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Rotation curve of the Galaxy from the motions of open star clusters

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Series of numerical statistical experiments were made to study the effect of random and systematic errors in the estimation of the rotation curve obtained using optical data. It was shown that modern proper motions of the open clusters contain enough information about the rotation of the Galaxy. By means of the radial velocity and proper motion data of the open clusters together with modern observational data of neutral hydrogen for the inner part of the Galaxy, the rotation curve for the interval of distances $R = 3$–15 kpc was constructed. The obtained rotation curve is not increasing.

Keywords: Galaxy; Open clusters; Rotation curve

1 Introduction

Rotation curve (RC) of the Galaxy plays a key role in the investigations of galactic structure, kinematics and dynamics. It contains the information for construction the models of mass distribution in the Galaxy and is often used for distance determinations for gaseous objects. Any investigation of noncircular motions in the Galaxy needs suitably smoothed rotation curve.

This important function is known at present with insufficient completeness, especially for large distances from the rotational axis of the Galaxy. In the exterior region of the galactic disk the tangent point method is inapplicable. The problems arising with the determination of the rotation curve can be seen in [1]. In the paper cited Fig. 1 compares the rotation curves determined from radio data and optics. These curves coincide well in inner region of the Galaxy but are very uncertain for its periphery.

It is well known that for outer parts of the Galaxy different methods are usually used for the determination of rotation curve. The inner part of RC is determined from the measurements of radioemission of HI and CO by the tangent point method (see [2–4] among others). For outer Galaxy this function is estimated mainly on the base of stellar distances determined in optical spectral range albeit precise radial velocities may be measured in radio. As examples of the estimation of RC we can mention Bobylev et al. [5] and Zabolotskikh et al. [6] among those referred to above.

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Note that the total characteristics of all estimates of this important function are some depression near $R = 10$ kpc (distance from rotational axes of the Galaxy) and then a steep rise in the peripheral zone of the Galaxy. But the most recent result based on distances with least errors is the estimate of Reid et al. [7] where distances were determined from the determination of trigonometric parallaxes of maser sources from the VLBA observations. This suggests that important role for the estimation of RC may play the errors in distances of objects used. Bearing in mind the idea of examination of influence of the errors in distances we decided to make new attempt of estimation of RC on the basis of distances and motions of open clusters. Besides this work was activated by the publication of new data on cluster radial velocities (Mermilliod et al. [8]) and the redetermination of cluster parameters on the base of 2MASS photometry and new proper motions by the authors (not published). The test of utility of proper motions of distant objects was another goal of this work.

2 Statistical numerical experiments

As a first step we have to investigate the influence of random errors in basic data on the process of estimation of RC. The fact that random errors in distances lead to biases in estimated kinematical parameters was emphasized long ago, and Feast and Shuttleworth [9] correction factors for their samples. But application of the correction factors is not an adequate procedure because these factors were derived for the case of small errors and do not account for the shape of distribution of distances.

To clear the influence of random errors on the estimation of RC we executed a series of numerical experiments. For every experiment we use artificial sample of 5000 "clusters" and for every cluster we created "observational data" using adequately distributed random numbers. For galactic longitudes we calculated uniformly distributed numbers in the interval 0°–360°, galactic latitudes are taken to be zero. Every artificial cluster had distance from the Sun r calculated as random number with exponential distribution density $f \propto \exp(-ar)$ with $r \in [0, 3]$ and the value of $a = 0.2$ kpc^{-1} was chosen for best fit of the distribution of cluster distances of our real sample. Radial velocities and proper motions for artificial clusters were calculated from Bottlinger's formulae

$$V_r = (\omega - \omega_O) R_O \sin l \cos b, \tag{1}$$

$$V_l = 4738 \cdot \mu_l \cdot r = (\omega - \omega_O) R_O \cos l \cos b - r\omega \cos b$$

with the use of RC taken from the previous paper of the authors [10]. In the expressions (1) V_r and V_l denote the values of radial and tangential velocities corrected for solar motion, $\omega = \omega(R)$ is the curve of rotational frequencies and ω_O is the same value for the solar circle, R_O is the distance of the Sun from rotational axis of the Galaxy, r – distance of object from the Sun, μ_l – component of proper motion in longitude.

