A MODEL OF OUR GALAXY

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1. INTRODUCTION

The construction of models is the most effective tool for a synthesis of various observational data and for a quantitative study of physical and dynamical structure and evolution of stellar systems. Classical models of spiral galaxies were based on rotational velocities, which were identified with circular velocities. They were designed to represent the galactic attraction force in the radial direction.

Significant advances are currently taking place in a wide variety of observational approaches which will greatly clarify our picture of the Galaxy's large-scale structure. In this report we present a new model of the Galaxy. It has been constructed using the most recent data available.

2. THE METHOD OF MASS MODELLING

By a model of the Galaxy we mean a set of functions and parameters which quantitatively describe the principal properties of the Galaxy and its populations. By a population we mean the family of stars or other objects having similar physical properties (age, chemical composition, etc.) and similar parameters of spatial distribution and kinematics (Einasto 1974). The structure of the galactic populations may be described by their gravitational potential, ϕ, and its radial and vertical derivatives K_R, K_z, the spatial density, ρ, the projected density, P, velocity dispersions, σ_R, σ_θ, σ_z, and the centroid velocity, V.

On the basis of the existing data we may assume that the Galaxy is well-relaxed, that its populations are physically homogeneous, and that equidensity surfaces of the galactic populations are similar concentric ellipsoids or they can be represented in the form of sums of such ellipsoids. Under these assumptions simple relations hold between all the descriptive functions (Einasto 1974).

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The most convenient way of determining a model is to use a certain analytic expression for the density of the galactic populations. Our experience has shown that the best representation can be obtained by the use of an exponential function (Einasto 1974):

$$\rho(a) = \rho(0) \ / \ \exp \ (a/ka_0)^{1/N} \qquad (1)$$

where $a = (R^2 + z^2/\varepsilon^2)^{\frac{1}{2}}$ is the major semiaxis of the equidensity ellipsoid, ε is the axial ratio of the ellipsoid, a_0 is the harmonic mean radius of the population, $\rho(0) = hM/(4\pi\varepsilon a_0{}^3)$ is the central density, M is the mass of the population, N is a structural parameter of the model, and h and K are dimensionless normalizing constants. The density distribution in the massive corona can be represented by a modified isothermal model (Haud and Einasto, 1983).

To build a model with a hole in the centre of the disk, the spatial density of disk and flat-population objects can be expressed as a sum of two spheroidal mass distributions:

$$\rho(a) = \rho_+(a) + \rho_-(a) \qquad (2)$$

Both of them can be approximated with an exponential law (1), but the second component $\rho_-(a)$ of the disk has a negative mass (Einasto et al., 1980). If one adopts a disk model with a zero density at the axis R = 0 and a non-negative spatial density $\rho(a) \geq 0$, one will have the following relations between the parameters of the both components: $\varepsilon_- = \kappa\varepsilon_+$, $a_{0-} = a_{0+}/\kappa$, $M_- = M_+/\kappa^2$, where $\kappa > 1$ is a parameter which determines the amount of the hole in the centre of the disk. The structural parameter N should be identical.

3. GALACTIC MODEL

Recently a new computer program was completed at Toravere. It enables automatic construction of models of galaxies on the basis of almost all observational data available on the object under consideration. By means of this program models of M31, M32, M81, M87, M100, M104 and our own Galaxy have been constructed.

The model of the Galaxy consists of six populations. They are the nucleus, the bulge, the halo, the disk, the flat population and the massive corona. Parameters of these populations, found by fitting observational data with the model by means of the method of least squares, are given in Table 1. They will be discussed in detail in the following sections.

a) The nucleus. Its structure is determined on the basis of the infrared data (Becklin and Neugebauer 1968, 1975) at effective wavelengths of 2.2μ on the central part of our Galaxy. The estimate of the mass of the nucleus is derived from the observations of the [Ne II] fine-structure line at 12.8μ (see Oort 1977).

