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ASTRONOMY AND ASTROPHYSICS

Ram-pressure accretion of intergalactic gas clouds by galaxies

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Abstract. Intergalactic gas clouds are captured and accreted by an encounter with gaseous halos of galaxies due to the ram-pressure friction. If clouds are captured by an elliptical galaxy embedded in a hot halo without rotation, they first form a circum-galactic band of cool gas and then fall toward the central region along an "accretion spiral", and probably act to fuel the AGN. If clouds are captured by a spiral galaxy with a rotating disk and halo, they form stochastic spiral arms in the outer region of the galaxy, while they make a ring feature in the inner region. The accretion rate is higher when clouds' encounter is retrograde with respect to the galaxy's rotation, while it is lower when the encounter is direct. This asymmetric accretion about the rotation axis results in a significant loss of angular momentum of the disk and halo, leading to a subsequent contraction of the galactic disk. When the encounter is off the galactic plane, retrograde clouds are captured and further accreted into the nuclear region along polar orbits. This accretion toward the central region feeds cool gas to the nucleus and will trigger starburst. Such an external fueling will act as the triggering mechanism for starburst in isolated spiral galaxies. The accretion of intergalactic clouds may also explain some peculiar kinematics of gas such as the counter-rotation in the central regions of some early-type galaxies. We point out that such a gas-dynamical process of accretion of intergalactic gas clouds, besides the gravitational effect, would have played an important role in the evolution and dynamics of primeval galaxies in the early universe, when the intergalactic space was rich in protogalactic gas clouds.

Key words: accretion – galaxies: halo – galaxies: kinematics and dynamics – galaxies: nuclei – intergalactic gas – ram-pressure

1. Introduction

The ram pressure, or the gas-dynamical pressure, of the intergalactic gas has been discussed in relation to stripping of interstellar gas from spiral galaxies and the origin of S0 galaxies in rich clusters of galaxies (Gunn & Gott 1972; Gisler 1979; Farouki & Shapiro 1980). The stripping is effective if the intergalactic gas density and the velocity of the galaxy against the intergalactic gas are high enough. On the other hand, if the intergalactic gas and clouds encounter the galaxy with smaller velocities, they will be accreted by the galaxy. However, this process of capture and merging of intergalactic clouds by a galaxy has not been thoroughly discussed. In this paper, we study effects of the ram-pressure by gaseous halos and disks of galaxies on motions of intergalactic gas clouds.

It has been suggested that accretion of circumgalactic and intergalactic gas clouds on galaxies might be a cause for cool gas observed around elliptical galaxies (e.g. Sandage 1961; Knapp 1988; Kormendy & Djorkovski 1989; van Gorkom et al. 1986; Wakamatsu 1990, 1991). In particular, H I absorption at redshifted velocities against radio active nuclei of elliptical galaxies suggests that infall of cool gas is a rather common phenomenon in elliptical radio galaxies (van Gorkom et al. 1986). Observations of a considerable number of early-type galaxies, where gas is orbiting perpendicularly or in a counter-rotating sense to the stellar rotation, have suggested the idea that the acquisition of gas from outside is not a rare event (Bertola 1987; Schweizer 1987; Bettoni et al. 1990; Baum et al. 1992).

Sources of the cool gas observed in early type galaxies may be of intergalactic origin, either tidal debris of colliding galaxies or of intrinsically intergalactic origin. In fact intergalactic H I clouds and tails have been extensively observed in interacting galaxy systems (e.g. Gottesman & Weliachev 1977; Weliachev et al. 1978; Combes 1978; Smith 1991). Intracluster H I clouds have been also detected in multiple systems like Leo triplet (Haynes et al. 1979) or around elliptical galaxies in the central regions of clusters (Sancisi et al. 1987). In our Local Group around the Galaxy, we also find similar H I clouds such as observed as high-velocity clouds, although their distances are still controversial (e.g. van Woerden et al. 1985). The H I gas in the Magellanic Stream is obviously a tidal debris of the large and small magellanic clouds during tidal interaction

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among themselves as well as with the Galaxy, and may be falling toward the Galaxy (Mathewson et al. 1979; Fujimoto & Sofue 1976, 1977).