Normally distributed random values with standard deviations 15 km/s were added to radial velocities of artificial points to imitate the sum of peculiar velocity and random error in V_r. It is senseless to treat the errors in V_r separately because of the great variations of the accuracies of observed radial velocities from cluster to cluster in

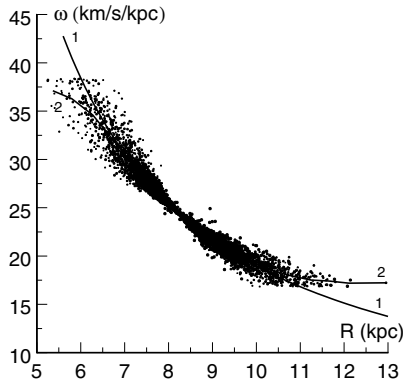


Figure 1 The estimates of rotational frequency ω for the points of artificial sample with radial velocities versus distance from the rotational axis of the Galaxy. Errors are inserted only in distances.

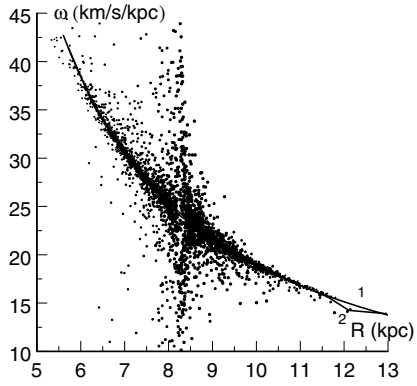


Figure 2 The result of numerical experiment with the sample of proper motions. The errors in distances and proper motions plus peculiar velocities are inserted in data. The great dispersion for estimates near $R = R_0$ is suppressed by the use of weights (see text).

real sample. As a mean error in proper motions the value of 0.24 mas/year was used which was added to the value of 12 km/s as standard deviation of peculiar velocities.

Within the scope of this work we used the values of constants: $R_O = 8.3$ kpc [11] which is close to that recommended by IAU value of 8.5 kpc but determined in the same distance scale as the values of cluster distances of our samples. The value of rotational frequency on Sun's distance was taken to be $\omega_O = 24.5$ km/s/kpc [12].

For the simulation of the influence of random errors in distances on the estimation of RC we inserted normally distributed errors in distance modulus of artificial clusters because just the modulus are determined by photometric methods and spectral parallaxes. The experiments were made with various values of dispersion of errors in distances.

Figure 1 shows the results of experiment where only errors in distances were inserted in the values of artificial sample with radial velocities. The large value of

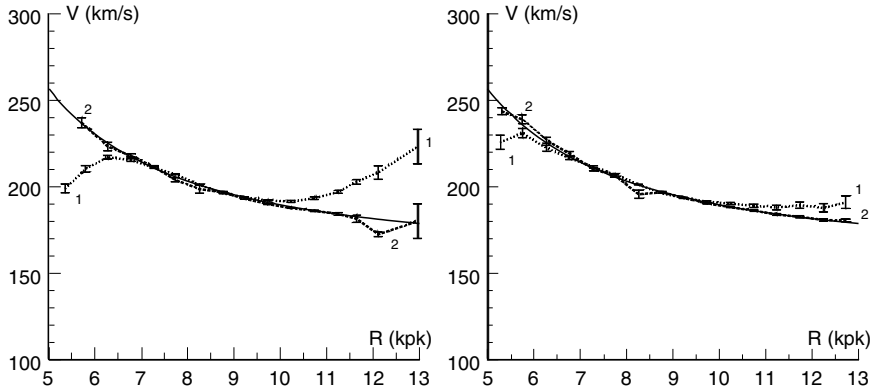


Figure 3 The results of numerical experiments expressed in the form of linear velocities of Galaxy rotation. Left panel – for radial velocities, right panel – for proper motions. Solid curve denotes initial RC, dotted curve (1–1).

standard deviation for this error $0^m.6$ was used to do the effect more marked. This value of standard deviation nearly three times exceeds the mean error of distance determination for open clusters but is specific for OB-stars in complex environment. In the figure two solid lines represent the initial RC (line denoted by 1–1) and mean values of estimates of ω in the 0.5 kpc intervals of R (curve 2–2). The bias growing with R for objects with large distances from the Sun is obvious. This bias is caused by the decline of density of points to the periphery and is a property of the distribution of distances but not the method of estimation.