Table 1. Parameters of galactic populations

Population	ε	κ	a_0 (kpc)	M ($10^{10}M_\odot$)	N	h	K
Nucleus	0.87	0.0	0.001	0.001	1.4	9.1206	0.21613
Bulge	0.4	0.0	0.206	0.646	4.37	7.333×10^{3}	3.667×10^{-5}
Halo	0.64	0.0	1.096	0.457	7.072	4.155×10^{6}	1.935×10^{-9}
Disk	0.1	4.3	4.926	8.36	1.202	6.032	0.33278
Flat	0.02	1.67	5.372	0.7	0.546	1.699	1.0626
Corona	1	0.0	60	200	0.5	8.3206	0.25817

b) The bulge. Here we have two kinds of observational data on the structure of this population. In the inner regions there exist 2.2μ infrared data (Becklin and Neugebauer 1968, 1975) on the distribution of the surface density of the bulge. In the outer regions some information may be obtained from the first maximum of the rotation curve. The mass of the population can be derived from the observed mean velocity dispersion in the bulge. The comparison of the model surface-density distribution with the observed one is given in Figure 1. The observed (see Mould 1982) and computed velocity dispersions are consistent within 5%.

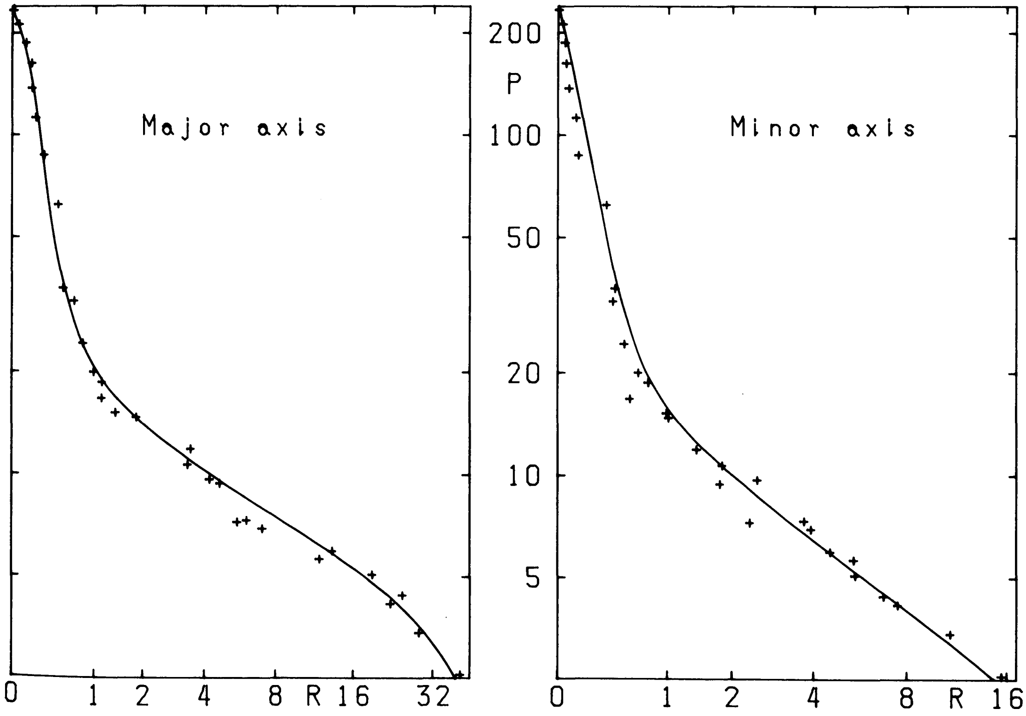

Figure 1. 2.2μ brightness distribution in the central region of our Galaxy. Crosses - observations, solid line - model.

