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Formation of disk galaxies

I. From a hot gaseous envelope

V. Missoulis[1,2]

[1] Sternberg Astronomical Institute, Moscow State University
[2] Astronomical Institute, National Observatory of Athens, P.O. Box 20048, GR-118 10 Athens, Greece

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Abstract. The problem of the formation of a disk galaxy from a spherical, rotating, hot, gaseous envelope is solved by the means of a 2-D hydrodynamic code. Thermal instability and formation of clouds, cloud evaporation due to the hot surroundings and ram pressure, dynamical interaction between the gas and the clouds, energy dissipation by cloud-cloud collisions and radiation cooling of the intercloud gas are taken into account. Thermal conductivity is ignored. The most important of the results obtained are as follows:

1. At the time of the formation of the disk, the phase transitions lead to angular momentum transfer from the outer to the inner regions. If the temperature initially is independent of the distance from the center, the most important factor of the angular momentum transfer is the evaporation of the clouds. If initially the temperature is smaller at the outer regions, the most important factor of the angular momentum transfer is cloud-cloud collisions.
2. The observed exponential profiles can be understood as the result of angular momentum transfer due to the viscosity, which becomes important after the violent stage of the formation of the gaseous disk.
3. The model can explain the origin of the HI clouds located at large distances from the axis of spiral galaxies.

Owing to the complicated mathematics, the gas–cloud dynamical interactions and the numerical method are presented only in the on-line version of the paper.

Key words: hydrodynamics – galaxies: formation – galaxies: spiral

1. Introduction

Every reliable theory of the formation and evolution of spiral galaxies must be in agreement with the observations not only of spiral galaxies in general, but also and of our galaxy. It is now clear that our galaxy is constituted of at least two subsystems: Disk and spherical subsystem which are clearly separated by a gap in age, metallicity, spatial distribution and kinematics (Marochnik & Suchkov 1984; Suchkov 1988a). We have the same picture in every well-observed spiral galaxy (Sharov 1982; Tenjes 1993; Van den Bergh 1991). Specifically in our galaxy, we observe at least two subsystems of the disk and two subsystems of the spherical subsystem (thick disk, thin disk and bulge, halo respectively). (Marochnik & Suchkov 1984; Marshakov & Suchkov 1977; Freeman 1987).

The origin of the discrete subsystems can be explained by the hot model (Suchkov 1988ab; Berman & Suchkov 1989). The main idea of this model is the following: The massive stars of the first stellar generation explode as supernovae and consequently they heat the surrounding gas to a temperature higher than that required for virial equilibrium. At this time the galaxy expands and no stars can be formed until the galaxy gets cold enough to collapse. The hot model explained many observational data of elliptical galaxies (Berman & Suchkov 1989,1991; Suchkov 1989) and qualitatively the gap in age and metallicity between the disk and the halo of our galaxy (Suchkov 1988b), but it has not yet elucidated the problem of the formation of disks. Such an analysis must be in agreement with all the observational data of the disk galaxies. In the most of them, we observe disk, halo and bulge (Freeman 1987). Although there is no doubt that the disk and the halo are clearly separated, there are many concurrent theories for the bulge. Many stars in it have metallicity typical for the disk (Rich 1990; Ortolani et al.1990), spatial distribution typical for the halo (Freeman 1987), kinematics between the disk and the halo (Harding 1990; Menzies 1990; Rich 1990) and age from the old halo to the young disk (O'Connell 1990). Many authors have the opinion that the bulge has been formed with the halo (Rich 1990; Ortolani et al.1990) and many others that it has been formed with the disk or separetely (Carney et al.1990; O'Connell 1990; Winge et al.1990). From the above discussion we conclude that any assumption about the age of stars of the bulge is reliable. So the fraction of the mass of the second stellar generation in the bulge can be from 0 to 100%. The mass of the disk of our galaxy is nearly $6.10^{10} M_\odot$ and the mass of the bulge is nearly $10^{10} M_\odot$ (Bahcall 1986). In the Sab galaxy M81, we have $M_{disk} = 5.4.10^{10} M_\odot$ and $M_{bul} = 3.10^{10} M_\odot$ (Tenjes 1992). So it is reliable to assume that the mass of the bulge is always smaller than the mass of the disk.

For the disk, we have the well-known exponential dependence on the distance from the center, with central mass depletion (Freeman 1970; Kormendy 1977; Zasov & Zotov 1989; Einasto & Haud 1989; Haud & Einasto 1989; Van den Bergh 1991; Tenjes 1993). The model of Silk & Norman (1981) that, due to angular momentum transfer by the clouds, the disk acquires an exponential profile cannot explain the origin of the central mass depletion in the disks.

In the present investigation, we will examine if the main features of the disks of spiral galaxies can be explained by the hot model. For this aim, we will investigate the evolution of a hot gaseous envelope in the gravitational field of a dark matter condensation, whereas a cloudy system will be subject of a future investigation. At the second section, we describe the model. The third section presents the results and a discussion of them. The last section gives the conclusions. The dynamical interactions between the gas and the clouds and the numerical scheme are described in the appendices.

2. Model construction

It is clear that rapidly rotating disks have been formed by a dissipative collapse with angular momentum conservation. The origin of the angular momentum is not clear. Chernin & Shakenov (1991), Gurevich & Chernin (1987), Chernin(1990, 1993) describe several possible ways of its appearance. The initial profile of the rotational velocity will be different for different ways, and we can say nothing about its properties. Since the profile of the initial rotation is unknown, we will use various rotational laws. We adopt

$$\omega = \begin{cases} \omega_0 & \text{for} \quad r \leq r_0 \\ \omega_0 . \left(\frac{r}{r_0}\right)^{-n} & \text{for} \quad r \geq r_0 \end{cases} \tag{1}$$

where ω is the angular velocity. $N = 0$ corresponds to solid-body rotation and $N = 1$ to constant rotational velocity at the outer regions.

The first numerical solutions showed that one cannot ignore thermal instability (Clayton 1978, Spitzer 1978), as we did in the 1-D case (Missoulis 1994). We assume cold and dense clouds with $T = 300K$ and intercloud gas with $T \geq 10^4$K. Instead of the three phase model (Clayton 1978) we assume a two-phase one: Cold clouds and intercloud gas with a wide range of density and temperature. This approximation is better, because it permits us to study the transformation of the hot ($T \approx 10^7$K) to the warm ($T \approx 10^4$K) phase without change of the key parameters ρ, ϵ, P, u (density, specific internal energy, pressure and velocity respectively). So the baryonic matter of the galaxy is constituted of clouds and intercloud gas.