The results of one of the experiments with proper motions sample are shown in Fig. 2. For large distances from solar circle one can see lesser dispersion of points because of small random errors in observed proper motions of open clusters and the bias caused by the errors in distances is absent. There is some compensation for the influence of errors in the second Bottlinger's formula which puts forward proper motions in comparison with radial velocities for kinematical problems of the Galaxy.

The results of experiments expressed in linear rotational velocities are shown in Fig. 3. The left panel of Fig. 3 shows the estimation of RC for artificial sample with the values of R truncated by 11 kpc and 6 kpc to display the distribution dependence of errors influence on the estimation. Curve (1–1) on left panel related with radial velocities shows apparently larger bias than that of right panel in the case of pure exponential distribution of distances. Even in the case of truncated distribution (curves 2–2 on both panels) the bias in for case of proper motions is absent.

Panels of Fig. 4 show the results of experiment with complete set of the errors. The random errors are inserted in distances, radial velocities and proper motions, and the peculiar motions are inserted too. Such plots may be used for the design of experiments but for estimation of RC we have to use the existing samples.

Summarizing the results of our statistical numerical experiments we come to the conclusions that:

1. Random errors in distances of objects used for the estimation of RC lead to

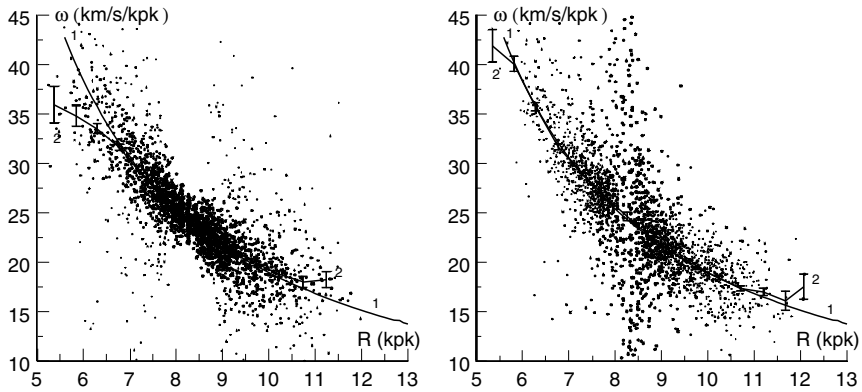


Figure 4 The results of experiment with errors inserted in distances, radial velocities (left panel) and proper motions simultaneously with peculiar motions.

inevitable bias of the curve for large distances from the Sun in the case of radial velocities based estimation. This bias strongly depends on the form of distances distribution, that is why the correction factors used earlier by Feast and Shuttleworth [9] are inadequate.

2. Modern proper motions of open clusters carry sufficient information for the kinematical investigations of galactic disk even for the most remote clusters. In conjunction with the weak influence of errors in distances on the estimation of parameters of kinematical models the proper motions have come forward as basic data for such problems.

To our regret the experiments cannot provide the corrections to the estimate of RC because the observational data on open clusters have strongly variable errors and consequently cannot be characterized by one value of dispersion. Moreover the dispersion of the errors may not be constant because of usual dependence on the distance from the Sun. The additional difficulties arise from the unknown form of real distribution of distances.

3 Estimation of the rotation curve of the Galaxy

We can see from the numerical experiments that the bias caused by random errors in distances is real and may account for the rise of RC in the peripheral zone of the Galaxy. It is a pity that we cannot use the corrections from the numerical experiments directly because the accuracies of cluster distances are different for various clusters and can not be characterized by one value of dispersion. More over we may suppose that this dispersion is growing with distance because e.g. of complication of interstellar absorption corrections. Besides that the genuine distribution of distance errors is not known at all. The bias originated from distance random errors is inherent to the distribution of distances.

