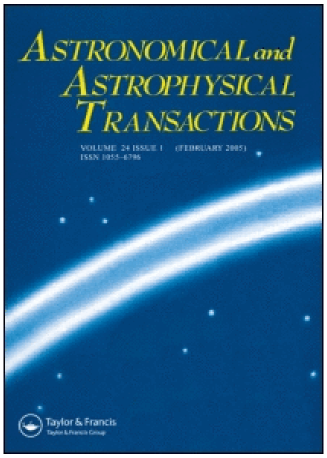

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OPEN CLUSTERS AS SPIRAL STRUCTURE TRACERS IN OUR GALAXY

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Using a homogeneous sample of 245 young galactic clusters, the characteristics of the spiral pattern of our Galaxy are estimated. The rotation velocity of the spiral pattern is determined to be $\Omega_P = 21.3$ km/s/kpc, and the pitch angle of the best-fit logarithmic spiral is $i = 7^\circ.8$. The Sagittarius and Perseus arms form a two-armed structure, whereas the Orion arm probably represents the next even mode of the spiral wave. The majority of galactic clusters fit well the obtained spiral structure, which supports the idea of the density-wave driven star formation.

KEY WORDS open clusters, galaxy, spiral structure.

1. INTRODUCTION

In the framework of the program of redetermination of the characteristics of galactic open clusters (OCL) undertaken on the basis of published UBV-photometry and the computer routine prepared for this purpose (Loktin and Matkin 1990; Matkin and Loktin 1990), we have compiled a catalogue containing homogeneous estimates of the distance moduli and ages for more than 320 galactic clusters. In this continuously updated catalogue, which will be published later, young clusters form a representative sample which can be used for galactic structure studies, in particular for the determination of the characteristics of the spiral pattern of our Galaxy.

It is well known that young OCL are good tracers of the spiral pattern because of a good quality of the distance and age estimates. An example of the picture of the spiral arms on the galactic plane can be found in Becker and Fenkart (1970) where young OCL delineate three distinct segments of spiral arms, namely the so-called Sagittarius–Carina arm, Orion and Perseus arms. During the last decade, there arised serious doubts in interpreting the distribution of young OCL on the galactic plane—see, e.g., Janes and Adler (1982), where no distinct spiral pattern was revealed. A similar result was obtained by Lyngä (1982). But Mdzinarishvili (1990) demonstrated that the inhomogeneity of these two compillative catalogues and the random errors of distance determinations can smear the really existing structure. In order to clarify the situation, we decided to use our nearly homogeneous data set on OCL distances and ages to obtain new information on the spiral structure of our Galaxy.

2. THE SAMPLE AND METHOD

We have accepted here that spiral arms really exist in the Galaxy and that the formation of the clusters is driven by spiral density waves, and determine the basic parameters of the spiral pattern, namely the pattern rotation velocity and the pitch angle of the spirals. For this purpose, we fit the apparent arm segments by a logarithmic spiral, so that the young objects are presumed to lie at the positions on the galactic plane given by

$$R = D_0 \exp[b(\phi_0 + \theta + (\Omega_G - \Omega_P)t], \tag{1}$$

provided the random motions have been neglected. In Eq. (1), R denotes the galactocentric distance, D_0 is the scale factor, ϕ_0 is the phase of the spiral, Ω_P is the angular velocity of the spiral pattern which is accepted to rotate as a rigid body, Ω_G is the angular velocity of rotation of the galactic disk at radius R, t is the age of the cluster, $b = \tan i$ with i the pitch angle of the spiral, and θ is the galactocentric azimuthal angle of the cluster. The term $(\Omega_G - \Omega_P)t$ accounts for the displacement of an object from the spiral arm because of the difference between the rotational velocities of the spiral pattern and the galactic disk.