All of the clouds are assumed identical. We adopt that the density of the gas in them is $\rho_{in} = 2.10^{-23}$g.cm^{-3} and the temperature of the gas is $T_{in} \approx 300$K. These conditions are in agreement with the results of Izotov & Kolesnik (1984), for the primordial clouds formed by thermal–chemical instability in the early universe and also with the predictions of the 2-phase model of the interstellar gas (Clayton 1978). We assume that the parameter ρ_{in} is invariant. Its value does not change even when the pressure of the intercloud gas changes. Also we assume that the filling factor cannot be greater than 0.8. When the filling factor reaches the critical value 0.8, the density of the gas inside the clouds (ρ_{in}) increases in such a way that the filling factor remains equal to 0.8. This constraint of the filling factor has been defined only for numerical stability. Its influence to the final structure of the disk is negligible, because at the stage when the density is so high, the evolution is almost complete. We ignore the formation of stars. This approximation can be supported as follows:

1. In disk galaxies, the stars are formed only in large complexes (Efremov 1989). Also the observations of superthin galaxies (Goad & Roberts 1981) indicate that galaxies without central condensations (and consequently without spiral shock waves) have small rates of star–formation. These facts lead to the conclusion that the star formation in disk galaxies is a large-scale process and can't be determined only by the local parameters.
2. Our numerical scheme leads to an artificial angular momentum transfer from the inner to the outer regions. So the mass of the inner regions grows artificially. Because of that in our model the star–formation switch-on time and other features of the population I will be unclear.

Because of these approximations one must see the final results critically. In fact, we can only obtain qualitative results. Also we can assume different star–formation switch-on times and use them as possible variants of the final structure of the disk.

For the dark halo, we make the following assumptions:

1. It is spherically symmetric and unchangeable
2. Its gravitational field can be described by the equation:

$$f(r) = \begin{cases} GM_v r/r_v r_{av}^2 & \text{for} \quad r \leq r_{av} \\ GM_v/r_v r & \text{for} \quad r_{av} < r < r_v \\ GM_v/r^2 & \text{for} \quad r_v \leq r \end{cases} \tag{2}$$

where f is the gravitational force due to the dark halo at distance r from the center of the system, M_v, r_v, r_{av} are the mass, the radius and the radius of the core of the dark halo respectively. We assume $M_v = 10^{12} M_{\odot}, r_v = 100Kpc, r_{av} = 6$Kpc. This value of the mass of the dark matter is based on observations of the satellite of our galaxy LeoI (Zaritsky et.al. 1989) and from the dynamics of the binary system Milky Way-Andromeda (Einasto & Lynden-Bell 1982). In both of those papers, M_v could even be more, but since there are many other authors who conclude a smaller value, we assume $M_v = 10^{12} M_{\odot}$. As far as our galaxy is a giant disk galaxy, the conclusions from it can be used to approximate every giant disk galaxy.The value of r_v is a direct outcome of the value of the mass and the reliable assumption that $M_v(r)/r \approx 10^{10} M_{\odot}/\mathrm{Kpc}$ (Suchkov 1988c, Rubin 1983, Rubin et.al.1985).

On the contrary, the baryonic matter is very changeable. Phase transitions and dynamical interactions are taking place.

2.1. Phase transitions

By thermal instability, the intercloud gas can be condensed and give dense, cold clouds. We assume a cloud formation rate as follows:

$$\frac{d\rho_{cl}}{dt}|_{TH} = \begin{cases} 0 & \text{for} T_g \geq 10^4\text{K or} \\ & P/k \leq 10^3\text{grad.cm}^{-3} \\ bL\rho_g^2/\epsilon_1 & \text{for} T_g < 10^4\text{K and} \\ & P/k > 10^3\text{grad.cm}^{-3} \end{cases} \quad (3)$$

where ρ_{cl}, ρ_g, T_g, L, k, ϵ_1, b are the local density of the cold phase and the intercloud gas, the temperature of the intercloud gas, the cooling function at $T = 10^4 K$, Boltzmann's constant, the specific internal energy of gas with $T = 10^4 K$ and the efficiency of the thermal instability, respectively. Since the cooling function decreases rapidly for temperatures lower than 10^4K, we assume that $b = 10^{-3}$, in agreement with Cowie et al.1981. P is defined as $P = P_{th} + e.\rho_{cl}\sigma^2/3$, where P_{th} is the thermal pressure, σ is random velocity of the 'gas' of clouds, $e = min\{1, \tau_c/\tau_{cool}\}$, τ_c, τ_{cool} are the cloud collision time and the cooling time of the gas, respectively. The use of the parameter P can be explained as follows: According to Shu et. al.(1972), a cloud can be formed only when the surrounding of the newly-formed condensation can press significantly the new condensation. Shu et al. have concluded that it should be $P_{th}/k \geq 10^3$grad.K^{-1}. Nevertheless, they have suggested that the ambient medium was nearly homogeneous. On the contrary, in the problem described here, we have to take into account the influence of other clouds. Specifically, a cloud moving with supersonic velocity can contribute significantly to the compression of the intercloud gas by the shock-wave due to its motion. Also a newly-formed condensation can be compressed by ram pressure. The influence of the clouds is described by the term $e.\rho_{cl}\sigma^2/3$. In the last expression, $\rho_{cl}\sigma^2/3$ is the ram pressure due to the random motion of the clouds and e is the efficiency of the ram pressure owing to the fact that the clouds do not collide only with newly-formed condensations, but also with other clouds. The role of the systematic velocity field of the 'gas' of clouds is ignored, since it affects mainly the acceleration of the newly-formed condensation. Cloud formation is possible in this way even when the density of the diffuse gas is smaller than the critical value of $n = 0.1\text{cm}^{-3}$ (Clayton 1978), if there is strong compression by randomly–moving clouds. The condition (3) is valid because with the adopted cooling function, we have $\tau_{cool} \approx 10^7$yr when $T \leq 10^4$K, $\rho_g = 2 \times 10^{-25}$g.cm^{-3} and $\tau_{cool} \approx 10^6$yr when $T \geq 10^2$K, $\rho_g = 2 \times 10^{-25}$g.cm^{-3}. These time-scales are much smaller than the dynamical time-scale of the system, $t_{rot} \approx 10^8$yr.

