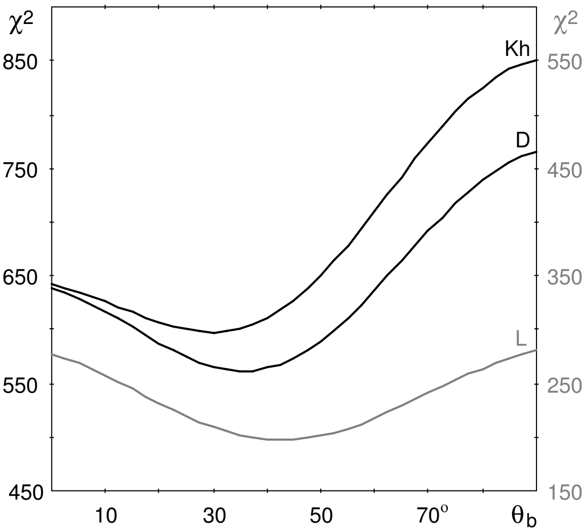

Fig. 2. The χ^2 functions calculated for different solar position angles θ_b with respect to the major axis of the bar. The letters "D", "Kh", and "L" denote the curves calculated for young open clusters from the catalogues by Dias et al. (2002), Kharchenko et al. (2013), and Loktin et al. (1994), respectively. The χ^2 curve calculated for the data by Loktin et al. (1994) is shown by the gray line, which is drawn for another range of the χ^2 values shown on the right vertical axis in gray. The three χ^2 curves reach their minima at $\theta_\mathrm{b} = 35 \pm 3°$ (D), $30 \pm 4°$ (Kh) and $43 \pm 3°$ (L).

Table1. Parameters of the samples.

Catalogue	N	σ	θ_b
Dias et al. (2002)	564	0.80 kpc	$35 \pm 3°$
Kharchenko et al. (2013)	613	0.81 kpc	$30 \pm 3°$
Loktin et al. (1994)	200	0.68 kpc	$43 \pm 3°$

rings and then adopted the smallest of the two values. We can see that three χ^2 functions computed for data from the catalogues by Dias at al. (2002), by Kharchenko et al. (2013), and by Loktin et al. (1994) reach their minima at $\theta_\mathrm{b} = 35 \pm 3°$, $30 \pm 4°$, and $43 \pm 3°$, respectively. Table 1 lists the parameters of the observed sample: the number of clusters N, the standard deviation σ of a cluster from the model position of the outer rings, and the angle θ_b corresponding to the minimum on the χ^2 curve. Averaging these three values gives the mean estimate $\theta_\mathrm{b} = 36 \pm 7°$.

An analysis aimed at investigating eventual bias of our method revealed a small ($\pm 5°$) systematic shift: the overdensity in the 1-kpc region from the Sun ($r < 1$ kpc) increases the estimated θ_b, whereas objects located in the direction of the anticenter at $y > 1.5$ kpc decrease it. The upper limit for the uncertainty including the systematic $\pm 5°$ and random $\pm 5°$ errors appears to be $\pm 10°$ (Mel'nik et al. 2016).

3. CONCLUSIONS

We studied the distribution of young open clusters with the data adopted from the catalogues by Dias at al. (2002), Kharchenko et al. (2013), and Loktin et al. (1994) in terms of the model of the Galactic ring R_1R_2'. The solar position angle that provides the best agreement between the distribution of observed clusters and that of model particles appears to be $\theta_b = 35°$, $30°$, and $43°$, respectively. It is "the tuning-fork-like" structure in the distribution of young clusters that determines the angle θ_b being close to 45°. At longitudes $l > 180°$ (quadrants III and IV) the two outer rings fuse together to form one spiral fragment – the Carina arm, whereas at longitudes $l < 180°$ (quadrants I and II) the two outer rings exist separately producing the Sagittarius and Perseus arm-fragments.

Note that our study of the sample of classical Cepheids yields $\theta_b = 37 \pm 13°$ for the position angle of the Sun with respect to the bar's major axis (Mel'nik et al. 2015a,b). The cause of this coincidence is the presence of a tuning-fork-like structure also in the Cepheid distribution.

We studied also the distribution of young open clusters and OB-associations with negative radial residual velocities V_R, which within 3 kpc of the Sun must outline the descending segment of the ring R_2. Clusters and OB-associations concentrate to the fragment of the leading spiral arm (see also Mel'nik 2005), what suggests that the Sun is located near the descending segment of the ring R_2. Furthermore, the azimuthal velocity V_T of these clusters and associations decreases with increasing x coordinate – a trend expected for objects of the ring R_2. For more details, see the full paper by Mel'nik et al. (2016).

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