Rewriting (1) yields

$$(1/b)\ln(R/D_0)\phi_0 + \Omega_G t - \Omega_P t + \theta, \tag{2}$$

and, introducing notation $x = \ln(R/D_0)$, $y = \phi_0 + \Omega_G t + \theta$ and $B = 1/b$, we obtain a linear form

$$Bx + \Omega_P t - y = 0, \tag{3}$$

which can be used for the estimation of Ω_P and B using the least squares method. The value of D_0 should be chosen as to minimize the sum of deviations from (3). The value of ϕ_0 is chosen to be equal to zero because the pitch angle of the spirals is small, and this choice is confirmed by our results.

For the rotation curve of the Galaxy, we have chosen the following simple expression:

$$\Omega_G(R) = 62.5/(1 + 0.21R^2), \tag{4}$$

where numerical values of the coefficients correspond to the following values of Oort's constants of Galactic rotation: $A = 15$ km/s/kpc and $B = -10$ km/s/kpc; the galactocentric distance of the Sun is chosen to be $R_0 = 8.5$ kpc. The choice of an appropriate rotation curve is a difficult task because even recent results are hardly consistent with each other; that is why we have chosen the simplest but plausible form of the rotation curve. The particular choice of the rotation curve is not crucial because of the moderate interval of galactocentric distances used in our investigation.

Our sample of young clusters consists of 251 objects with the age logarithms less than 8.0. We use as many clusters from our catalogue as possible keeping in mind the differences in the quality of the data for different clusters. These young clusters do not show any appreciable shift from their parent spirals associated with their random motion, and we avoid the difficulties of assigning older clusters to particular fragments of the spiral arms, which is a difficult problem even for younger clusters when the characteristics of the spiral pattern are not known.

Firstly, we have attributed 107 clusters to the Sagittarius arm, 108 ones to the Orion arm and 36 to the Perseus arm.

The next step is the choice of the type of the spiral pattern, namely the number of the arms, or, in other words, the phase shifts for each arm (see Eq. (1)). We have performed three least squares solutions to solve this problem. For the first solution, we used the clusters of the Perseus and Sagittarius arms only, the former group of clusters being shifted by π in phase. This value of the phase shift defines a two-armed spiral pattern. The problem has a solution of this type, which means that a two-armed structure can be real. For the second solution, we adopted the phase shift of π for the Orion arm clusters and 2π for the Perseus arm, which defines a two armed pattern embracing the Orion arm. The solution does not exist in this case, namely there is no value of D_0 to minimize the deviations from (3). For the third solution, we used the shift π for the clusters of the Perseus arm and $\pi/2$ for the objects in the Orion arm, which defines a four-armed pattern. In this case the solution exists and the results for Ω_P and i coincide with those for the first solution. We can conclude that our sample is consistent with a four-armed sprial pattern in our Galaxy. After the preliminary estimation of D_0, b and Ω_P we rejected six clusters with the largest deviations and refined the attribution of the clusters to particular arms. Then we finally have a sample of 245 clusters, with 106 clusters attributed to Sagittarius arm, 100, to the Orion arm and 39, to the Perseus arm.

3. RESULTS AND DISCUSSION OF ERRORS

The least squares solution of the form (3) for the case of a four-armed pattern yields the following estimates: $D_0 = 7.2$ kpc, $\Omega_0 = (22.4 \pm 0.3)$ km/s/kpc, $i = 8^\circ \cdot 2 \pm 1^\circ \cdot 4$. But we have to recognize that our regression model does not agree well with the classic least squares procedure because of random errors on both sides of Eq. (3), and the resulting estimates may be biased. We solve this problem by numerical experiments, which provide us corrections for our estimates.

It is worth noting that numerical experiments yield the real estimates of the accuracy of the distances and ages of our sample clusters because for the simulation of the distribution of the clusters on the galactic plane we have to choose the values of the mean random errors in our data. We have estimated the mean error of the distance moduli to be $0^m \cdot 27$, and that for the age logarithm, 0.20. These are of course, upper estimates of the mean random errors because of, for example, probable systematic errors, depending on the age, in the distance moduli.