The clouds can evaporate and give intercloud gas. The explanation of the evaporation law is unclear. Cowie & McKee (1977), Cowie et al. (1981), McKee & Cowie (1977) have investigated the problem of cloud evaporation by thermal conductivity. In our problem, the role of the shock-wave is expected to be much more significant and therefore the model of thermal conductivity is rather inadequate. Murray et al.(1993) have investigated a model of cloud evaporation due to ram pressure by assuming a quasi-steady state ambient medium. This approximation is not reliable in our problem. Also the clouds often interact with a shock wave. In this case, we expect violent evolution of a cloud when the shock wave crosses the cloud surface, and consequently the pressure equilibrium between the cloud and its surrounding gas is destroyed. The interaction of a cloud with a shock wave has been examined by Krebs & Hillebrandt (1983), but their result was more qualitative than quantitative. Due to the rather unclear nature of the evaporation law, we will assume simply that the cloud evaporation rate is proportional to the energy of the wind and the shocked gas per unit volume plus the ram pressure. So we have:

$$\frac{d\rho_{cl}}{dt}\|_{SUR} = \beta\rho_g\rho_{cl}. \left[\epsilon + \frac{(u_g - u_{cl})^2 + \sigma^2}{2}\right] \quad (4)$$

where u_g, u_{cl} are the velocities of the gas and the clouds respectively, ϵ is the specific internal energy of the gas, β parameter for normalization,defined as

$$\beta = \frac{V}{M_g.\epsilon_g.\tau_{cl}}$$

where V is the total volume of the system, M_g, ϵ_g the mass and the initial internal energy of the gas, τ_{cl} the cloud evaporation time. It is obvious that the cloud evaporation time depends on the internal properties of the cloud as density, temperature, existence of magnetic fields etc. Because of this uncertainty, we will examine models with different values of the parameter τ_{cl} (see Subsect. 2.2).

We cannot ignore the role of the cloud–cloud collisions. We assume that all the collisions are completely inelastic, so that after collision clouds merge to one body. We adopt the model of Brosche (1970) that half of the kinetic energy of the clouds is dissipated at one collision.

For the collision time, we have $\tau_c = 1/4\pi N r^2\sigma$, where N is the number density of the "gas" of clouds. We have $N = \rho_{cl}/m_0$, $m_0 = 4\pi\rho_{in}r^3/3$ where m_0 is the mass of a single cloud and r is the radius of the clouds. From these equations, we obtain

$$\tau_c = \frac{\rho_{in}^{2/3} m_0^{1/3}}{4.8\rho_{cl}\sigma} \quad (5)$$

The thermal instability cannot form gravitationally unstable condensations. From the Eq. (5) we can see that the role of the parameter m_0 is small, so we can assume that $m_0 = M_J/10$, where M_J is the Jeans mass for the clouds of our problem ($T = 300$K, $\rho_{in} \approx 2.10^{-23}$g.cm^{-3}).

Because of the phase transitions, a transfer of mass, angular momentum and energy occurs from one phase to the other. We define:

$$\dot{\rho}_{cl} = -\frac{d\rho_{cl}}{dt}\|_{SUR} \quad (6)$$

$$\dot{\rho}_g = -\frac{d\rho_{cl}}{dt}\|_{TH} \quad (7)$$

The phase transitions and the momentum, energy, etc. transfer can be described by the equations:

$$\Delta\rho_{cl} = (\dot{\rho}_{cl} - \dot{\rho}_g)\Delta t \quad (8)$$

$$\Delta\rho_g = (-\dot{\rho}_{cl} + \dot{\rho}_g)\Delta t \quad (9)$$

$$\Delta(\rho_{cl}A_{cl}) = (\dot{\rho}_{cl}A_{cl} - \dot{\rho}_g A_g)\Delta t \quad (10)$$

$$\Delta(\rho_g A_g) = (-\dot{\rho}_{cl}A_{cl} + \dot{\rho}_g A_g)\Delta t \quad (11)$$

where A can be either specific angular momentum or the velocity. The situation for the energy is less simple because at a phase transition there is dissipation of energy. At a cloud-cloud collision, half of the kinetic energy is lost. So we have:

$$\frac{dE_{cl}}{dt}\|_{COL} = -\frac{\sigma^2}{4\tau_c} \quad (12)$$

where σ is the random velocity of the clouds and E_{cl} the total specific kinetical energy of the 'gas' of clouds (The sum of the kinetical energy due to the systematic velocity field and the random motion of the clouds). The gas that escapes from a cloud is assumed to be cold ($T = 0$). The intercloud gas can form clouds only when it loses its thermal energy, so we assume that the gas is cold at the time of cloud formation. Because of that, we obtain for the energy transfer:

$$\Delta(\rho_{cl}E_{cl}) = (\dot{\rho}_{cl}E_{cl} - \dot{\rho}_g u_g^2/2 - \rho_{cl}\frac{\sigma^2}{4\tau_c})\Delta t \quad (13)$$

$$\Delta(\rho_g E_g) = (-\dot{\rho}_{cl}E_{cl} + \dot{\rho}_g E_g)\Delta t \quad (14)$$

where E_g is the specific internal plus kinetic energy of the gas. For the clouds, it is necessary to estimate the kinetic energy separately for the motion perpendicular to the plane of symmetry and for the parallel one. So from the Eq. (13), we have:

$$\Delta(\rho_{cl}E_{rf}) = [\dot{\rho}_{cl}E_{rf} - \dot{\rho}_g(u_{g,r}^2 + u_{g,f}^2)/2 - \rho_{cl}\frac{\sigma_r^2 + \sigma_f^2}{4\tau_c}]\Delta t \quad (15)$$

$$\Delta(\rho_{cl}E_z) = [\dot{\rho}_{cl}E_z - \dot{\rho}_g u_{g,z}^2/2 - \rho_{cl}\frac{\sigma_z^2}{4\tau_c}]\Delta t \quad (16)$$

Owing to the very complicated mathematics, the dynamical interactions are described only in appendix A, available only in the www page at http:// link.springer.de

2.2. Parameters of the models

We solve the problem of a diffuse envelope of hot gas by a numerical scheme. We adopt that $M_g = 10^{11}M_\odot$, r_0 =4Kpc, $R_0 = 80$Kpc, $M_{cl} = 0$.

For the cloud evaporation time-scale, we assume that $\tau_{cl} = 1.5 \times 10^8$yrs for the series A and $\tau_{cl} = \infty$ (the clouds do not evaporate) for the series B.

For the density of the gas, we adopt:

$$\rho_g = \begin{cases} \rho_{0g} & \text{for } r \le r_0 \\ \rho_{0g}.(r/r_0)^{-s} & \text{for } r_0 \le r \le R_0 \end{cases}$$

Table 1. The initial parameters of the models. T_g is measured in 10^7K, ω_0 is measured in Km.s^{-1}. Kpc^{-1} and J/M in 10^3 Kpc.Km.s^{-1}

No	T_g	s	ω_0	n	J/M
1	3	2	8	1	1.2
2	3	2	0.8	0	1.6
3	2	0	16	1	3.6
4	2	0	1.6	0	5.7
5	2	0	8	1	1.8
6	2	0	0.8	0	2.9
7	fig.1	1	16	1	3.2
8	fig.1	1	1.1	0	3.2
9	fig.1	1	16	1	3.2
10	fig.1	1	1.1	0	3.2
11	1	0	1.6	0	5.7

In Table 1 the values of the parameters T_g, s, ω_0, n, J/M for these models are presented.