Another cause of bias in the determination of RC originates from the method of estimation. It is known (see e.g. [13]) that in the presence of random errors in

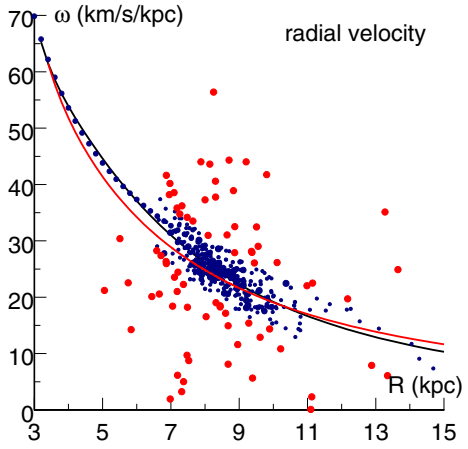


Figure 5 The estimates of rotational frequencies for clusters of radial velocities sample. Red line – initial solution for all clusters of the sample, blue line – final solution after rejection deviant points. Red circles denote rejected clusters.

independent variables the estimates of regression model parameters by the list squares method are biased. This means that any method of the estimation may cause a bias. In this situation the only thing that we can do is to use some robust method to diminish the bias by suppressing the influence of deviant points.

For the estimation of RC of our Galaxy we use the data on open clusters. The cluster positions and distances from the Sun are chosen from the current version of "Homogeneous catalogue of open clusters parameters" [14] and some from the catalogue of Dias et al. [15]. To our collection of cluster radial velocities we add the values from [8]. The sample of clusters with radial velocities appeared to be 434 clusters. Proper motions are taken from [12], and some new unpublished determinations for the region of anticenter are added which gives 415 clusters. Age based selection is not performed because of low fractions of old clusters in the samples.

The motions of clusters are corrected for the solar motions with the components $U_O = 8.5$ km/s, $V_O = 14.8$ km/s, $W_O = 7$ km/s [16], which were calculated relatively for stars with near circular galactic orbits. The well-known solar motion of Dehnen and Binney [17] is not used because it is related to a tiny volume of the Galaxy around the Sun.

Here we estimated RC in the form of polynomial in reciprocal powers of distances from the rotational axis:

$$\omega = a/R + b/R^2 + c/R^3 + d/R^4. \tag{2}$$

This approach gives a smooth curve without wavy distortion of velocity field caused probably by spiral arms. The coefficients of polynomial (2) are determined by weighted least squares method separately for the samples based on radial velocities and proper motions.

For every cluster we estimated the value of rotational frequency ω from appropriate Bottlinger's formula. Figure 5 shows these estimates for radial velocities sample.

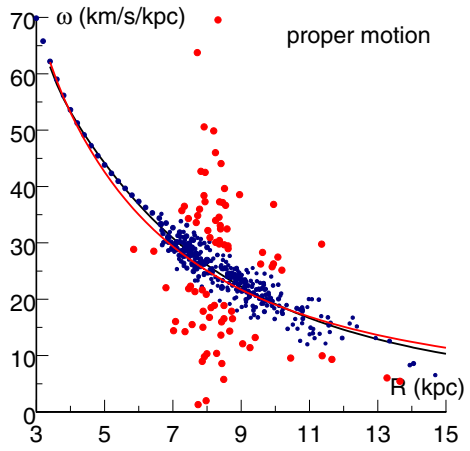


Figure 6 The same as in Fig. 5 for proper motions sample. The behavior of RC for large R is determined by the same three clusters as for radial velocities sample.

Here in the figure small filled circles denote cluster points, large random points are estimates, rejected during the estimation of RC, set of large circles in left part of the figure denotes data from HI radio observations of McClure-Griffiths and Dikey [4]. These 28 points are used to get a more precise estimate of RC for inner Galaxy where our cluster samples fail to give reasonable results and are taken from the mean line of Fig. 8 in this work.

We can notice some shift of these points with larger values of R in the bulk of points of our sample which is the consequence of another value of solar motion used by McClure-Griffiths and Dickey [4]. As we use the least squares method for estimation of RC the contribution of deviant points is minimal.