The corrected estimates of the spiral pattern parameters are $D_0 = 7.2$ kpc (no correction required), $\Omega_P = 21.3$ km/s/kpc, $i = 7^\circ \cdot 8$. Then we verify once more the reality of the Orion arm, because numerous, well-studied nearby clusters can form a spurious arm. For this purpose we have excluded the clusters belonging to this arm from the sample. Then the corrected estimates of the spiral pattern parameters are $D = 7.4$ kpc, $\Omega_P = (21.2 \pm 0.3)$ km/s/kpc and $i = 6^\circ \cdot 8 \pm 1^\circ \cdot 6$. The statistical insignificance of the difference between the solutions obtained with and without the Orion clusters and the weak increase of the root mean square deviation means that the clusters of the Orion arm fit well the chosen form of the spiral pattern.

The distribution of the clusters of our sample in projection on the galactic plane is shown in Figure 1. The scatter around the spiral arms is large in spite of the

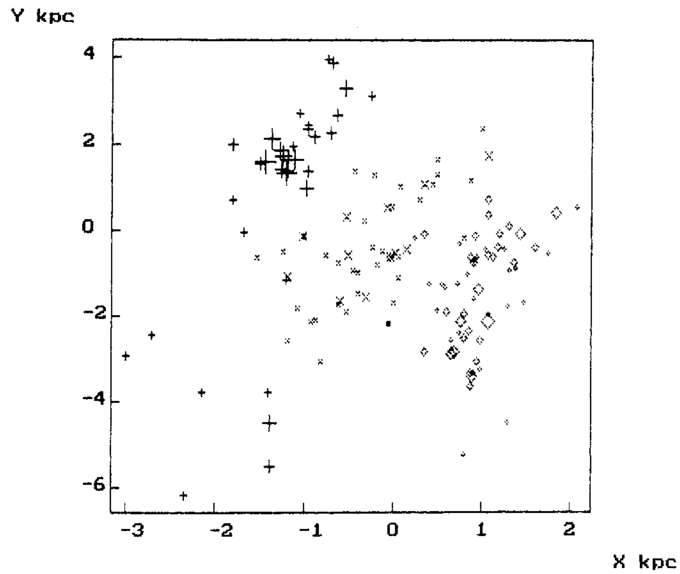

Figure 1 Distribution of OCLs in projection on the Galactic plane. The clusters belonging to the Sagittarius arm are labelled by rhombuses, those of the Orion arm clusters, by crosses, and those of the Perseus arm, by plusses.

high quality of the data. We tried to shift the clusters according to the magnitude of the age effect, but the result was poor—the scatter remains nearly the same. This implies that some effects cause a nonzero scatter. First, one should look for the effects of the systematic errors of various kinds in our estimates of the spiral structure parameters. With the help of further numerical simulations, we treated the following possible effects of systematic errors:

(1) A wrong choice of the rotation curve of the galaxy

(2) A wrong value of R_0 or, in other words, an error in cluster distance scale

(3) An error in the cluster distance scale depending on the age,

(4) Galactic abundance gradient which causes an error in the cluster distance depending on the galactocentric distance

Numerous numerical experiments performed lead us to the conclusion that none of the mentioned effects cause appreciable bias in our estimates of the spiral pattern parameters and affect the scatter around the calculated spiral arms.

To decide how much scatter can be attributed to random errors, consider the deviations from Eq. (3) in more detail. We should keep in mind that these deviations are the displacements of the clusters from the spirals in the phase coordinate (see Eqs. (1)–(3)). In Figure 2 these deviations are represented as a function of the galactocentric distance R. It is interesting to note that the deviations vary nearly linearly with R, with a very small scatter. This means that most of OCL in our sample fit perfectly well the rotating spiral structure. We can say, in addition, that our artificial sprials have somewhat wrong values of the pitch angle i, though the error of i is not so great because of the tightness of the