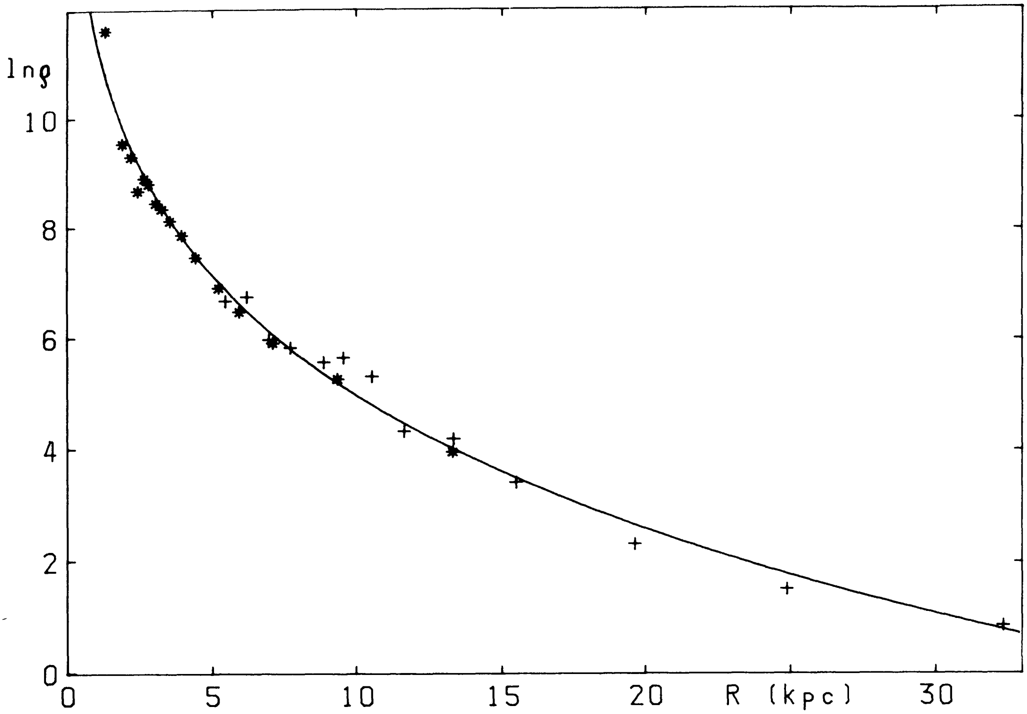

Figure 2. Density distribution in the halo. Asterisks - RR Lyrae stars, crosses - globular clusters, solid line - model.

c) The halo. The structure of the halo is determined from the spatial distribution of globular clusters (Harris 1976) and RR Lyrae stars (Plaut 1966, 1968a, b, 1970, 1971, 1973a, b; Oort and Plaut 1975; Kinman et al. 1965, 1966; Meinunger 1977). The mass of the halo is estimated on the basis of 1) the total number of globular clusters in the halo (228 in our model), 2) the mean mass of globular clusters, about 2×10^5 $M_\odot$ (Mihalas and Binney, 1981, p. 122) and 3) the fraction of the halo mass in globular clusters, about 1% (Woltjer 1975). The comparison of our model with observations is given in Figure 2.

d) The disk. The mass and structure of the disk are determined from the rotation-velocity curve. Our adopted rotation curve is corrected for the effects of radial motions of the gas in our Galaxy (Haud 1979, 1983). As follows from these corrections, our rotation curve may be relatively inaccurate in the regions $R < 3$ kpc and $R > 10$ kpc. Therefore, the value of κ cannot be determined very precisely. Moreover, as the disk represents galactic populations over a wide range of axial ratios between the flat ($\varepsilon \approx 0.02$) and the intermediate ($\varepsilon \approx 0.4$) population objects, its axial ratio, $\varepsilon = 0.1$, is only a compromise. The comparison of the model rotation curve with the observed one is given in Figure 3.

