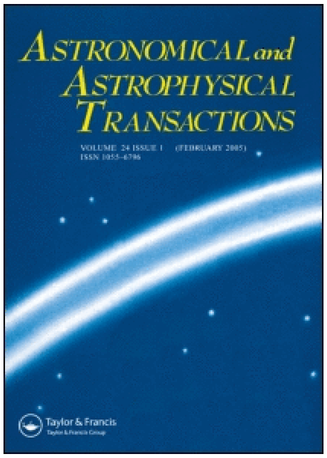

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DISSIPATIVE N-BODY CODE FOR GALACTIC EVOLUTION

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The evolving galaxy is considered as a system of baryonic fragments embedded into the static dark non-baryonic (DH) and baryonic (BH) halo and subjected to gravitational and viscous interactions. Although the chemical evolution of each separate fragment is treated in the frame of the one-zone closed box model with instantaneous recycling, its star formation (SF) activity is a function of the mean local gas density and, therefore, is strongly influenced by other interacting fragments. In spite of its simplicity this model provides a realistic description of the process of galaxy formation and evolution over the Hubble timescale.

KEY WORDS Galactic evolution, galaxy formation, dissipative N-body code

1 INTRODUCTION

Recent advances in extragalactic astrophysics show the close link of the dynamical evolution of a disk galaxy and its chemical and photometric behaviour over the Hubble timescale. In spite of the remarkable succes of the modern theory of galactic chemical evolution in explaining the properties of evolving galaxies (Pagel, 1994) its serious shortcomings concern the multiparameter character and practical neglect of dynamical effects. The inclusion of simplified dynamics into the chemical network (Samland and Hensler, 1996) and vice versa the inclusion of a simplified chemical scheme into the sophisticated 3D hydrodynamical code (Steinmetz and Muller, 1994; Berczik and Kravchuk, 1997) gives very promising results and allows us to avoid the formal approach typical of standard theory.

In this paper the interplay between the dynamical evolution of a disk galaxy and its chemical behaviour is studied in the framework of a simplified model which provides a realistic description of the process of galaxy formation and evolution over the cosmological timescale.

2 INITIAL CONDITIONS

The evolving galaxy is treated as a system of baryonic fragments embedded into the extended halo composed of dark non-baryonic and baryonic matter. The halo is modelled as a static structure with dark (DH) and diluted baryonic (BH) halo components having Plummer-type density profiles (Douphole and Colin, 1995):

$$\rho_{\rm BH}(r) = \frac{M_{\rm BH}}{(4/3)\pi b_{\rm BH}^3} \frac{b_{\rm BH}^5}{(r^2 + b_{\rm BH}^2)^{5/2}}$$

and

$$\rho_{\rm DMH}(r) = \frac{M_{\rm DMH}}{(4/3) b_{\rm DMH}^3} \frac{b_{\rm DMH}^5}{(r^2 + b_{\rm DMH}^2)^{5/2}},$$

where

$$\begin{array}{rclrcl} M_{\rm DMH} & = & 10^{12}\, M_\odot, & b_{\rm DMH} & = & 25\,{\rm kpc}, \\ M_{\rm BH} & = & 10^{11}\, M_\odot, & b_{\rm BH} & = & 15\,{\rm kpc}. \end{array}$$

The dense baryonic matter (future galaxy disk and bulge) of total mass $M_{\rm gas} = 10^{11} M_\odot$ is assumed to be distributed among $N = 2109$ particle-fragments. The single particle density profile is also assumed to be a Plummer one. Its mass is taken to be $m_i = M_{\rm gas}/N$ and radius $h_i = 1$ kpc. Initially all particles are smoothly placed inside a sphere of radius $R_{\rm gas} = 50$ kpc and are involved in the Hubble flow ($H_0 = 75$ km s^{-1} Mpc^{-1}) and solid-body rotation around the z-axis. The initial motion of this system is described as:

$$\boldsymbol{V}(x,y,z) = [\boldsymbol{\Omega}(x,y,z) \times \boldsymbol{r}] + H_0 \cdot \boldsymbol{r} + \boldsymbol{DV}(x,y,z),$$

where $\boldsymbol{\Omega}(x,y,z) = (0,0,1) \cdot \Omega_{\rm cir}$ is an angular velocity of the rotating sphere, $\Omega_{\rm cir} = V_{\rm cir}/R_{\rm gas}$ and

$$V_{\rm cir} = \sqrt{G \frac{M_{\rm gas} + M_{\rm DMH} + M_{\rm BH}}{R_{\rm gas}}}.$$

The components DV_x, DV_y, DV_z of the random velocity vector $\boldsymbol{DV}$ are assumed to be initially randomly distributed within an interval 0–10 km s^{-1}.

3 N-BODY CODE

The dynamical evolution of baryonic matter fragments which are subjected to gravitational influences of the DM-baryonic halo and interfragment interactions is followed by means of an effective N-body integrator with individual time step. The dynamics of such an N-body system is described by the following equations:

$$\left\{ \begin{array}{rcl} {\rm d}\boldsymbol{R}_i/\,{\rm d}t & = & \boldsymbol{V}_i, \\ {\rm d}\boldsymbol{V}_i/\,{\rm d}t & = & \boldsymbol{A}_i(\boldsymbol{R}, \boldsymbol{V}). \end{array} \right. \qquad (1)$$

The acceleration of the i-th particle $\boldsymbol{A}_i$ is defined as a sum of three components:

$$\boldsymbol{A}_i = \boldsymbol{A}_i^{\mathrm{INT}} + \boldsymbol{A}_i^{\mathrm{EXT}} + \boldsymbol{A}_i^{\mathrm{VISC}}, \tag{2}$$

where the first term $\boldsymbol{A}_i^{\mathrm{INT}}$ accounts for gravitational interactions between fragments. The second one $\boldsymbol{A}_i^{\mathrm{EXT}}$ is defined as an external gravitational acceleration caused by the DM and baryonic halo. The last term $\boldsymbol{A}_i^{\mathrm{VISC}}$ corresponds to the viscous deceleration of a fragment when passing through the baryonic halo.

The gravitational interaction between fragments is defined as the interaction of N Plummer profile elements:

$$\boldsymbol{A}_i^{\mathrm{INT}} = -G \sum_{j=1, j\neq i}^{N} \frac{m_j}{(\boldsymbol{R}_{ij}^2 + h_{ij}^2)^{3/2}} \boldsymbol{R}_{ij}. \tag{3}$$

Here $h_{ij} = (h_i + h_j)/2$ and $\boldsymbol{R}_{ij} = \boldsymbol{R}_i - \boldsymbol{R}_j$.

Noting that the halo DM and baryonic components are also Plummer spheres the second term becomes:

$$\boldsymbol{A}_i^{\mathrm{EXT}} = -G \left(\frac{M_{\mathrm{DMH}}}{(\boldsymbol{R}_i^2 + b_{\mathrm{DMH}}^2)^{3/2}} + \frac{M_{\mathrm{BH}}}{(\boldsymbol{R}_i^2 + b_{\mathrm{BH}}^2)^{3/2}} \right) \boldsymbol{R}_i. \tag{4}$$

The form of the last term $\boldsymbol{A}_i^{\mathrm{VISC}}$ will be discussed in the next subsection.

The characteristic time step δt_i in the integration procedure for each particle is defined as:

$$\delta t_i = \mathrm{Const} \cdot \min_j \left[\sqrt{\frac{|\boldsymbol{R}_{ij}|}{|\boldsymbol{A}_{ij}|}}, \frac{|\boldsymbol{R}_{ij}|}{|\boldsymbol{V}_{ij}|} \right], \tag{5}$$

where $\boldsymbol{V}_{ij} = \boldsymbol{V}_i - \boldsymbol{V}_j$ and $\boldsymbol{A}_{ij} = \boldsymbol{A}_i - \boldsymbol{A}_j$.