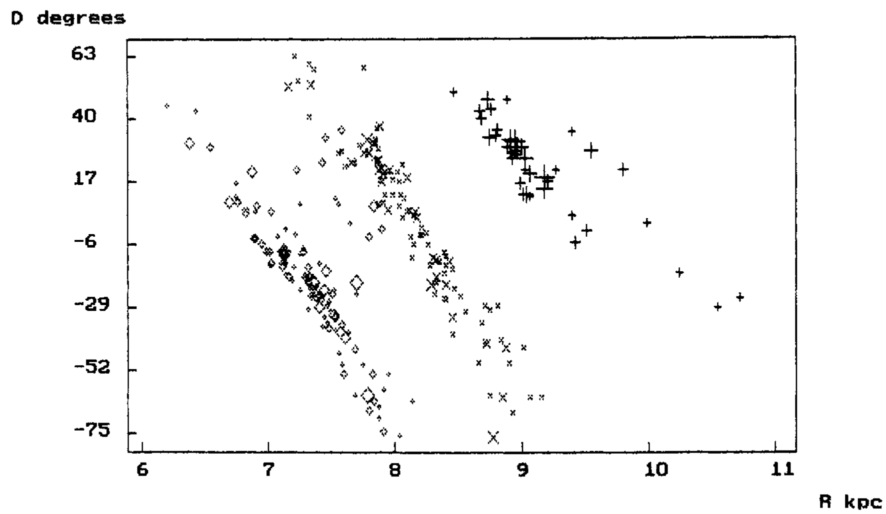

Figure 2 The deviations in the phase angle versus the galactocentric distance for the clusters of the sample. The notation is the same as in Fig. 1.

spirals (indeed, in this case any weak deviation from the spiral along the R direction causes a large deviation in phase). We can conclude that a logarithmic spiral is not a quite adequate approximation to the arms in our Galaxy. One can say that a logarithmic spiral cannot represent the pitch angle and location for several spiral arms simultaneously. We should mention that the solution for the Sagittarius arm clusters alone gives a considerably larger value of the pitch angle ($i = 26.8$) but nearly the same value $\Omega_P = 22.7$ km/s/kpc as compared to the case of all three arms included. To try another form of the spiral, we performed the derivation of spiral pattern parameters for the form based on the Archimedian spiral:

$$R = D_0(\phi_0 + \theta + (\Omega_G - \Omega_P)t)^n. \tag{5}$$

However, our attempts to obtain the spiral pattern parameters for such spirals failed. This means that this model cannot fit the open cluster data for all three arm segments simultaneously.

Figure 2 refers to our original sample, without any verification of the attribution of the clusters to proper spiral arms. One can see that such a figure can help in correcting the attribution. The size of the symbols in Fig. 2 is proportional to the statistical weight of the particular cluster. We can see that most of the clusters with high-quality data group around straight lines having nearly equal inclinations.

4. CONCLUSIONS

Using homogeneous data on open clusters taken from our newly created catalogue, we have estimated the parameters of the spiral pattern in our Galaxy. The values derived for a best-fit logarithmic spiral are: the rotation velocity of the spiral structure, $\Omega_P = 21.3$ km/s/kpc; the pitch angle of spirals, $i = 7° \cdot 8$; the scale parameter, $D_0 = 7.2$ kpc. For these values of the parameters and the adopted galactic rotation curve, the corotation radius is between the Orion and Perseus arms. The Sagittarius and Perseus arms form a two-armed structure, while the Orion arm is real but belongs to the even mode of the next higher order. A logarithmic spiral with a common origin for all arms cannot represent well the spiral arms of our Galaxy and we have to search for a more sophisticated model.

Most of the clusters of our sample are located close to their parent spirals, which supports the idea of the spiral-wave-driven star formation. This is expecially clear in Fig. 2 where one can see a small dispersion of points around the "arms". To obtain a more precise picture of the spiral pattern in our Galaxy one needs better data for remote young and intermediate-age open clusters.

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