We use various values of them to estimate their influence on the final result. The temperature has been chosen so high that the mass of the second stellar generation and the mass that escapes from the system will be of the same order of magnitude. For $s = 2$, the angular velocity has been chosen in such way that the rotational velocity at $R = R_0/2$ is independent of the parameter n. The angular velocity has been chosen by the same idea for $s = 0$ and also we examine models with small and large angular velocities. For the models 7—10 with non–constant gas temperature, the angular velocity has been chosen in such way that the parameter J/M is independent of the parameter n. For series B, we examine one more model (B11) which is the similar to B4, but its initial temperature is 2 times smaller. It will be clear in the following section why the initial rotational velocity of the models has been chosen in different ways in depending on the value of the parameter s and the initial temperature profile. The influence of the parameter R_0 is small. The value of the parameter r_0 is assumed small so that different values of the parameter n lead to significant difference of the initial situation. The mass of the gas is of the same order of magnitude as the baryonic mass of our galaxy, and the initial mass of the clouds is assumed equal to zero because the aim of the present paper is to investigate the evolution of a hot gaseous envelope.

3. Results and discussion

We solve the equations of the previous section by a numerical scheme described in appendix B, available in http:// link.springer.de. The approximations of the model construction are many, and because of that we can obtain only qualitative results. We are especially interested in estimating the masses of the bulge and the disk and the surface density profile of the disk.

For the estimation of the M_{bul}, we will take into account only the second stellar generation. We expect that $0 < M_{bul} < M_{disk}$. The boundary between the bulge and the disk is not clear. If the surface density has a minimum near 2Kpc, we will assume that this is the boundary of the bulge. If the minimum is inside the 1Kpc periphery, we will assume that this is the boundary of the

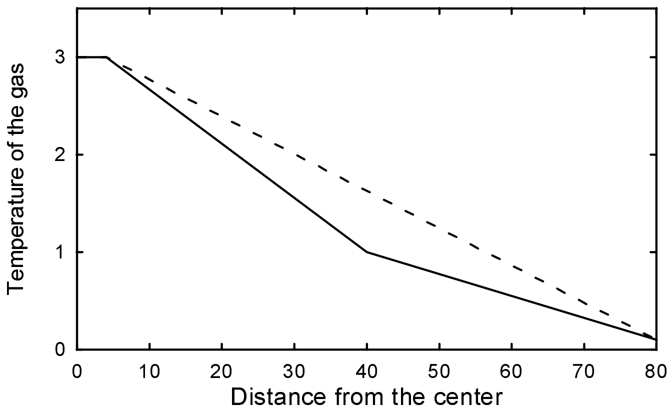

Fig. 1. The initial temperature of the gas as a function of the distance from the center for the models 7, 8 (solid line), 9, 10 (dashed line)

Table 2. The results of the series A models at $t = 4Gyrs$ (index "1") and at $t = 6Gyrs$ (index "2"). The masses are measured in $10^9 M_\odot$. The zero values are used when the mass is smaller than $10^9 M_\odot$.

No	M^1_{bul}	M^1_{disk}	M^2_{bul}	M^2_{disk}
1	78.7	0	84.2	0
2	80.4	0	89.0	0
3	0	65.4	0	82.0
4	0	61.0	7.8	64.2
5	0	76.8	0	84.2
6	0	63.2	3.5	74.1
7	0	74.0	1.5	71.2
8	0	71.5	15.0	57.5
9	0	74.8	0	74.4
10	0	59.6	18.0	56.0

Table 3. The same as Table 2 for the models of series B.

No	M^1_{bul}	M^1_{disk}	M^2_{bul}	M^2_{disk}
1	68.1	0	71.7	0
2	77.5	0	87.0	0
3	0	10.1	25.7	1.0
4	8.2	0	19.5	2.0
5	15.9	31.3	49.0	5.8
6	19.4	2.4	54.3	2.0
7	0	74.0	0	72.9
8	0	67.1	0	77.2
9	0	73.7	0	72.0
10	0	61.3	18.9	52.6
11	2.2	35.7	16.7	43.3

bulge. Unfortunately, there are situations with 2 or no minimum. In these cases we will estimate the boundary in the following way: If the boundary between the bulge and the disk is well defined at t=4Gyrs we will assume that the boundary at t=6Gyrs is the same. If the boundary is not well defined at t=4Gyrs, we will estimate it by the dependence of the surface density on the radius. This estimation will not be based on any concrete criteria. It will be subjective. In this case, we can only say that the distance of the boundary of the bulge from the rotational axis will always be assumed greater than 1Kpc. The mass of the disk is estimated from the total mass within the periphery with radius 18Kpc and the mass of the bulge. The disk should have exponential luminosity profile with central mass depletion. The exponential profile can be explained by the idea that the angular momentum is transferred from the inner to the outer regions due to viscosity occurring by the random motion of the clouds (Silk & Norman 1981, Gorbatskij & Serbin 1983, Lin & Pringle 1987, Saio & Yoshii 1990, Firmani et. al. 1996). Because of that, we can assume that the disks acquire the observed exponential profile after the stage of violent energy dissipation of the gas and the formation of a gaseous disk. From the above discussion, we can understand that a model is acceptable if its final situation has the following properties:

1. $M_{bul} < M_{disk}$
2. The surface density has a minimum at the boundary disk–bulge, or the bulge does not exist and the surface density has minimum at the rotational axis.

We take snap-shots for t=4 and t=6Gyr for every model. The resulting situations are presented in Tables 2, 3. One can see that the failure of the models 1, 2 of both series is obvious. The outer gas layers leave the system forever and the inner ones collapse to the center and form the bulge. From Tables 2, 3 one sees that the mass of the bulge is much larger than the mass of the disk. This result can be explained as follows: The inner regions are denser than the outer ones and the initial temperature is the same. So the cooling time will be smaller at the inner regions. The inner layers also feel the pressure of the outer ones, which does not permit them to expand. As result, a cold nucleus is formed when the outer layers are still hot. On the other hand, the outer layers feel the pressure of the inner ones due to the hot gas. They also feel weak gravitational force, and consequently they can expand and leave the system for ever. The picture is the same as in Berman & Suchkov (1989, 1991), Missoulis (1994). So only the inner layers with small specific angular momentum will contribute to the formation of the second stellar generation, and the disk will be weak because of that.

From the above discussion it is clear that the reason of the formation of strong bulges is not the artificial angular momentum transfer occurring due to our numerical scheme, but the fact that the outer layers with large specific angular momentum escape and only the inner layers with small specific angular momentum contribute to the formation of the second stellar generation. We can also see that the bulge is stronger when $n = 0$, although in this case the parameter J/M is larger. This result can be explained as follows: When $n = 0$, the specific angular momentum of the outer layers is larger than in the case $n = 1$. So for the same mass ejection, the angular momentum ejection is larger when $n = 0$. On the contrary, the specific angular momentum of the inner layers is smaller when $n = 0$, so a larger fraction of the initial mass can be accreted to the nucleus.