Here Const is a numerical parameter equal to Const $= 10^{-2}$ that provides a nice momentum and energy conservation over the integration interval of about 15 Gyr. For example, in the conservative case (when the viscosity of the system is set equal to 0), the final total error in the energy equation is less than 1%.

4 VISCOSITY MODEL

The viscosity term $\boldsymbol{A}_i^{\mathrm{VISC}}$ is artificially introduced into the model so as to match the results of the more sophisticated SPH approach on dynamical evolution of disk galaxies. The best fit of results of this simplified approach with SPH modelling data (see, e.g. Berczik and Kravchuk, 1997) is achived when the momentum exchange between the baryonic halo and moving particles is modelled by the following expression:

$$\boldsymbol{A}_i^{\mathrm{VISC}} = -k \boldsymbol{V}_i \frac{|\boldsymbol{V}_i|}{R_{\mathrm{VISC}}} \frac{\rho_{\mathrm{BH}}(r)}{\rho_{\mathrm{VISC}}} \frac{m_i^{\mathrm{gas}}}{m_i^{\mathrm{gas}} + m_i^{\mathrm{star}}}. \tag{6}$$

Here ρ_{VISC} and R_{VISC} are numerical parameters set equal to $\rho_{\mathrm{VISC}} = 0.2\ \mathrm{cm}^{-3}$ and $R_{\mathrm{VISC}} = 10$ kpc. The vector $\boldsymbol{V}_i$; is a particle velocity vector. It is to be noted that a single particle is assumed to have a total mass which doesn't change with time and is defined as the sum $m_i \equiv m_i^{\text{gas}} + m_i^{\text{star}}$ But the masses of its gas and star components m_i^{gas} and m_i^{star} are variable values and are defined by the temporal evolutionary status of the given fragment. Initially $m_i^{\text{star}} = 0$. The results of the fit show that for the z component of viscosity the term $k = 1$. In the galactic plane where it is necessary to account for the baryonic halo and the partial corrotation of baryonic fragments the dynamical friction is decreased and for the x, y components of viscosity the term k is reduced to the value 0.15.

5 DENSITY DEFINITION

In the framework of the multifragmented model the definition of the local gas density is introduced in the SPH manner, e.g. the local gas density depends on the total mass of matter contained in the sphere of radius H_i around the ith particle. For each ith particle the value of its smoothing radius H_i is chosen (using the quicksort algorithm) requiring that the volume within this radius comprises $N_{\text{B}} = 21$ nearest particles (i.e. $\approx 1\%$ of the total number of particles N). Therefore, the total mass M_i and density of gas ρ_i inside this sphere are defined as

$$M_i = \sum_{j=1}^{N} \Delta m_{ij}^{\text{gas}}, \quad \rho_i = \frac{M_i}{(4/3)\pi H_i^3}, \tag{7}$$

where $\Delta m_{ij}^{\text{gas}}$ is defined as

$$\begin{array}{ll} \text{if} & |\boldsymbol{R}_{ij}| > (H_i + h_j) \Rightarrow \Delta m_{ij}^{\text{gas}} = 0, \\ \text{if} & |\boldsymbol{R}_{ij}| < (H_i - h_j) \Rightarrow \Delta m_{ij}^{\text{gas}} = m_j^{\text{gas}}, \\ \text{else} & \Delta m_{ij}^{\text{gas}} = m_j^{\text{gas}} \dfrac{H_i + h_j - |\boldsymbol{R}_{ij}|}{2h_j}. \end{array}$$