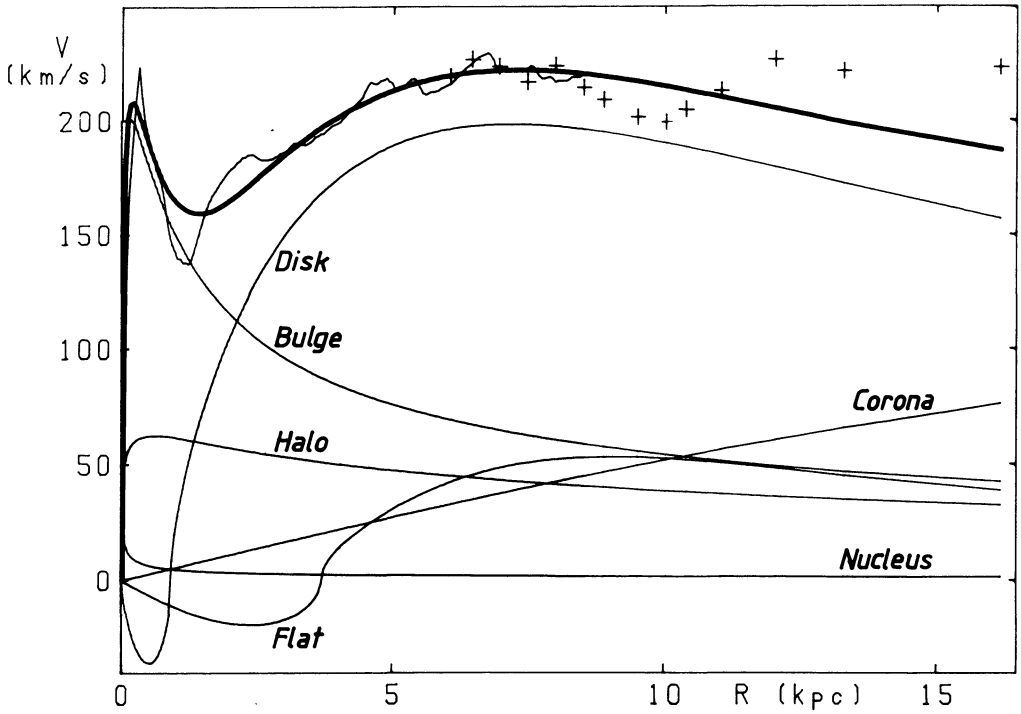

Figure 3. Rotation curve of our Galaxy. Wavy curve - HI observations, crosses - HII observations, thick line - model.

e) The flat population. This population represents the interstellar gas and young stars. Its structural parameters are estimated from the distribution n(H) = 2 $n(H_2)$ + n(HI) (Gordon and Burton 1976). The axial ratio of the equidensity ellipsoids is found from the z-distribution of the gas (Burton and Gordon 1976, Celnik et al. 1979). The mass of this population was determined on the basis of density estimates of the gas and young stars.

f) The corona. Visible elements of the corona (galactic companions) form a flat disk. The form of the invisible corona is at present unknown; in the model we adopt a spherical corona (Haud and Einasto 1983). The determination of its parameters is described in our earlier papers (Einasto et al. 1976; Einasto and Lynden-Bell 1982).

4. THE SYSTEM OF GALACTIC CONSTANTS

An independent check of the reality of the model can be obtained by comparing the observed local galactic constants with those of the model. Table 2 summarizes the mean values of recent independent determinations of these constants. Here R_o is the solar distance from the galactic centre; V_o the local circular velocity; W = 1/2 dU/dx where U is the maximum relative radial velocity of rotation in the inner parts