From Tables 2, 3 one can see that in some cases the models with initial temperature independent of the distance from the center give reliable results. Specifically in Figs. 2–3 one can see

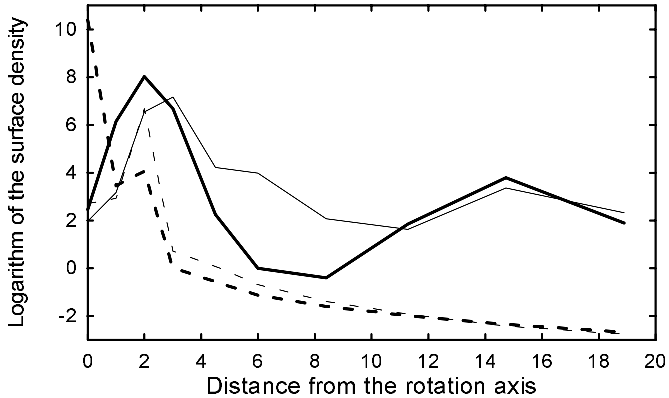

Fig. 2. The dependence of the surface density (in $M_\odot$.pc^{-2}) on the distance from the center (in Kpc) for the models A3, B3. Thin solid line: A3 for t=4Gyr. Thick solid line: A3 for t=6Gyr. Thin dashed line: B3 for t=4Gyr. Thick dashed line: B3 for t=6Gyr.

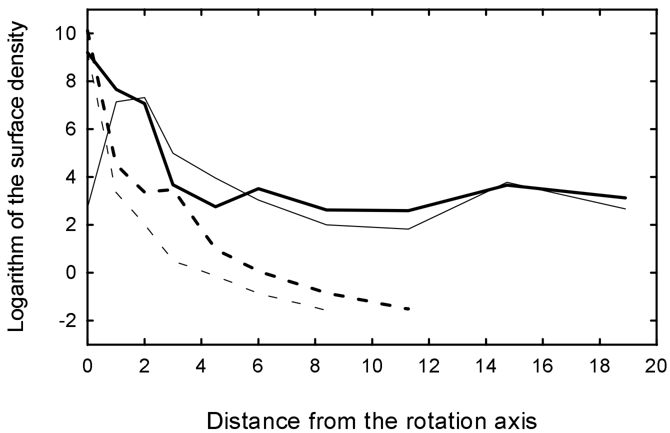

Fig. 3. The dependence of the surface density on the distance from the center for the models A4, B4. Thin solid line: A4 for t=4Gyr. Thick solid line: A4 for t=6Gyr. Thin dashed line: B4 for t=4Gyr. Thick dashed line: B4 for t=6Gyr.

the surface density profiles of the models 3 and 4. From these figures we can see that the models A3, A4 form strong disks and weak bulges whereas the models B3, B4 form strong bulges and weak disks. This result can be explained as follows: Fig. 3 makes clear that in model A4 a large fraction of the mass of the disk is located in regions close to the center, so the difference is not as large as the comparison of the masses of the disks and the bulges indicates. Similarly for the model A3, over 70% of the mass of the disk is located inside 5Kpc from the rotational axis. Then as concluded in Suchkov & Berman (1988) for a non-rotating gaseous envelope, hydrodynamic equilibrium $\rho\mathbf{g} + \nabla P = 0$ establishes very soon. So the density at the inner regions will be larger than at the outer regions and, if the temperature is the same in the inner and the outer regions, the cooling time will be smaller at the inner regions. It will be the same in the case of initially equal temperatures and adiabatic condensation of the central regions. At the earliest stages of the evolution, the role of rotation is negligible and hydrodynamic equilibrium can be established. Afterwards, the rotational velocity becomes large

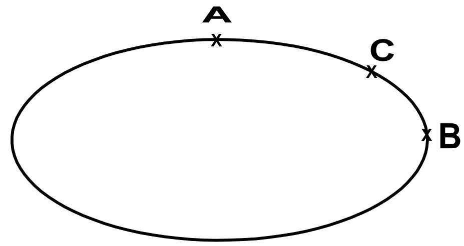

Fig. 4. A schematic picture of the angular momentum transfer by cloud evaporation and cloud-cloud collisions. The ellipsis is the projection of the trajectory of the cloud on the plane of symmetry. The cloud A is formed at the point A and C is the equilibrium radius of the cloud C where also the collision is assumed to take place.

and no further condensation perpendicular to the galactic axis is possible. The inner layers continue cooling and their density remains almost constant. Consequently, their pressure decreases. At this stage, the inner layers can reach regions closer to the galactic axis than their angular momentum would permit them, because of the pressure of their outer neighbours. If there were not angular momentum transfer, as a final result we would expect that the surface density would steadily increase towards the galactic center. Nevertheless, the clouds formed at the inner regions will feel no more the pressure from the outer regions, so they will leave the inner regions. To examine the effect of such phase transitions we assume a cloud forming at point A (see Fig. 4) with rotational velocity larger than $\sqrt{g_A r_A}$ (g_A, r_A are the gravitational force at point A and its distance from the center respectively). The cloud will move on an elliptical trajectory with pericentric distance r_A and anticentric distance r_B. In series A, the cloud evaporates along its trajectory and consequently transfers its mass and angular momentum to distances larger than r_A. The specific angular momentum there is larger than the specific angular momentum of the cloud, so the specific angular momentum of the outer regions is reduced. On the other hand, the region of point A loses mass and consequently the pressure there decreases. So mass from the outer regions can flow towards the center. The specific angular momentum of the outer regions is larger, so the specific angular momentum of the region of point A is increased. The formation of clouds leads to angular momentum transfer from the outer to the inner regions. This mechanism is similar to the idea of the violent angular momentum transfer that is described in Missoulis (1997). In series B, the clouds do not evaporate and no angular momentum is transferred. By the mechanism described above, the small density of the models A3, A4 at the central regions can be explained as deficiency of gas with small specific angular momentum. Similarly, the small mass of the disk in models B3, B4 can be explained as a deficiency of gas with large specific angular momentum.