In the current works, however, only the gravitational effects have been considered in order for gas clouds to be captured and accreted by galaxies. For instance, dynamical friction by massive halos plays a role to merge massive objects like galaxies (White 1978; McGlyn & Ostriker 1980; Barnes 1989), while it is less effective for smaller mass objects such as tidal debris and gas clouds. Namely, the gravitation is not efficient for merging and capture of tidal debris and H I clouds. Therefore, effects other than gravity should plays an essential role in the accretion of intergalactic gas to galaxies. We point out that such a gas-dynamical process of accretion of intergalactic gas clouds, besides the gravitational effect, would have affected the evolution as well as dynamics, such as the change of angular momentum, of primeval galaxies in the early universe, when the intergalactic space was rich in protogalactic gas clouds.

Recently we proposed a ram-pressure accretion model for merging intergalactic gas clouds (Wakamatsu 1990, 1991; Sofue & Wakamatsu 1991, 1992). In our model we took into account gas-dynamical interaction of the clouds with hot gaseous halos and intergalactic gas around elliptical galaxies embedded in an extended hot (X-ray) gaseous halo. We further discussed accretion by spiral galaxies due to their hot gaseous halos and disks in galactic rotation, and have shown the possibility of fueling the nuclei and triggering starburst in isolated galaxies.

In this paper we describe the ram-pressure accretion (RPA) model in full details and discuss related problems. In Sect. 2 we compare the stripping and accretion conditions of the intergalactic gas, and formulate equations used in our model. In Sect. 3 we compute orbits of individual clouds for elliptical and spiral galaxies in various circumstances. In Sect. 4 we discuss the accretion processes of clouds into the nuclear regions of elliptical and spiral galaxies based on numerical simulation, and point out the possibility of feeding active galactic nuclei (AGN) and starburst activity. In Sect. 5 we discuss related problems, such as angular momentum transfer between the disk and intergalactic clouds, etc., and describe the implication of the present model on various astrophysical phenomena in galaxies.

2. Ram-pressure accretion model

2.1. *Gravitationally bound intergalactic H I clouds*

In this work, we treat ballistic orbits of intergalactic H I gas clouds orbiting around galaxies surrounded by hot gaseous halo as well as by intergalactic diffuse gas. We assume that each cloud is a gravitationally bound system. We take the following size and mass for the cloud, which are about the same order as those for inter-galactic H I clumps (debris) as observed in the Magellanic Stream (Mathewson et al. 1979; van Woerden et al. 1985): radius of the H I cloud is taken to be $R \sim 0.5$–1 kpc, density of $\rho_{\rm H\,I} \sim 0.5$–$1 m_{\rm H}\,{\rm cm}^{-3}$, and mass of $m_{\rm H\,I} \sim 0.6$–$10\;10^7 M_{\odot}$. The gravitational force by the cloud is assumed to be in a balance with internal motion of $10 \sim 20$ km s^{-1}, which is of the order of observed velocity dispersion in debris in the Magellanic Stream (e.g. Mathewson et al. 1979). We may also conjecture that H I clumps in intergalactic debris observed around interacting galaxies (e.g. Gottesman & Weliachev 1977; Weliachev et al. 1978; Smith 1991) would satisfy a similar condition of gravitational confinement, since they are considered to have survived for orbiting time scale around parent galaxies.

On the other hand, the internal motion, such as turbulence, would be dissipated by the friction among eddies, and the cloud might collapse. However, instabilities on the cloud surface due to interaction with the intergalactic gas, such as the Kelvin–Helmholtz instability, would excite and maintain the internal motion. In fact, H I clumps in the Magellanic Stream are thought to have been maintained for billions of years (Fujimoto & Sofue 1976), and have survived from collapse, cascade and/or evaporation. Detailed discussion of excitation mechanisms of internal motion and instabilities of clouds are out of the scope of this paper.

2.2. *Accretion condition for a cloud*

The condition for stripping of interstellar gas in spiral galaxies by intergalactic diffuse gas is given by $\rho_0 v_{\rm G}^2 > 2\pi G \sigma_{\rm s} \sigma_{\rm g} \sim \rho_{\rm g} v_{\rm esc}^2$, where G is the gravitational constant, ρ_0 is the intergalactic gas density, $\sigma_{\rm s}$ and $\sigma_{\rm g}$ are the galaxy surface mass densities of stellar and gaseous matter, respectively, $v_{\rm G}$ is the galaxy velocity, and $v_{\rm esc}$ is the escaping velocity from the galaxy disk (Gunn & Gott 1972; Gisler 1979; Farouki & Shapiro 1980). Since spiral galaxies possess gaseous disks, and even gaseous halos, we may suppose that the above condition is rather rarely satisfied for spiral galaxies. If the above condition is not satisfied, the intergalactic gas would be accreted by the galaxy disk, provided that $(\gamma k/m_{\rm H}) T_0 \sim c_0^2 < v_{\rm esc}^2$ is satisfied simultaneously. Here T_0 and c_0 are the temperature and sound velocity of the intergalactic gas, respectively, $v_{\rm esc}$ is the escaping velocity from the disk, $\gamma = 3/2$, k and $m_{\rm H}$ are the Boltzmann constant and hydrogen mass, respectively. In our model, we consider just this opposite case to the stripping; namely a ram-pressure accretion of intergalactic clouds.