6 STAR FORMATION AND SN EXPLOSIONS

A forming disk galaxy is modelled as a system of interacting fragments (called particles) embedded into the extended halo. Each particle is composed of gas and stellar components and its total mass is defined as $m_i \equiv m_i^{\text{gas}} + m_i^{\text{star}}$. Initially all particles are purely gaseous and, therefore, initially $m_i^{\text{star}} = 0$. To follow a particle star formation (SF) activity a special timemark t_i^{begSF} is introduced which initially is set equal to $t_i^{\text{begSF}} = 0$. The particles eligible for star formation events are chosen as particles which still have a sufficient amount of the gas component and their densities exceed some critical value ρ_{minSF} during some fixed time interval Δt_{SF} (of the order of the free-fall time):

$$\left\{\begin{array}{rcl} \rho_i & > & \rho_{\mathrm{minSF}}, \\ t_i - t_i^{\mathrm{begSF}} & > & \Delta t_{\mathrm{SF}}, \\ \dfrac{m_i^{\mathrm{gas}}}{m_i^{\mathrm{gas}} + m_i^{\mathrm{star}}} & > & 10^{-4}. \end{array}\right. \tag{8}$$

Here $\Delta t_{\mathrm{SF}} = 50$ Myr, and $\rho_{\mathrm{minSF}} = 0.01\ \mathrm{cm}^{-3}$ (this last value is not crucial and is only a limiting one).

If the particle was subjected to SF activity the parameter t_i^{begSF} is set equal to $t_i^{\mathrm{begSF}} = t_i$, and m_i^{star} and m_i^{gas} are redefined as

$$\left\{\begin{array}{rcl} m_i^{\mathrm{star}} & = & \epsilon(1-R)m_i^{\mathrm{gas}} + m_i^{\mathrm{star}}, \\ m_i^{\mathrm{gas}} & = & (1-\epsilon(1-R))m_i^{\mathrm{gas}}. \end{array}\right. \tag{9}$$

Here ϵ is the SF efficiency which is defined as

$$\epsilon = \alpha \frac{\rho_i}{\rho_{\mathrm{SF}}} \left[1 - \exp\left(-\frac{\rho_{\mathrm{SF}}}{\rho_i}\right)\right]. \tag{10}$$

Therefore

$$\begin{array}{lccc} \text{if} & \dfrac{\rho_i}{\rho_{\mathrm{SF}}} \to 0 & \Rightarrow & \epsilon \to \alpha \dfrac{\rho_i}{\rho_{\mathrm{SF}}}, \\ \text{if} & \dfrac{\rho_{\mathrm{SF}}}{\rho_i} \to 0 & \Rightarrow & \epsilon \to \alpha. \end{array}$$

To match the available observational data on star formation efficiency (see e.g. Wilking and Lada, 1983) the parameters α and ρ_{SF} are set equal to $\alpha = 0.5$ and $\rho_{\mathrm{SF}} = 10\ \mathrm{cm}^{-3}$. The chemical evolution of each separate fragment is treated in the frame of the one-zone closed box model with instantaneous recycling. In this approach the returned fraction of gas from evolved stars is given a standard value $R = 0.25$.

Following the instantenuous recycling approximation it is assumed that after each SF and SN explosion the heavy-element-enriched gas is returned to the system and mixed with old (heavy-element-deficient) gas. After each act of SF and SN explosions the value of heavy element abundances of the gas in the particle is upgraded according to:

$$Z_i = Z_i + \frac{\epsilon R \Delta Z}{1 - \epsilon(1-R)}. \tag{11}$$

The value $\Delta Z = 0.01$ is used as an average value for all values of $Z = 0.001$–0.04 (see Berczik and Kravchuk, 1997). Initially $Z_i = 0.0$ for all particles.

7 CONCLUSION

The proposed simple model provides a self-consistent picture of the process of galaxy formation, and its dynamical and chemical evolution is in agreement with the results

