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S. A. Kutuzov \(^a\); L. P. Ossipkov \(^a\)

\(^a\) Department of Cosmic Technologies and Applied Astroodynamics, Faculty of Applied Mathematics and Control Processes, St. Petersburg State University, Staryj Peterhof, St. Petersburg, Russia

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GALAXY MODELLING AND ORBITS OF VARIOUS OBJECTS

S. A. KUTUZOV and L. P. OSSIPKOV
Department of Cosmic Technologies and Applied Astrodynamics,
Faculty of Applied Mathematics and Control Processes,
St. Petersburg State University, 2, Bibliotechnaya pl., Staryj Peterhof,
St. Petersburg, 198504, Russia
E-mail leo@dyna.astro.spbu.ru
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The equipotential method for galaxy modelling is briefly outlined. A two-component model of our Galaxy was constructed using the method and galactic orbits of various objects were calculated. The statistics of orbital elements for open clusters, high-velocity stars, globular clusters, and short-periodic variables are given.

KEY WORDS Stellar dynamics and celestial mechanics, galaxy: structure, open clusters: orbits, globular clusters: orbits, stars: orbits

1 INTRODUCTION

There are various ways of modelling galactic gravitational fields. Galaxy models are often built starting with ellipsoidal equidensity surfaces and density laws in the equatorial plane. It is known that this procedure leads to many mathematical difficulties. The equipotential method avoids them. Kuzmin (1953, 1956) and Miyamoto and Nagai (1975) were first to apply this method. A general theory was developed by us in a number of papers (e.g. Kutuzov and Ossipkov, 1981, 1986, 2001; Ossipkov, 1997). The equipotential method enables us to determine the so-called ‘augmented density’ that is necessary for finding steady distribution functions (Binney and Ossipkov, 2000). Knowledge of the gravitational potential of our Galaxy is essential if one is to determine the orbits of observed objects. Here we briefly summarize the main results of such studies.

2 GALAXY MODELLING USING THE EQUIPOTENTIAL METHOD

We recall the equipotential method for galaxy modelling. We express the gravitational potential \( \Phi \) as a product of a scale factor \( \Phi_0 \) and a dimensionless function \( \varphi \)
of a single variable $\xi$ that labels the equipotential surfaces, $\Phi(r) = \Phi_0 \varphi(\xi)$. The geometry of equipotential surfaces is determined by a function $f$ of a dimensionless vector argument through $\xi^2 = f(r/r_0)$ with $r_0$ a scale parameter. The density law is obtained from Poisson’s equation $4\pi G \rho = -\nabla^2 \Phi$ which becomes

$$\frac{4\pi G r_0^2}{\Phi_0} \rho(r) = -\varphi' \nabla^2 \varphi - \varphi' (\nabla \varphi)^2$$

(1)

where $' = d/d(\xi^2)$. The function $f(r/r_0)$ cannot be directly determined from observations.

Below we restrict ourselves with axisymmetric models. Let $\varpi, \phi, \zeta$ be dimensionless cylindrical coordinates. We can suppose that $f(\varpi, 0) = \xi^2$. Now rewrite Eq. (1) as

$$\frac{4\pi G r_0^2}{\Phi_0} \rho(\varpi, \zeta) = P_1(\varpi, \zeta) \omega^2(\xi) + 2 P_2(\varpi, \zeta) (\omega^2(\xi))'$$

(2)

where $2P_1 = \nabla^2 f$, $4P_2 = (\partial f/\partial \varpi)^2 + (\partial f/\partial \zeta)^2$, and $\omega = (-2 \varphi')^{1/2}$ is a generalization of circular velocity for $\zeta \neq 0$.

Generally we consider equipotentials as surfaces of the eighth order (Kutuzov and Ossipkov, 1976, 1980). Their equation is as the following:

$$\xi^2 = (p - \epsilon)^2 + (1 + \gamma) \omega^2 - 1,$$

(3)

where $p^2 = \gamma (1-\epsilon^2) \omega^2 + (1+q)^2$, $q^2 = \xi^2 + (1+\gamma \omega^2) \epsilon^2$. Here $\epsilon, \gamma$ are dimensionless structure parameters. $\epsilon \in [0, 1]$ is a sphericity parameter, namely, a model will be spherical for $\epsilon = 1$. The parameter $\gamma$ is equal to 0 for equipotential surfaces of Miyamoto and Nagai (1975) and it is equal to 1 for Kuzmin’s (1753) equipotentials. Note that surfaces will be quartic for these two cases.