Before describing our model in detail (next subsection), we first give a rough estimation for accretion conditions of a simple cloud moving though the diffuse intergalactic gas. Suppose a gas cloud of radius R and a uniform density $\rho_{\rm c}$, so that a mass of $m = (4\pi/3)\rho_{\rm c} R^3$, moving in a diffuse gas of density ρ_0 which is at rest. Then the cloud suffers ram pressure force $\pi R^2 \rho_0 v^2$, so that we have

$$m\frac{dv}{dt} = -\pi R^2 \rho_0 v^2. \tag{1}$$

This gives a simple solution as

$$v = \frac{v_0}{t/\tau_0 + 1}, \tag{2}$$

where v_0 is the initial velocity, and

$$\tau_0 = \frac{4}{3}\frac{\rho_c}{\rho_0}\frac{R}{v_0} \tag{3}$$

is the time scale for a cloud braking. This is equivalent to the condition that a cloud stops after it moves through the intergalactic gas for $L \sim v_0 \tau_0 \sim \rho_c R/\rho_0$, or $\rho_c R \sim \rho_0 L$. If we take $\rho_c \sim 1 m_H\,\mathrm{cm}^{-3}$, $\rho_0 \sim 10^{-3} m_H\,\mathrm{cm}^{-3}$, $R \sim 1$ kpc and $v_0 \sim 1000$–$100\ \mathrm{km\,s^{-1}}$, we obtain $\tau_0 \sim 10^9$–10^{10} yr, respectively. Hence, we can see that a cloud, which is moving through intergalactic gas of density typical for the central region of rich clusters of galaxies, is decelerated within the Hubble time. Moreover, if there exists nearby galaxies with gaseous halos, which pass by the cloud at velocities and impact parameters smaller than critical values as given below, they may be more easily captured and merged by galaxies.

If gravitation by a nearby galaxy is dominant, a criterion for the cloud to be captured by the galaxy due to ram pressure braking is given as $mv^2 < \pi R^2 L \rho_0 v_{esc}^2$, where $v_{esc} \sim (GM/p)^{1/2}$ is an escaping velocity from the galaxy's gravitational potential at p, and L is a path length of the cloud through the galaxy gas and may be approximated as $L \sim \pi p$, and p is the impact parameter of the encounter. Then we obtain a criterion as

$$v < v_{crit} \sim (\pi p \rho_0 / R \rho_c)^{1/2} v_{esc}. \tag{4}$$

For a galaxy mass of $M \sim 10^{11} M_\odot$ and a halo gas density of the order of $\rho_0 \sim 10^{-3} m_H\,\mathrm{cm}^{-3}$ at a radius $r \sim p \sim 10$ kpc, we obtain $v_{crit} \sim 100\ \mathrm{km\,s^{-1}}$. If the encounter is almost head-on and the cloud penetrates the galactic disk, the critical velocity is much higher.

Once a cloud is captured, it orbits around the galaxy at radius r. If the background gas is at rest, the cloud is simply accreted toward the galaxy center. The time scale for accretion is given approximately by Eq. (3), i.e.

$$\tau_{ac} \sim \frac{\rho_c R}{\rho_0 v_{rot}}, \tag{5}$$

where $v_{rot} \sim (GM/r)^{1/2}$ is the rotation velocity of the galaxy. For the same parameters as above, we obtain $\tau_{ac} \sim 10^9$ yr for $v_{rot} \sim 100$–$200\ \mathrm{km\,s^{-1}}$. Therefore, a cloud orbiting around a galaxy with a gas halo can fall toward the galaxy in a time scale short enough compared to the Hubble time. In our model we assume that the cloud velocity relative to the hot gas is about 100–200 $\mathrm{km\,s^{-1}}$, while the gas temperature is $\sim 10^{6-8}$ K. This means that the cloud motion is sub-sonic.