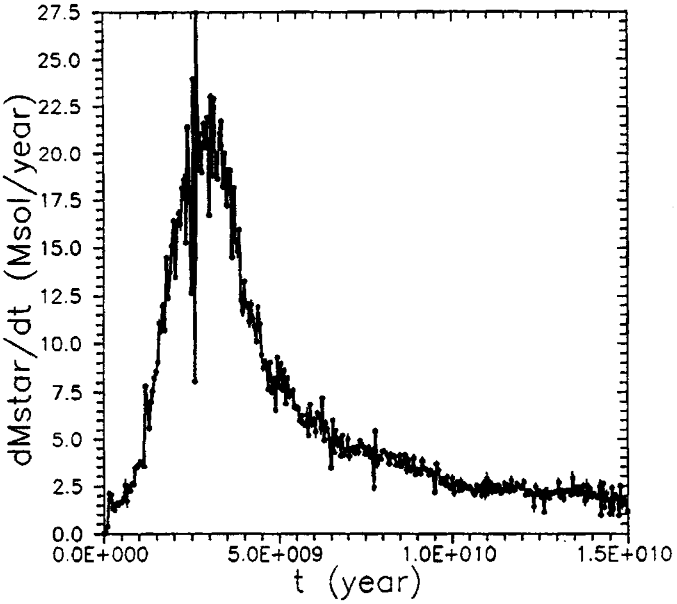

Figure 1 The variation of total star formation rate of a forming disk galaxy with time.

of more sophisticated approaches (see e.g. Steinmetz and Muller, 1994; Raiteri *et al.*, 1996; Samland and Hensler, 1996; Berczik and Kravchuk, 1997).

- The rapidly rotating protogalaxy finally forms a three-component system resembling typical spiral galaxies: a thin disk and spheroidal component made of gas and/or stars and a dark matter halo.

- Figure 1 and Figure 2 show respectively the star formation rate and the total galactic stellar mass as a function of time. Figure 3 shows the cylindrical distribution of stellar (upper curve) and gaseous (lower one) components of the final model disk galaxy as a function of distance from the galactic center in the galactic plane.

- The total star formation rate (SFR) is a succession of short bursts which doesn't exceed 28 $M_{\odot}$ yr^{-1}. During the first 2 Gyr of evolution only about 20% of the total galactic mass is transformed into stars. The SFR gradually decreases, during the further evolution, to the value of about 2 $M_{\odot}$ yr^{-1} typical for our own Galaxy. The final total stellar and gas mass of the model galaxy disk are about 92% and 8%. All these data as well as surface density distributions of stellar and gaseous components (see Figure 4) are in nice agreement with present day observational data (Kuijken and Gilmore, 1989; Pagel, 1994).

- The metallicities and the global metallicity gradient resemble distributions observed in our own Galaxy (Figure 5). The averaged observed value of the

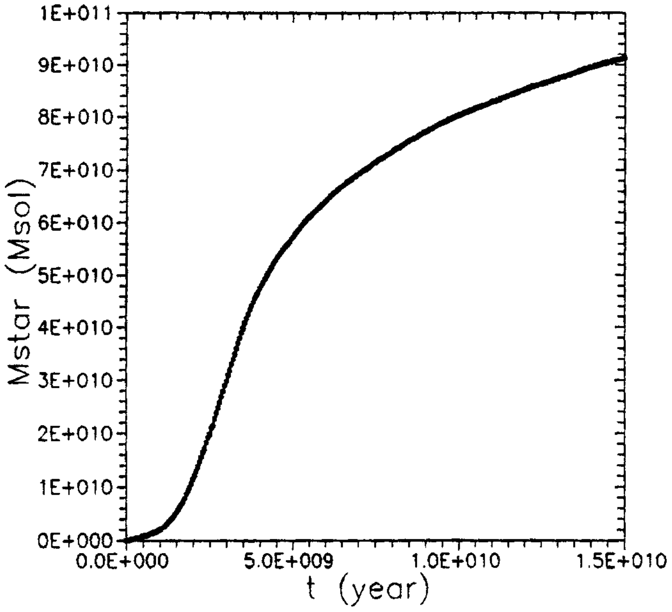

Figure 2 The growth of the galactic stellar mass with time.