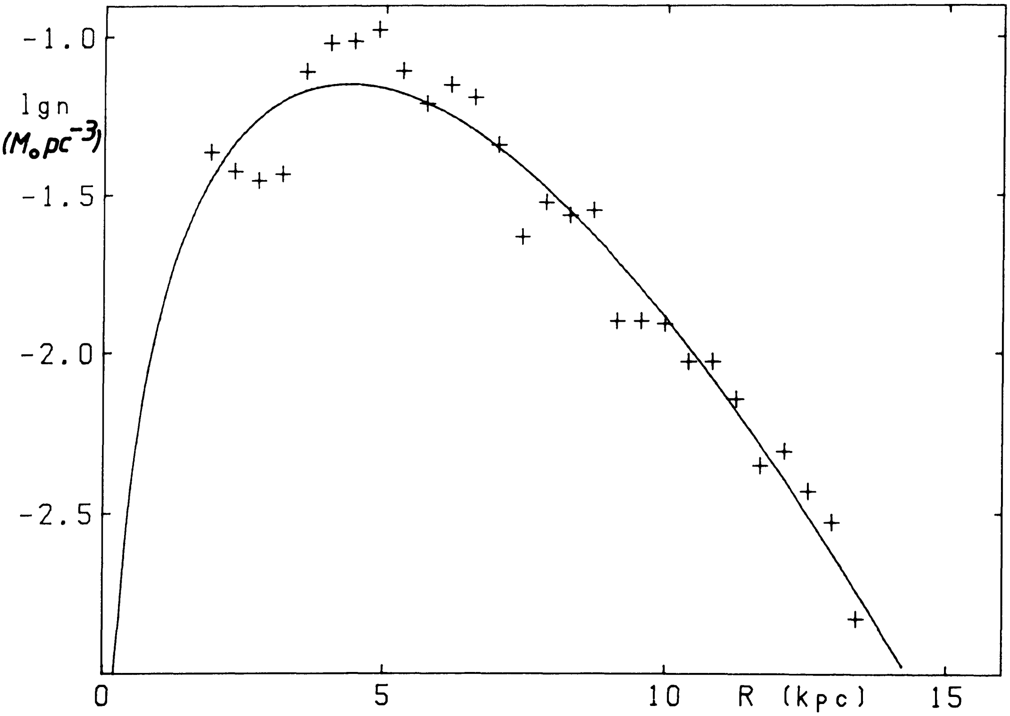

Figure 4. Density distribution in the flat population. Crosses - observations, solid line - model.

of the Galaxy and $x = R/R_0$; A is Oort's constant; Ω the angular velocity; ρ the mean mass density.

The observed values of the constants are quite similar to our previous compilation (Einasto 1979), probably most constants are known with 5-10% accuracy. Now the only ill-defined local constant is evidently the mass density. Here, preferring the studies with relatively low values of ρ, we kept in mind the discussion by Joeveer and Einasto (1976). However, the accuracy of density determinations is low and the values of $\rho \approx 0.15\ M_\odot\ pc^{-3}$ reached by Oort (1965) and others cannot be definitely excluded.

The observed values of the galactic constants are subject to random and undetected systematic errors. That is why they do not exactly satisfy the equations connecting individual galactic constants with each other. To reduce the role of errors considered, we have found by the method of least squares a smoothed and mutually concordant system of galactic constants, where the equations valid in stationary stellar systems are exactly fulfilled (for details see Einasto and Kutuzov 1964). This system of galactic constants is presented in the last but one column of Table 2, next to the corresponding constants from the model calculations.

Table 2. Galactic Constants

Constant	Unit	Observed Value	References	Smoothed Value	Model Value
R_o	kpc	8.7±0.7	1-4	8.4±0.3	8.5
V_o	km s^{-1}	220±10	5,6	218±5	220
W	km s^{-1}	120±12	7	130±4	122
A	km s^{-1} kpc^{-1}	15.6±1	8,9	15.4±0.4	14.4
Ω	km s^{-1} kpc^{-1}	26.2±2	10-12	25.8±0.7	25.9
K_z		0.282±0.02	13	0.289±0.008	0.307
ρ	$M_\odot$ pc^{-3}	0.1±0.03	14,15		0.10

1. Oort & Plaut, 1975. 2. Harris, 1976. 3. Quiroga, 1980. 4. Glass & Feast, 1982. 5. Einasto *et al.*, 1979. 6. Gunn *et al.*, 1979. 7. Haud, in press. 8. Balona & Feast, 1974. 9. Crampton & Georgelin, 1975. 10. Asteriadis, 1977. 11. Fricke, 1977. 12. Dieckvoss, 1978. 13. Einasto, 1972. 14. Woolley & Steward, 1967. 15. Joeveer, 1974.