2.3. Equations of motion and mass models for galaxies

The ram-pressure accretion process of intergalactic clouds would be a complicated process and should be analyzed in a hydrodynamical treatment, and it has not been studied in detail as yet. However, in order to clarify some interesting astronomical phenomena observed in some elliptical as well as disk galaxies, we adopt here a simple ballistic model as described below, which is a similar way to that adopted by Farouki & Shapiro (1980) for tracing the stripping motion of interstellar gas clouds. Limitation of the present model is briefly discussed in Sect. 5.

The ram pressure (dynamical pressure) force on an intergalactic gas cloud (test cloud) is given by $-\pi R^2 \rho(\boldsymbol{r}) \Delta v^2$, where $\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{V}$ is the relative velocity of a cloud with respect to the halo gas which is moving (rotating) at a velocity $\boldsymbol{V}$, and $\rho(\boldsymbol{r})$ is the density of diffuse gas at a position $\boldsymbol{r}$ around a galaxy concerned, which includes contributions from the intergalactic diffuse gas and the halo gas of the galaxy. The equation of motion can be written as

$$m\frac{d^2\boldsymbol{r}}{dt^2} = m\frac{\partial \Phi}{\partial \boldsymbol{r}} - \pi R^2 \rho(\boldsymbol{r}) \Delta v \Delta \boldsymbol{v}, \tag{6}$$

with $\boldsymbol{v} = d\boldsymbol{r}/dt$ and $\boldsymbol{r} = (x, y, z)$ being the cloud position with respect to the galaxy center. Or, more conveniently we obtain

$$\frac{d^2\boldsymbol{r}}{dt^2} = \frac{\partial \Phi}{\partial \boldsymbol{r}} - \frac{3\rho(\boldsymbol{r})}{4R\rho_c} \Delta v \Delta \boldsymbol{v}, \tag{7}$$

where ρ_c is the mass density of an accreting cloud.

The gravitational potential of the galaxy is approximated by a modified Miyamoto & Nagai's (1975) potential:

$$\Phi = \sum_{i=1}^{3} \frac{GM_i}{\mu_i}, \tag{8}$$

and

$$\mu_i = \sqrt{\varpi^2 + (a_i + \sqrt{z^2 + b_i^2})^2}, \tag{9}$$

where $\varpi = (x^2 + y^2)^{1/2}$, M_i, a_i and b_i are the masses and scale radii for the ith mass component of the galaxy. For spiral galaxies we assume three mass components: a central bulge ($i=1$); disk ($i=2$); and a massive halo ($i=3$). Values for the parameters are given in Table 1, which are typical for a spiral galaxy like the Milky Way Galaxy. For elliptical galaxies we assume one component, for which $a_1 = a_E = 0$ so that the potential represents a Plummer's law:

$$\Phi = \frac{GM_E}{\sqrt{r^2 + b_E^2}}. \tag{10}$$

Values for elliptical galaxies used in the simulation are also given in Table 1.

Table 1. Parameters for the gravitational potential

i	Mass component	M_i ($M_\odot$)	a_i (kpc)	b_i (kpc)
Spiral galaxies[a]				
1	Central bulge	$2.05\ 10^{10}$	0	0.495
2	Disk	$2.547\ 10^{11}$	7.258	0.520
3	Massive halo	$3\ 10^{11}$	20	20
Elliptical galaxies (Plummer potential)				
E	Spherical system	$2.31\ 10^{11}$	0	10

[a] Miyamoto & Nagai (1975).

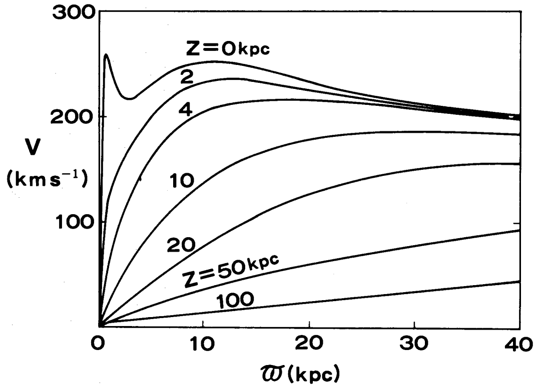

Fig. 1. Rotation curves of the gaseous disk and halo in a spiral galaxy. The galaxy has three mass components: a stellar bulge. a stellar disk and a massive halo. The curves are shown at various heights z from the galactic plane