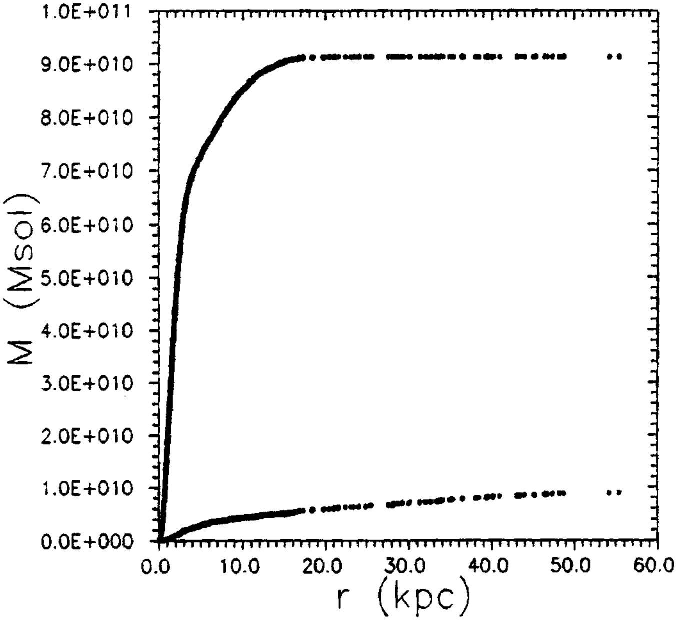

Figure 3 The cylindrical distribution of masses of stellar (upper curve) and gaseous (lower one) components as a function of distance from the galactic centre in the galactic plane.

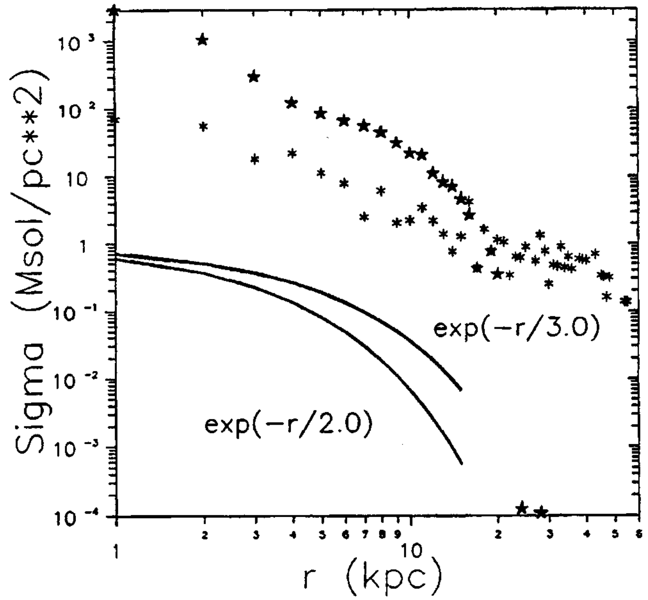

Figure 4 The surface density radial distributions of stellar and gaseous components (the stellar component is shown by filled stars, the gaseous one by asterisks). Theoretical distributions (not scaled) of surface density for radial exponential scale lengths 2.0 and 3.0 kpc are shown below by lines.