For the solution we used weights accounting for the dependence of amount of information about Galaxy rotation on galactic longitude: $p_v = \mid \sin l \cos b/\sigma_{Vr} \mid$ for radial velocity sample and $p_\mu = \mid 10 \cos l + 1 \mid /\sqrt{(\sigma_{\mu\alpha}^2 + \sigma_{\mu\delta}^2)}$ for proper motion sample, these values are multiplied by the weights proportional to the quality of observational data.

The method used for obtaining the final solution for RC is the progressive rejection of deviant clusters from the sample. We get the least squares method solution for the whole sample and reject some deviant points, get a new solution, reject some more points and so on. The dependence of rms deviation on the number of points in the sample prompts where we can finish the process. For two of our samples we rejected near 40% clusters. Sequential rejection is the use of the main idea of robust methods – the suppression of the influence of the wings of distribution on the estimation of mean values.

Figure 6 shows the estimation of RC from the proper motions sample. This plot is quite similar to Fig. 5. This means that proper motions are a really good base for kinematical investigations (see the dispersion of points about the curves). We can see that the rejection of deviant points shifts curves in the same direction both for radial velocities and proper motions.

Table 1. Coefficients of the polynomial approximating the curve of rotational frequencies for our Galaxy.

Coefficients	a (km/s)	b (km/s/kpc)	c (km/s/kpc^2)	d (km/s/kpc^3)
Sample	57.1	2198.3	-9429.6	12657.0
V_r	±28.9	±459.8	±2262.8	±3496.0
Sample	3.37	3066.6	-13683.1	19117.0
μ_l	±26.1	±427.9	±184.8	±3498.1
Weighted	30.2	2632.4	-11556.4	15887.0
mean	±27.5	±443.9	±2223.8	±3497.0

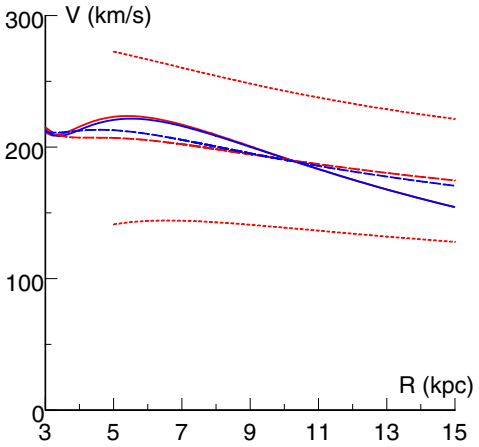


Figure 7 Linear velocities rotation curves for radial velocities and proper motions samples before and after the rejection procedure implemented.

The coefficients of the polynomial approximating the rotation frequencies curve are given in Table 1 both for radial velocities and proper motions samples and mean curve. We can claim that this polynomial is useful for the distance interval of $R =$ 3–15 kpc.

The results of our calculations in the form of linear velocities are shown in Fig. 7. Here solid curves denote the final solutions of the RC for radial velocities and proper motions samples which became nearly coincident after the rejection of deviant points from the samples separately. Dashed curves show the starting curves obtained for the whole samples, and dotted curves show 2σ error corridor for the radial velocities starting sample.

4 Discussion

In conclusion we have to say that the determination of rotation curve of the Galaxy on the base of large samples of open clusters radial velocities and proper motions in

conjunction with the set of numerical experiments allow us to make definite conclusions:

1. Proper motions of distant open clusters contain sufficient information on galactic rotation to be used in kinematical investigations on a par with radial velocities. Independence of proper motion solutions on random errors in object distances stresses the opportunity of proper motions.

2. The influence of random errors on the estimation process should be checked in every case of nonlinear transformation of random values. This influence is the inherent property of distribution and may appear in any method of estimation.

3. Rotation curve of the Galaxy from the motions of open clusters may be downward. But this behavior of the curve is defined by a few clusters and may be caused by noncircular orbiting of this group in the Galaxy. Nevertheless it is not rising, and the rise of curve may be completely explained by the influence of random errors in distances of the objects used.

We have not concentrated on the problem of what kind of RC we determined in the sense of closeness of our rotation curve with curve of circular rotation. The determination of the circular rotation curve implies the selection of objects with small eccentricities of galactic orbits which is difficult for remote clusters.

We have to conclude finally that the behavior of rotation curve in galactic periphery up until now is enigmatic and new observations of very distant objects of anticenter are urgent.

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