In fact, angular momentum can be transferred also by cloud–cloud collisions. When a cloud A with specific angular momentum h_A and mass m_A collides at point C (see Fig. 4) with a cloud having mass m_C and specific angular momentum $h_C > h_A$, the two clouds will merge to one body with specific angular momentum $(m_C h_C + m_A h_A)/(m_C + m_A)$. So the equilibrium distance of the merger will be larger than r_A but smaller than r_C. Nevertheless this mechanism of angular momentum transfer is not effective since the inner regions form clouds earlier than the outer ones. So the clouds formed at one region will not transfer their angular momentum until the outer regions form significant numbers of clouds. The numerical simulations show that the cold inner regions with $T = 10^4 K$ are always surrounded by regions with temperatures as high as $10^7 K$, so in series B the angular momentum transfer is negligible. Consequently a strong bulge is formed. On the contrary, in model B11 with 2 times smaller temperature than model B4, the cooling time of the gas is smaller and consequently clouds can be formed in larger regions than in model B4. Consequently angular momentum can be transferred by collisions. Because of that, the model B11 forms a strong disk. By comparing the density profile of model B11 (Fig. 5) with the profiles of models A4, B4 (Fig. 3) one can see that the profile B11 resembles that of A4 rather than that of B4. It is possible that the bulges in models B3, B4, A4 for t=6Gyrs have been enhanced by the artificial angular momentum transfer of the numerical scheme, but there is no doubt that in the models B3—B6 without cloud evaporation the mass concentrates to the center. At the contrary, cloud evaporation can evacuate the center by mechanism of violent angular momentum transfer.

Another important result is that the models A give more massive second stellar generation than the models B. This result can be understood because the cloud evaporation leads to energy dissipation. There are two reasons for the energy dissipation due to the evaporation of the clouds: i) The intercloud gas is mixed with cooler gas so its temperature decreases, ii) The density of the intercloud gas increases and consequently increases the rate of energy loss by radiation cooling. With the adopted cooling function, for $10^5 K < T < 4 \times 10^7 K$ we obtain $\tau_{cool} \propto T^{1.6}$. So if the mass of the cold gas that escapes from an evaporating cloud is equal to the mass of the warm gas of its surroundings, the cooling time of the warm gas will be 6 times smaller. On the other hand, when the clouds evaporate, the time-scale τ_c increases and consequently the energy dissipation rate by cloud-cloud collisions decreases. From the above discussion, we can understand that in models A3—A6 the energy dissipation due to the evaporation of the clouds is more important than the energy dissipation due to cloud-cloud collisions.

In models 7—10, a strong disk and a weak bulge are formed in both series A, B. This result was expected: In the case of large temperature gradient, it is possible that the outer regions will start forming clouds earlier than the inner regions. This result can be understood because, from the adopted cooling function, we have $\tau_{cool} \propto T^{1.6}$ for $10^5 K < T < 4.10^7 K$. So the outer ”cold” diffuse layers will form clouds earlier than the inner hot ”dense” ones. Specifically in the present problem one can see that the cooling time of the gas is very small at the outer regions, small at the central regions and large at the intermediate regions. So the pressure of the outer layers will stop acting on the intermediate ones. Consequently, the intermediate layers will expand and in the end will remain only the layers with either very small or very large specific angular momentum in the system. In Figs. 6, 7 one can see the surface density profiles of models 9, 10. The profiles of models 7, 8 are similar. The most important result is the existence of 2 peaks: One near the center and one at distance about 15Kpc from the rotational axis. This result is in agreement with the suggestion that the outer and the inner layers remain in the system, whereas the intermediate layers fly away. The role of the formation of clouds in these models is crucial, because if clouds were not formed at the outer layers, the outer layers would be ejected by the pressure of the intermediate layers and perhaps the intermediate layers could not fly away. Secondly, the formation of clouds at the outer regions leads to a ’switch-on’ of the angular momentum transfer. Specifically, the clouds that will be formed at the outer regions will start moving on trajectories with large eccentricities, so they can reach regions very close to the center. In series A, a large fraction of their mass will evaporate there and it will be mixed with the gas of the inner regions of the system. In this way, the clouds from the outer regions will transfer angular momentum to the inner layers of the system. In both series A and B, if the eccentricities of the trajectories of the clouds that formed at the outer regions are close to unity, then the clouds will reach regions very close to the center. By colliding there with the clouds that formed at the central regions, the specific angular momentum of the latter will increase and consequently their distance from the rotational axis. In this way, the central regions are evacuated. With the adopted gravitational field and rotation laws, a cloud formed at distance 80Kpc from the rotational axis can reach regions with $r = 12.4\,\mathrm{Kpc}$ when $n = 1$ and $r = 19.2\,\mathrm{Kpc}$ when $n = 0$. Only 14% of the initial baryonic mass of the system is closer to the rotational axis than 20Kpc, so one can understand how important role the angular momentum transfer can play.

The similarity of the profiles of the models with and without cloud evaporation indicates that in the situation where the temperature of the gas decreases at the outer regions, the most important factors of the angular momentum transfer are the cloud collisions and the escape of the intermediate gas layers. The similarity of the profiles of the models with $n = 1$ and those with $n = 0$ indicates that the angular momentum transfer is so strong that the role of the initial rotational profile is small. By the assumption that the role of evaporation of the clouds is not very important one can understand the result that the masses of the disks are nearly the same for the series A and B: There is small energy dissipation due to the evaporation of clouds. In models 1, 2, the masses of the bulges are nearly equal because the collapse is so rapid that the clouds have not much time to evaporate. For model A7, one can see that the disk is more massive at t=4Gyrs than at t=6Gyrs. This result can be understood as outflow of matter with large specific angular momentum.

So the models with temperature decreasing with distance from the center give disks with central mass depletion. It is very interesting that the initial conditions of these models can be explained more easily as result of the action of an old stellar population with strong central condensation that as the bulge+halo system. Nevertheless, the dependence of the surface density on

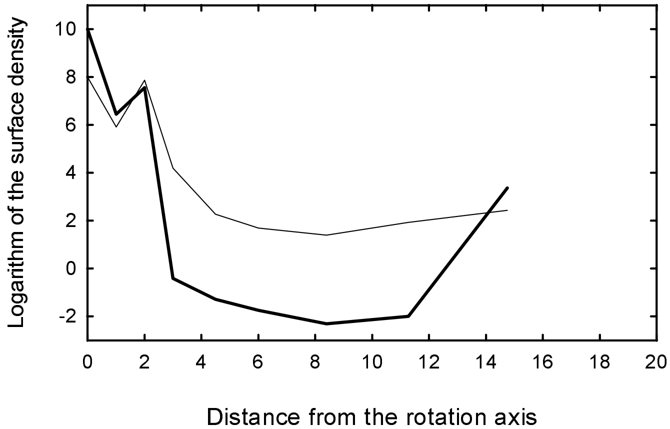

Fig. 5. The dependence of the surface density on the distance from the center for the model B11. Thin line: t=4Gyr. Thick line: t=6Gyr.