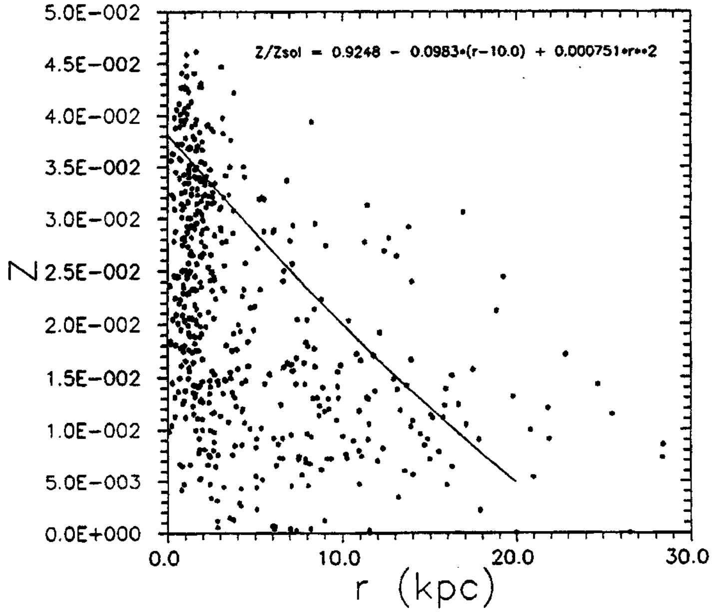

Figure 5 The radial distribution of heavy element abundances (the averaged observed distribution of z for our Galaxy is shown by the solid line).

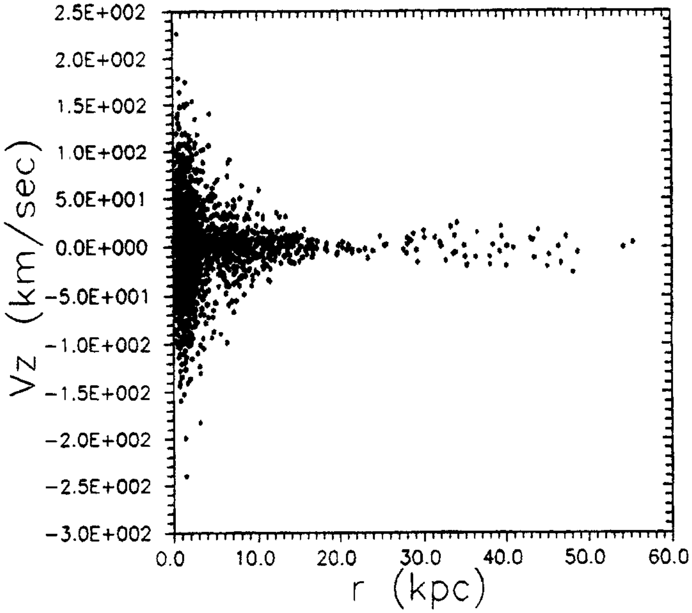

Figure 6 The final distribution of V_z velocities of baryonic gas-stellar particles.

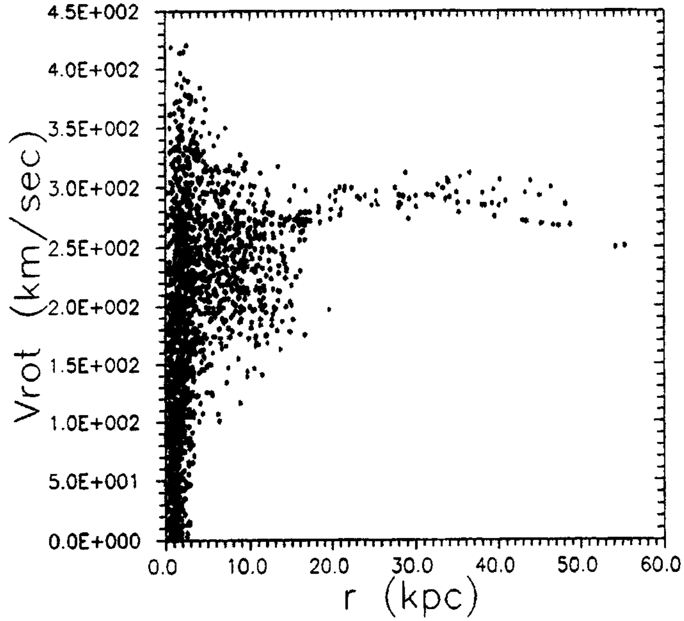

Figure 7 The final galaxy rotation curve.

global metallicity $Z/Z_{\odot}(r)$ (see Pagel, 1994) is shown in Figure 5 as a solid line.

- The disk component posesses a typical spiral galaxy rotation curve and the distribution of radial and V_z velocities of baryonic particles clearly show the presence of the central bulge (see Figure 6 and Figure 7).

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