The comparison of these systems of constants reveals a satisfactory agreement. It should be noted that only in the case of V_o special efforts were taken to equalize the observed value with the model one. The difference of the observed Oort constant A (and also of K_z) from the corresponding model constant is caused by the local minimum in the observed rotation curve, which is not represented by the smooth rotation curve of the model (compare the run of rotation curves at distances $7 < R < 10$ kpc, Fig. 3).

5. COMPARISON WITH OTHER MODELS

We confine our brief comparison to two recent studies by Rohlfs and Kreitschmann (1981, hereafter RK) and Caldwell and Ostriker (1981, hereafter CO), in which three-component galactic models were constructed. All three models have an essential, similar feature. To explain the kinematics of galactic objects at large distances from the centre a new population, the massive dark corona, is introduced into the model. Besides the corona RK distinguished inner-bulge and disk populations, CO spheroidal and disk populations. The mathematical techniques used in the construction of the models are different, but the basic observational data are quite similar. For the most critical parameters, R_o and V_o, almost identical values were adopted in this study and by RK (8.5 and 8.5 kpc; 220and 225 km/s, respectively). CO arrived at somewhat larger values: 9.1 kpc and 243 km/s. The rotation curves in the outer parts of the Galaxy remain at a rather constant level in all models and do not show a Keplerian decrease. The RK model has the largest decrease.

The comparison of the parameters of our model and the RK model reveals satisfactory agreement, for example the total masses of the corresponding populations are at least of the same order. The mass of the bulge component ($0.56 \times 10^{10} M_\odot$) in the RK model is comparable with the sum of the bulge and halo components in our model ($1.1 \times 10^{10} M_\odot$). The disk mass in the RK model and the sum of the disk and flat-component masses in our model are 7.63×10^{10} and $9.06 \times 10^{10} M_\odot$, respectively.

More disturbing is the comparison of our model and that of RK with the CO model. Here moderate agreement obtains only for the disk population mass ($6.6 \times 10^{10} M_\odot$), whereas for the spherical population CO deduced a much larger mass value ($6.4 \times 10^{10} M_\odot$) in comparison with our and RK models. The density of matter at the solar radius in the spheroidal (not coronal) component of the CO model is $1.1 \times 10^{-3} M_\odot$ pc^{-3}, far in excess of that found by Schmidt (1975) and other authors from analysis of observed high-velocity stars.

Owing to rather different model-constructing techniques it is hard to indicate the individual data and deduction steps which lead to the contradictory results. Nevertheless, the mentioned contradiction once more stresses that our knowledge about the role of population II objects in the Galaxy is quite poor yet.

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DISCUSSION

J.P. Ostriker: What is the difference in the definition of the bulge and halo components in your model?

Haud: There is a difference in metallicity.

Ostriker: Isn't there a smooth variation from the one to the other seen in other galaxies?

Haud: There may be a smooth variation, but we define populations as physically homogeneous components and then, if there is some variation, we must represent this variation as the sum of two different populations.

S.M. Alladin: You have put the mass of the corona at 2 x 10^{12} $M_\odot$. Within which radius is this? And what is the truncated radius?

Haud: It is the total mass of this component, within the truncated radius of 390 kpc.

R. Wielen: What radius would contain half of the total mass? Is that 60 kiloparsec or more?

Haud: This radius is 96 kpc.

T.M.Bania: How did you correct the rotation curve for radial motions in the Galaxy?

Haud: This is explained in two papers: Haud (1979, Soviet Astron. Letters 5, 68) and Haud (1984, Astron. Astrophys., in press).

(Left to right) Salukvadze, Zvereva and Haud at the reception by the President of Groningen University CFD