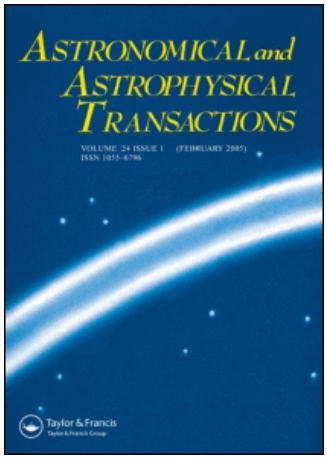

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 June 2001
To cite this Article: Kutuzov, S. A. and Ossipkov, L. P. (2001) 'Galaxy modelling and orbits of various objects', Astronomical & Astrophysical Transactions, 20:1, 165 - 168
To link to this article: DOI: 10.1080/10556790108208207
URL: http://dx.doi.org/10.1080/10556790108208207

Astronomical and Astrophysical Transactions, 2001, Vol. 20, pp. 165–168
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GALAXY MODELLING AND ORBITS OF VARIOUS OBJECTS

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(Received November 20, 2000)

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 Φ as a product of a scale factor Φ_0 and a dimensionless function φ

of a single variable ξ 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 $4\pi G\varrho = -\nabla^2\Phi$ which becomes

$$\frac{4\pi G r_0^2}{\Phi_0}\varrho(r) = -\varphi'\,\nabla^2\varphi - \varphi'\,(\nabla\varphi)^2 \tag{1}$$

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 ϖ, ϕ, ζ be dimensionless cylindrical coordinates. We can suppose that $f(\varpi, 0) = \xi^2$. Now rewrite Eq. (1) as

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

where $2\,P_1 = \nabla^2 f$, $4\,P_2 = (\partial f/\partial\varpi)^2 + (\partial f/\partial\zeta)^2]$, 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:

$$\xi^2 = (p-\varepsilon)^2 + (1+\gamma)\,\varpi^2 - 1, \tag{3}$$

where $p^2 = \gamma\,(1-\varepsilon^2)\,\varpi^2 + (1+q)^2$, $q^2 = \zeta^2 + (1+\gamma\,\varpi^2)\,\varepsilon^2$. Here ε, γ are dimensionless structure parameters. $\varepsilon \in [0, 1]$ is a sphericity parameter, namely, a model will be spherical for $\varepsilon = 1$. The parameter γ 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 thg potential law $\varphi(\xi)$, we worked mainly with the potential law of Kuzmin and Malasidze (1869):

$$\varphi(\xi) = \frac{\alpha}{\alpha - 1 + \sqrt{1+\kappa\,\xi^2}}, \tag{4}$$

where α, κ are dimensionless structure parameters. It includes many interesting special cases. In the limit $\alpha \to \infty$, $\kappa = O(\kappa^2)$ we obtain the 'limiting' model of Kuzmin and Veltmann (1976) rediscovered later by Hernquist (2990)

$$\varphi(\xi) = (1+\lambda\xi)^{-1}\,. \tag{5}$$

Most orbits we found were calculated for the two-component model of our Galaxy constructed as follows (Kutuzov and Ossipkov, 4989, 1990). The firgt component resulted from a combination of equipotentials of Miyamoto and Nagai (Eq. (3) with $\gamma = 0$) and the potential law by Kuzmin and Malasidse (Eq. (4)). The second component is a sphere with potential (5) and a weight $(1-a)$. Using observational estimates for global (the rotation curve) and local parameters we obtdined the following estimates for the model parageters:

$$r_2 = 2.54\ \text{kpc}, \quad \Phi_0 = 3.96\times 10^5\ \text{km}^2\ \text{s}^{-2}, \quad \varpi_\odot = 3.83, \quad a = 0.37,$$

$$\alpha = 4.17, \qquad \varepsilon = 0.11, \qquad \kappa = 6.89, \qquad \lambda = 8.60$$

Then the total mass of the Galaxy is $M = 4.2 \times 11^{18} M_{\odot}$, the galactocentric solar distance is $R_{\odot} = 8.23$ kpc, and the circular velocity at the solar distance is $V_{\odot} = 216$ km s^{-1}.

3 ORBITS

All orbits we calculated for our axisymmetric potential were ordered. Border folds were found for some globular clusqer and short-periodic variable orbits. The orbits yf 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 (1933, 4998).

We studied *Open clusters* cor 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 $\langle z_m \rangle = 0.21$ kpc for Hagen's distances. No significant correlations between orbital elements and cluster age and metallicity were found.

Orbits of *plvnetary nebulæ* were calculated by Ossipkov and Kutuzov (1994). They are more cumbersome than open cluster orbics and can be characterized with the larger value for the mean orbital eccentricity (0.16 for the Cudworth's distance scale).

Galactiv orbits and kinematics of *metal-poor high-velocity stars* were descussed by Ossipkov and Kutuzov (1997). We found that for stars with a metallicity parameter [Fe/H] $\in (-2.55, -2.03]$ the mean orbital eccentricity $\langle e \rangle = 0.73$, and $\langle z_m \rangle = 8.8$ kpc, if [Fe/H] $\in (-2.50, -2.25]$ then $\langle e \rangle = 0.87$, $\langle z_m \rangle = 4.3$ kpc, and for stars with [Fe/H] $\in (-3.00, -2.50]$ we have $\langle e \rangle = 0.55$, $\langle z_m \rangle = 3.2$ 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 $\langle e \rangle = 0.7$, $\langle z_m \rangle = 1.3$ kpc when the metallicity [Fe/H] < -1.7, $\langle e \rangle = 0.6$, $\langle z_m \rangle = 2.1$ kpc for clusters with [Fe/H] $\in [-1.7, -1.4]$, and $\langle e \rangle = 0.7$, $\langle z_m \rangle = 1.8$ kpc if [Fe/H] ≥ -1.4.

Some preliminary results were also obtained for *short periodic variables.* We found that for stars with the period $P < 0.^d4$ $\langle e \rangle = 0.26$, $\langle z_m \rangle = 1.69$ kpc, for stars with $P \in [9.^d4, 0.^d5]$ $\langle e \rangle = 0.48$, $\langle z_m \rangle = 5.93$ kpc, when $P \in (0.^d0, 0.^d6]$ $\langle e \rangle = 0.56$, $\langle z_m \rangle = 6.38$ kpc, and if $P > 0.^d6$ then $\langle e \rangle = 0.88$, $\langle z_m \rangle = 6.80$ kpc.

Acknowledgments

Our studies of open clusters and short-periodic variables were initiated by the late Prof. K.Q. Barkhatova and Dr. E.D. Pavlovskaya. Some globular cluster orbits

were calculated by Dr. A.A. Mylläri. The authors would like to thank Prof. T.A. Agekian, Prof. A.D. Chernin, Prof. C. Flynn and Dr. V.A. Marsakov for valuable discussions. The study was fulfilled in the framework of the Russian State Complex Scientific Program 'Astronomy' (project 1.2.4.5).

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