As for the potential law $\varphi(\xi)$, we worked mainly with the potential law of Kuzmin and Malasidze (1869):

$$\varphi(\xi) = \frac{\alpha}{\alpha - 1 + \sqrt{1 + \kappa \xi^2}},$$

(4)

where $\alpha, \kappa$ are dimensionless structure parameters. It includes many interesting special cases. In the limit $\alpha \to \infty$, $\kappa = O(\xi^2)$ we obtain the ‘limiting’ model of Kuzmin and Veltmann (1976) rediscovered later by Hernquist (1990)

$$\varphi(\xi) = (1 + \lambda \xi)^{-1}.$$  

(5)

Most orbits we found were calculated for the two-component model of our Galaxy constructed as follows (Kutuzov and Ossipkov, 1989, 1990). The first component resulted from a combination of equipotentials of Miyamoto and Nagai (Eq. (3) with $\gamma = 0$) and the potential law by Kuzmin and Malasidze (Eq. (4)). The second component is a sphere with potential (5) and a weight $(1 - \alpha)$. Using observational estimates for global (the rotation curve) and local parameters we obtained the following estimates for the model parameters:

$$r_2 = 2.54 \text{ kpc}, \quad \Phi_0 = 3.96 \times 10^5 \text{ km}^2 \text{ s}^{-2}, \quad \omega_0 = 3.83, \quad a = 0.37,$$
\[ \alpha = 4.17, \quad \varepsilon = 0.11, \quad \kappa = 6.89, \quad \lambda = 8.60 \]

Then the total mass of the Galaxy is \( M = 4.2 \times 10^{11} M_\odot \), the galactocentric solar distance is \( R_\odot = 8.23 \text{kpc} \), and the circular velocity at the solar distance is \( V_\odot = 216 \text{km s}^{-1} \).

3 ORBITS

All orbits we calculated for our axisymmetric potential were ordered. Border folds were found for some globular cluster and short-periodic variable orbits. The orbits of several globular clusters were simple tube ones (filling inclined boxes). Let consider orbit properties for various galactic subsystems. Brief summaries of our first results were given by Ossipkov and Kutuzov (1993, 1998).

We studied Open clusters for some decades, and the main results were reviewed by Ossipkov et al. (1997). Orbital elements for six distance scales are given by Kutuzov and Ossipkov (1996), and a statistical analysis was carried out by Ossipkov (1990). We found that all orbits fill rectangular boxes. The mean orbital eccentricity is equal to \( \langle e \rangle = 0.06 \) and the mean height of orbits is \( \langle z_m \rangle = 0.21 \text{kpc} \) for Hagen’s distances. No significant correlations between orbital elements and cluster age and metallicity were found.

Orbits of planetary nebulae were calculated by Ossipkov and Kutuzov (1994). They are more cumbersome than open cluster orbits and can be characterized with the larger value for the mean orbital eccentricity \( (0.16 \text{ for the Cudworth’s distance scale}) \).

Galactic orbits and kinematics of metal-poor high-velocity stars were discussed by Ossipkov and Kutuzov (1997). We found that for stars with a metallicity parameter \([\text{Fe/H}] \in (-2.55, -2.03)\) the mean orbital eccentricity \( \langle e \rangle = 0.73 \), and \( \langle z_m \rangle = 8.8 \text{kpc} \), if \([\text{Fe/H}] \in (-2.50, -2.25)\) then \( \langle e \rangle = 0.87 \), \( \langle z_m \rangle = 4.3 \text{kpc} \), and for stars with \([\text{Fe/H}] \in (-3.00, -2.50)\) we have \( \langle e \rangle = 0.55 \), \( \langle z_m \rangle = 3.2 \text{kpc} \).

Orbital elements of globular clusters for various sets of observational data were given by Ossipkov et al. (1996). New orbits based on proper motions absolutized to Hipparcos stars were calculated by us last year (Kutuzov and Ossipkov, 1999). We found that for clusters with Hipparcos based astrometry \( \langle e \rangle = 0.7 \), \( \langle z_m \rangle = 1.3 \text{kpc} \) when the metallicity \([\text{Fe/H}] < -1.7\), \( \langle e \rangle = 0.6 \), \( \langle z_m \rangle = 2.1 \text{kpc} \) for clusters with \([\text{Fe/H}] \in [-1.7, -1.4]\), and \( \langle e \rangle = 0.7 \), \( \langle z_m \rangle = 1.8 \text{kpc} \) if \([\text{Fe/H}] \geq -1.4\).

Some preliminary results were also obtained for short periodic variables. We found that for stars with the period \( P < 0.4^d \) \( \langle e \rangle = 0.26 \), \( \langle z_m \rangle = 1.69 \text{kpc} \), for stars with \( P \in [0.4^d, 0.6^d] \) \( \langle e \rangle = 0.48 \), \( \langle z_m \rangle = 5.93 \text{kpc} \), when \( P \in (0.4^d, 0.6^d) \) \( \langle e \rangle = 0.56 \), \( \langle z_m \rangle = 6.38 \text{kpc} \), and if \( P > 0.6^d \) then \( \langle e \rangle = 0.88 \), \( \langle z_m \rangle = 6.80 \text{kpc} \).

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