2.4. Models for gaseous halos and intergalactic gas

We assume a density distribution of a hot gas halo around a spiral galaxy as

$$\rho(\varpi, z) = \rho_0 + \frac{\rho_{\rm H}}{(\varpi/\varpi_{\rm H})^2 + (z/z_{\rm H})^2 + 1} + \frac{\rho_{\rm D}}{(\varpi/\varpi_{\rm D})^2 + (z/z_{\rm D})^2 + 1}, \tag{11}$$

where $\rho_{\rm H}$, $\varpi_{\rm H}$ and $z_{\rm H}$ are parameters representing the distribution of halo gas density, $\rho_{\rm D}$, $\varpi_{\rm D}$ and $z_{\rm D}$ are those for the disk component, and ρ_0 is the intergalactic gas density. Values of the parameters are given in Table 2.

The halo gas in spiral galaxies is assumed to be rotating around the z axis at a velocity with its centrifugal force balancing the galaxy's gravity toward the z-axis:

$$V(\varpi, z) = \sqrt{\sum_{i=1}^{3} \frac{V_i^2}{\mu_i^2}}\ \varpi, \tag{12}$$

where

$$V_i(\varpi, z) = \sqrt{\frac{GM_i}{\mu_i}}. \tag{13}$$

We assume that the gas is in a hydrostatic equilibrium in the z-direction, so that $V_z = 0$, and pressure gradient in ϖ direction is neglected. Figure 1 shows the rotation curve of the gaseous component represented by Eq. (12) at various height z from the galactic plane. Note that the rotation velocity decreases rapidly with z in the polar region of the galaxy.

The above assumption would be too simplified and somewhat artificial. In particular, the neglection of pressure gradient in ϖ direction may cause an overestimation of the rotation speed of the halo gas. However, if we were able to solve the halo-gas motion self-consistently, we must probably take into account circulation in the halo, which includes z, ϖ, and ϕ motions. Furthermore, the rotating gaseous halo should be coupled to the disk by viscosity. These questions are out of the scope of the present work. We comment that, observationally, the rotation of halo gas in spiral galaxies is controversial: some galaxies like our Galaxy and NGC 891 show almost the same halo rotation as the disk (Garcia-Brillo et al. 1992; Sofue & Nakai 1993), while some like M 82 shows very slow halo rotation (Sofue et al. 1992).

For elliptical galaxies we assume a spherical gas halo without rotation, and the density distribution is written in the form

$$\rho(r) = \rho_0 + \rho_{\rm E}[(r/r_{\rm E})^2 + 1]^\beta, \tag{14}$$

where $\beta \sim -0.75$ is taken from Fabbiano (1989), and other parameters are given in Table 2.

For the density distribution as expressed by Eq. (14) to be maintained, the central region must have cooling inflow and the hot gas must be supplied somewhere in the galaxy, as has been extensively discussed in relation to the cooling flow problem (e.g. Forman 1988; Thomas 1988; Fabbiano 1989). However, we here simply assume that the halo gas in elliptical galaxies is at rest and is neither rotating nor has radial flow, so that the gas is in a hydrostatic equilibrium with the gravity. This may require a somehow artificial temperature distribution. This argument applies also to the density distribution in spiral galaxies as expressed by Eq. (11): The assumption that the gas is in a hydrostatic equilibrium in the direction perpendicular to the galactic plane requires an artificial temperature distribution. However, we think it is sufficient for our present purpose to follow the global accretion process of clouds, and essential characteristics of the numerical results presented in the next section may not change even if we take into account more realistic density and/or temperature distributions. Modeling of the accretion process, in particular that in the very inner regions, taking into account more realistic density models with in- and out-flows will be discussed in a separate paper. This includes, for example, an effect of the cooling flow which may promote the accretion in the central region of elliptical galaxies.