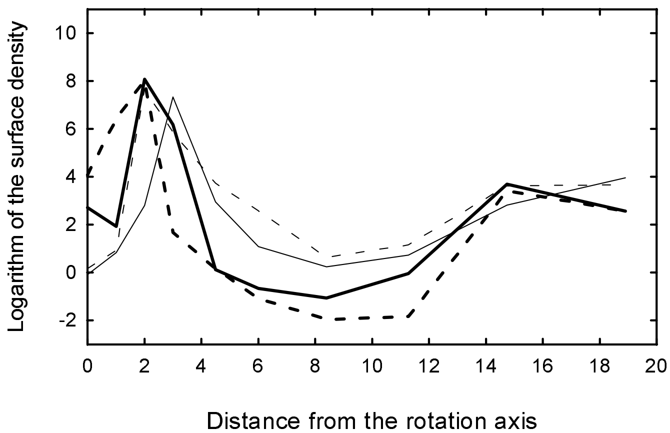

Fig. 6. The dependence of the surface density on the distance from the center for the models A9, B9. Thin solid line: A9 for t=4Gyr. Thick solid line: A9 for t=6Gyr. Thin dashed line: B9 for t=4Gyr. Thick dashed line: B9 for t=6Gyr.

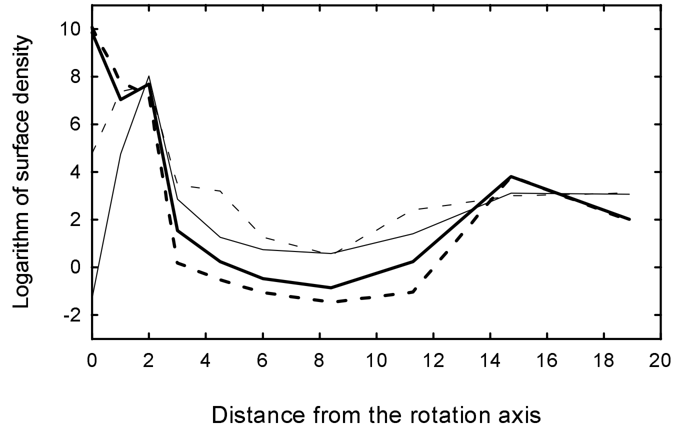

Fig. 7. The dependence of the surface density on the distance from the center for the models A10, B10. Thin solid line: A10 for t=4Gyr. Thick solid line: A10 for t=6Gyr. Thin dashed line: B10 for t=4Gyr. Thick dashed line: B10 for t=6Gyr.

the distance from the rotational axis does not resemble the expected exponential profile.

The resulting surface density profile can be understood if we assume that the viscosity due to the random motions of the clouds can redistribute the mass and give the observed exponential profile. There are several papers which indicate that the origin of the observed exponential profile is the mass redistribution which takes place in a disk when the angular momentum is transferred due to the viscosity (Gott & Thuan 1976, Silk & Norman 1981, Lin & Pringle 1987, Saio & Yoshii 1990, Firmani et. al. 1996, Gorbatskij & Serbin 1983). All of these models suggest that the angular momentum is transferred outwards. This is not in disagreement with the result of the present investigation that at the time of the formation of the disk the angular momentum is transferred inwards, because of the different assumptions of our model.

Specifically Gott & Thuan (1976) have assumed that the cloud-cloud collisions are completely elastic and that no phase transitions are taking place. In our model, we have assumed that the cloud-cloud collisions are inelastic and also that the evaporation of clouds and the formation of new ones is possible. On the other hand Silk & Norman (1981), Lin & Pringle (1987), Saio & Yoshi (1990), Firmani et. al.(1996), Gorbatskij & Serbin (1983) have examined the evolution of a gaseous disk where the gas and the clouds are moving on nearly circular trajectories and the gravitational force is balanced by the rotation. They have also assumed that the mean free path of the clouds is small and consequently they have taken into account only local effects. In our model, the key factors for angular momentum transfer outwards are the inelastic cloud-cloud collisions, the phase transitions, the non-circular motion of the clouds and the large mean free path of the clouds.

The model of the viscosity is not in dissagreement with the model of the violent angular momentum transfer, because these physical procedures are separated in time. Violent angular momentum transfer takes place at the time of the formation of the disk and the model of the angular momentum transfer due to the viscosity is important when the disk had already formed. From the above discussion we can conclude that the disks initially have strong density inhomogeneities. The exponential profile is acquired afterwards because of the viscosity. It is necessary to estimate the time required for a disk to acquire exponential profile. Nevertheless there is not any certain answer to this question. Firmani et al.(1996) have concluded that the exponential profile is established at much smaller time-scale than the age of the disk even in the case of a flat initial density profile. This result depends on the star-formation rate, as concluded in Saio & Yoshii (1990). The models examined here indicate that the initial deviation of the density profile from the exponential model can be much larger than Firmani et al. have assumed. According to Lin & Pringle (1987), the viscosity is more effective when the viscocity time-scale is close to the star formation time-scale.

From the above discussion, we can understand the result of Freeman (1970) that there are 2 types of surface density profiles: In Freeman's type I galaxies, the angular momentum transfer due to the viscosity was effective enough to erase any central mass depletion of the early disk or the angular momentum had not redistributed significantly during the formation of the gaseous disk. Because of that, the luminosity profile can be described by an exponential law. In Freeman's type II galaxies, the viscosity was not so effective or the angular momentum had been strongly redistributed. Because of that, today the observed luminosity at $r_1 < r < r_2$ is smaller than that expected by the exponential law and the luminosity of the neighbouring regions. The existence of central peak which is observed in the galaxies of type II can be understood as the influence of the bulge.

Another important result is that the models 7—10 can explain the origin of the observed HI clouds at large distances from the galactic axis. Specifically the resulted surface density at $r \simeq 15\,\mathrm{Kpc}$ is about $40 M_{\odot}$.pc^{-2}. If we assume that the thickness of the disk is 1Kpc, we obtain $\rho \simeq 3$g.cm^{-24}. This density is sufficient for the formation of clouds due to thermal instability. Afterwards the viscosity destroyes these peaks, but the HI clouds remain. The nearly solar abundance of these clouds can be understood if we assume that the initial gaseous envelope has been heated and enriched in heavy elements by the supernova explosions of the stars of the bulge and the halo. This assumption is in agreement with the idea of the hot model (Suchkov 1988ab; Berman & Suchkov 1989).

4. Conclusions

We have studied in this paper the formation of a disk by a dissipative collapse of a gaseous sphere with angular momentum conservation. Although the approximations in the model construction were many, it is clear that at the time of the formation of the disk the angular momentum is transferred from the outer to the inner regions when the following conditions are satisfied:

1. The cloud formation due to thermal instability of the cooling gas is important.
2. The clouds are moving on non-circular trajectories and their mean free path is large.
3. The clouds can evaporate and leave their material along their trajectories or they can collide inelastically with other clouds. The effects of cloud evaporation are more important when the initial temperature of the gas does not depend on the distance from the center, whereas when the temperature decreases at the outer regions, the role of the cloud-cloud collisions becomes more important.