We solve the differential equations by using the Runge–Kutta–Gill method. The time step of integration

Table 2. Parameters for ram-pressure accretion model

Intergalactic gas	
ρ_0	$10^{-5--3} m_H\,\mathrm{cm}^{-3}$
Intracluster gas	
ρ_0	$10^{-3} m_H\,\mathrm{cm}^{-3}$
Spiral galaxies	
ρ_H	$0.01 m_H\,\mathrm{cm}^{-3}$
ϖ_H	15 kpc
z_H	10 kpc
ρ_D	$1 m_H\,\mathrm{cm}^{-3}$
ϖ_D	10 kpc
z_D	0.2 kpc
Elliptical galaxies	
ρ_E	$0.1 m_H\,\mathrm{cm}^{-3}$
r_E	10 kpc
H I cloud	
$\rho_{\mathrm{H\,I}}$	$0.5\text{–}1 m_H\,\mathrm{cm}^{-3}$
R	0.5–1 kpc
$m=(4\pi/3)R^3\rho_{\mathrm{H\,I}}$	$0.6\text{–}10\ 10^7 M_\odot$

was taken to be 0.1–1.0 10^7 yr. It was chosen to be smaller than 0.1 times the dynamical time scale of each test particle (cloud) at the closest approach to the galaxy center, often the one at the center if a cloud crosses the vicinity of nucleus. Numerical errors accumulated in the period of orbit integration, which was typically 2–4 10^9 yr for each cloud, were estimated to be negligibly small compared to the cloud size. For an initial condition we assume that an H I cloud approaches the galaxy starting from a position at $x=200$ kpc and $y=p$ with an initial velocity v_0 parallel to the x axis, or from a position high above the rotation plane along an inclined orbit to the rotation plane.

3. Cloud orbits

3.1. Non-rotating halo: elliptical galaxies

First we consider the accretion of intergalactic clouds onto elliptical galaxies embedded in an intergalactic diffuse gas and a hot gaseous halo, which have been observed in the X-ray emission (Forman et al. 1979; Fabbiano 1989; Fabian et al. 1991; Thomas 1988; Sofue & Wakamatsu 1991). As the cloud approaches the galaxy, it is accelerated by the increasing gravity of the galaxy and its velocity increases. Since the ram pressure is proportional to ρv^2, it exerts stronger deceleration (friction) on the cloud for increasing velocity as well as for increasing density of the halo gas toward the galaxy. Thus the motion changes to a bound orbit, and the cloud is trapped by the galaxy.

Figure 2a shows an orbit for a case when the galaxy has no gaseous halo and no gaseous disk [$\rho_E=0$ in Eq. (14)], but is embedded in a uniform intergalactic gas of density $\rho_0=10^{-3} m_H\,\mathrm{cm}^{-3}$. The cloud is decelerated and captured by the galaxy's potential. Then it is gradually accreted toward the center. Figure 2b is a case for a spherical non-rotating halo, where $\rho_E=0.1 m_H\,\mathrm{cm}^{-3}$, and $r_E=10$ kpc. In this case, the cloud is rapidly accreted toward the galaxy center, once it is trapped by the galaxy.

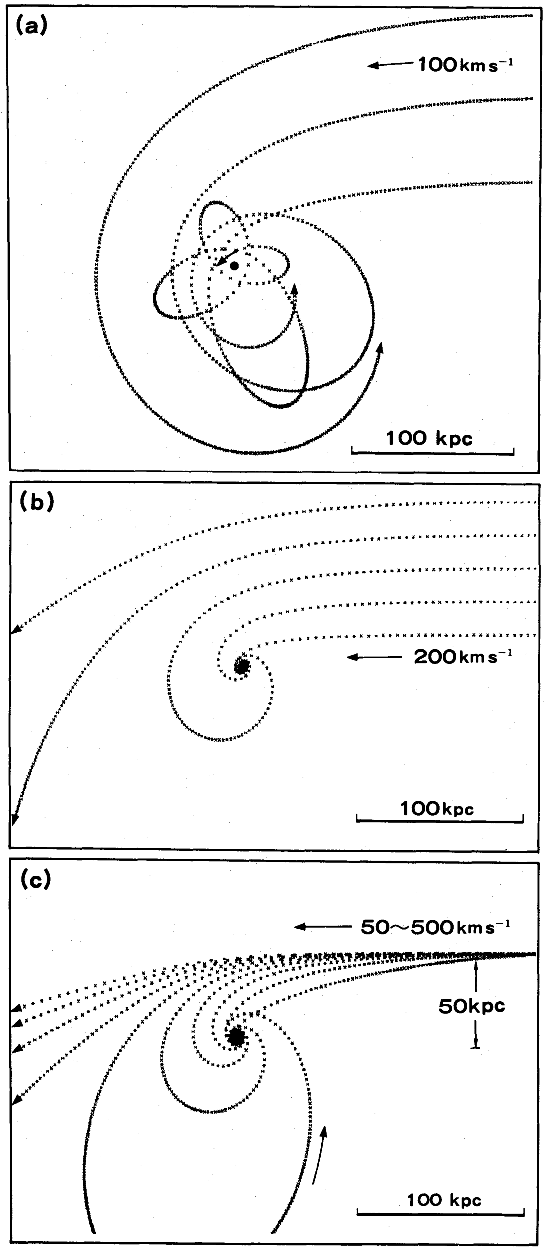

Fig. 2a–c. Hyperbolic encounter of H I clouds with an elliptical galaxy embedded in a hot gas halo at rest (Sofue & Wakamatsu 1991). **a** If there is intergalactic gas of density $\rho_0 \sim 10^{-3} m_H\,\mathrm{cm}^{-3}$, the clouds are captured by the galaxy. The impact parameters are 50, 100 and 150 kpc and an injection velocity 100 km s^{-1}. The cloud position is plotted by the dots every 2 10^7 yr interval. **b** If there exist a hot halo and intergalactic gas, clouds are captured and further accreted toward the galaxy. Orbits for various impact parameters are shown for injection velocity 200 km s^{-1}. **c** Same as **b** but for a fixed impact parameter, 50 kpc, and for various injection velocities for 50 to 500 km s^{-1}

The accretion from $r=50$–100 kpc to $r\sim 10$ kpc region occurs typically in one orbital rotation after the perigalactic passage, or typically within 10^9 yr. Afterwards, due to an increasing gravity and increasing ram pressure near the galaxy, the cloud is rapidly accreted to the central region within additional few rotations, where one rotation takes typically 10^8 yr at $r<\sim 10$ kpc. The clouds are further accreted toward the center in a few more rotation, and may fuel the nucleus (Sofue & Wakamatsu 1991).

In our model, we took an initial condition for a cloud moving along a hyperbolic orbit. If H I clouds come from tidal debris from a companion galaxy orbiting around an elliptical, we may take bounds orbit as the initial condition. Namely, if we start from an initial condition in which clouds are rotating around a galaxy in a ring or on an elliptical orbit, they are also accreted rapidly toward the disk. This can be readily seen from the present simulation: we may start from a certain point on the simulated orbits after the perigalactic passage in Fig. 2.

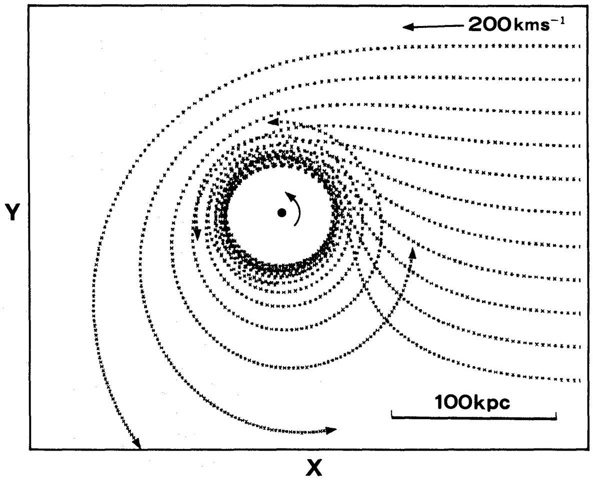

Fig. 3. Ram pressure accretion of a cloud by a hot gas halo which is rotating with the galaxy. Note that for direct and retrograde clouds form rings with an almost constant radius. The galactic rotation is in a counter-clockwise on the (x, y) plane

3.2. Rotating halo and disk: spiral galaxies

The existence of hot gaseous halos around spiral galaxies has been repeatedly claimed since the pioneering work by Spitzer (1956). Evidence for the existence of a halo component around spiral galaxies has been obtained for several edge-on galaxies: Our Galaxy has an ionized gaseous halo extending for 3–5 kpc from the galactic plane with a gas density of $\sim 10^{-3} m_{\rm H}\,{\rm cm}^{-3}$ (de Boer & Savage 1983). NGC 4631 is embedded in an extended H I envelope (Weliachew et al. 1978). This galaxy has also an extended magnetic corona of several kpc extent, which would be associated with a significant amount of ionized gas (Hummel et al. 1988). M 82 is also surrounded by an extended envelope composed of H I gas, molecular gas, and hot (X-ray) corona (Gottesmann et al. 1977; Sofue et al. 1991; Tsura et al. 1991). Hence, we may suppose that some spiral galaxies, though it might not be for all, possess an extended gaseous corona in addition to the disk.