Due to the angular momentum redistribution, a disk with high inhomogeneities in density can be formed. Afterwards, it acquires the well-known exponential profile due to viscocity. In this way one can understand the origin of both the exponential profile and the central mass depletion in many disks of spiral galaxies.

Especially interesting are the models where the initial temperature is decreasing at the periphery, because such dependence is expected when the gas has been heaten by a bulge+halo system with strong central condensation. In these models, it is possible that the intermediate layers will have larger cooling times than the inner and the outer ones, so that they will escape from the system. The numerical solutions show that this idea can explain the origin of HI clouds rich in heavy elements, located at large distances from the galactic axis.

It is obvious that the here adopted initial situation in fact is not the first stage. It is necessary to understand how this hot envelope could be formed. So one must examine earlier stages and to answer this question. Nevertheless, the model described here succeeded to explain many properties of the disks of spiral galaxies. It is possible that more reliable initial conditions will give more reliable results and for this point a lot of work has to be done.

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References

Bahcall J.N.1986, ARA&A Vol.24, p.577
Belotserkovskij O.M., Davidov Yu.M. 1981, Dissipational properties of differential schemes. Moscow, In Russian
Belotserkovskij O.M., Davidov Yu.M.1982, The method of great particles in the gas-dynamics. Moscow, In Russian
Berman V.G., Suchkov A.A.1989, Afz. Vol.30, No1, p.48
Berman V.G., Suchkov A.A.1991, Ap&SS Vol.184, p.169
Black D.C., Bodenheimer P.1975, ApJ. Vol.199, p.619
Boss A.P.1980, ApJ. Vol.236, p.619
Brosche P.1970, A&A Vol.6, p.240
Carney B.W., Latham D.W., Laird J.B.1990, ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.127
Chernin A.D.1990, The rotation of the galaxies. Moscow, In Russian.
Chernin A.D.1993, A&A Vol.267, p.315
Chernin A.D., Shakenov M.B.1991, SvA Lett. Vol.17, No4.
Clayton D.D.1978, The cloudy state of interstellar matter. In "protostars and planets I" Gehrels T., Shapley, M. p.13 Arizona
Cowie L.L., McKee C.F.1977, ApJ Vol.211, p.135
Cowie L.L., McKee C.M., Ostriker J.P.1981, ApJ Vol.247, p.908
Dorfi E.1982, A&A Vol.114, p.151
Efremov Yu.N.1989, Sov.Sci.Rev. E. Ap. Space Phys. Vol.7, p.105
Einasto J., Haud U.1989, A&A Vol.223, p.89
Einasto J., Lynden-Bell D.1982, MNRAS Vol.199, p.67
Firmani C., Hernandez X., Galagher J.1996, A&A Vol.308, p.403
Freeman K.C.1970, ApJ Vol.160, p.811
Freeman K.C.1987, ARA&A Vol.25, p.603
Goad J.W., Roberts M.S.1981, ApJ Vol.250, p.79
Gorbatskij V.G., Serbin V.M.1983, Afz Vol.19, No1, p.79
Gott J.R., Thuan T.X.1976, ApJ Vol.204, p.649
Gurevich L.E., Chernin A.D.1987, The origin of the galaxies and stars. Moscow, In Russian.
Harding P.1990, ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.105
Haud U., Einasto J.1989, A&A Vol.223, p.95
Izotov Yu.I., Kolesnik I.G.1984, SvA Vol.28, No1, p.15
Kormendy J.1977, ApJ. Vol.217, p.406
Krebs, Hillebrandt 1983, A&A Vol.128, p.411
Landau L.D., Lifshits E.M.1988, Theoretical physics. VI.Fluid mechanics. Moscow, In Russian.
Lin D.N.C., Pringle J.E.1987, ApJ. Vol.320, p.L87
Marochnic L.S., Suchkov A.A.1984, The galaxy (In Russian), Nauka, Moscow (Engl. ed. in Gordon and Breach, 1994)
Marshakov V.A., Suchkov A.A.1977, SvA Vol.21, No6

McKee C.F., Cowie L.L.1977, ApJ Vol.215, p.213
Menzies J.W.1990, ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.15
Missoulis V.1994, SvA Vol.71, No1, p.17
Missoulis V.1997, Galaxy Interactions at low and high redshifts, IAU symposium 186, 26–30 August 1997, Kyoto, Japan .....in press
Murray S.D., White S.D.M., Blondin J.M., Lin D.N.C.1993, ApJ. Vol.407, p.588
O' Connell R.W.1990, ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.187
Ortolani S., Barbuy B., Bica E.1990., ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.167
Rich R.M.1990, ESO/CTIO Workshop on BULGES OF GALAXIES. La Serena, Chile 16-19/1/1990, p.65
Rubin V.1983, Sci. Vol.220, No4604, p.1339
Rubin V.C., Burnstein D., Kent W., Ford Jr., Thonnard N.1985, ApJ Vol.289, p.81
Saio H., Yoshii Y.1990, ApJ. Vol.363, p.40
Samarskij A.A., Popov Yu.P.1992, Differential methods of the solutions of gas-dynamics problems. Moscow, In Russian.
Sharov A.S.1982, The Andromeda nebula. Moscow, In Russian
Shu F.H., Millione V., Gebel W., Yuan C., Goldsmith D.W., Roberts W.W. 1972, ApJ Vol.173, p.557
Silk J., Norman C.1981, ApJ. Vol.247, p.59
Spitzer L.1978, Physical processes in the interstellar matter
Suchkov A.A.1988a, Galaxies well-known and puzzling ones. Moscow, In Russian
Suchkov A.A.1988b, SvA. Vol.32, No1, p.1-6
Suchkov A.A.1988c, Afz. Vol.28, No2, p.279
Suchkov A.A.1989, SvA.Lett. Vol.15, No2, p.92
Suchkov A.A., Berman V.G.1988, Afz Vol.28, p.87
Tenjes P.1992, Baltic Astronomy Vol.1, p.7
Tenjes P.1993, Ph.D.Thesis Observatory of Tartu, Estonia
Van den Bergh S.1991, PASP Vol.103, p.1053
Winge C., Storchi-Bergmann T., Pastoriza M.G.1990, ESO/STIO Workshop on BULGES OF GALAXIES. La Serena, Chile, 16-19/1/1990, p.325
Zaritsky, Olszewski, Schommer, Peterson, Aaronson 1989, ApJ Vol.345, p.759
Zasov A.V., Zotov V.M.1989, SvA.Lett. Vol.15, No2, p.90