We mention that in an early phase of galaxy evolution when galaxies were gas-richer and star-formation activity was much higher than at present, spiral as well as S0 galaxies, and probably even elliptical galaxies, would have been embedded in denser circumgalactic gaseous halos. In fact evidences have been accumulated for high-redshift QSO absorption lines due to halos of intervening galaxies, which are often suggested to be occurring through extended ionized corona as large as about 100 kpc (e.g. Blades 1987; Weymann et al. 1979; Bregman 1981). Therefore the RPA (ram-pressure accretion) model could be more efficiently applied to primeval galaxies in the early universe.

We consider a case where the gaseous halo and disk whose density distribution is given by Eq. (11) are rotating in a spiral galaxy obeying Eq. (12). Figure 3 shows calculated orbits for several clouds with different injection conditions within the galactic plane. Here and hereafter, the spiral galaxy is rotating in a counter-clockwise in the (x, y) plane around the z axis. If the orbital angular momentum of a cloud is parallel to the galaxy rotation, or if a cloud approaches the galaxy on a "direct (prograde) encounter" orbit, its relative velocity against the halo gas is smaller than in a non-rotating case. Then, the ram pressure is relatively smaller, so that the accretion is less effective. Consequently, the capture frequency of clouds becomes smaller, although the accretion process itself is similar to a non-rotating halo case. However, a quite different behaviour is observed after the capture. Once a cloud is captured by the halo, its orbiting velocity is forced to reach the halo rotation velocity by the ram friction until it attains a corotation with the disk gas. Then the accretion stops, and the cloud orbits around the galaxy in a circular ring, where the centrifugal force balances the gravity.

When a cloud approaches along a "head-on collision" and "retrograde" orbits in the (x, y) plane, the rotating halo exerts force on the cloud to pull into corotation. Then the cloud gains angular momentum and rotating motion, and tends to have a circular ring orbit. If the orbital rotation is anti-parallel to the halo rotation, or retrograde, halo gas exerts much higher ram pressure on the cloud because of higher relative velocity. Then, the ram friction and accretion are more effective and faster. Furthermore, clouds are pulled into an orbit in a counter-rotation with respect to their initial angular momentum, and they begin to co-rotate with the halo gas. Finally the clouds attain a ring orbit similar to the previous cases of direct encounter and head-on collision. For head-on and retrograde encounters, the final ring radii are almost constant irrespective of the initial velocity of clouds, unless the velocity is too high so that the clouds pass by on hyperbolic orbits.

Fig. 4a–d. Off-plane encounters of clouds with a disk galaxy rotating in a counter-clockwide in the (x, y) plane. The capture frequency is asymmetric with respect to the x axis due to the rotation of gas disk and halo: Capture chance for retrograde clouds is much higher than direct ones

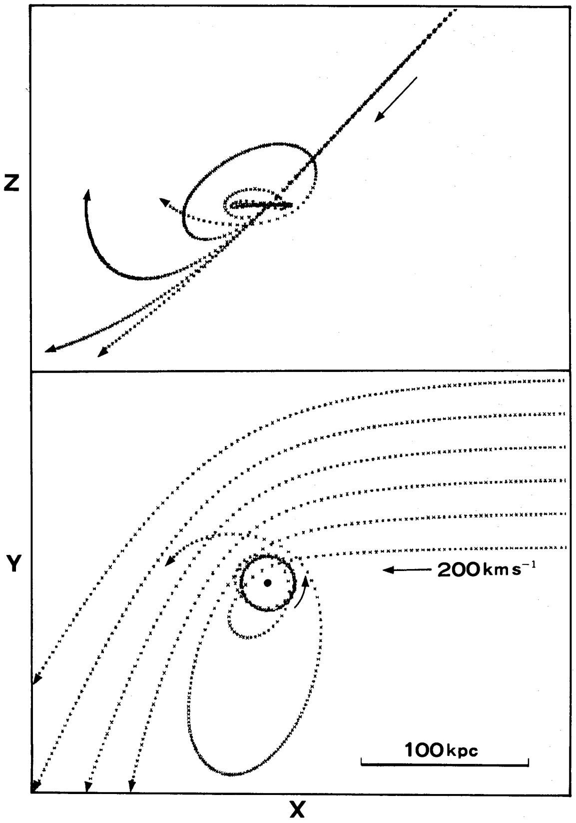

Fig. 4a. Direct (prograde) encounter at 45° with the (x, y) plane

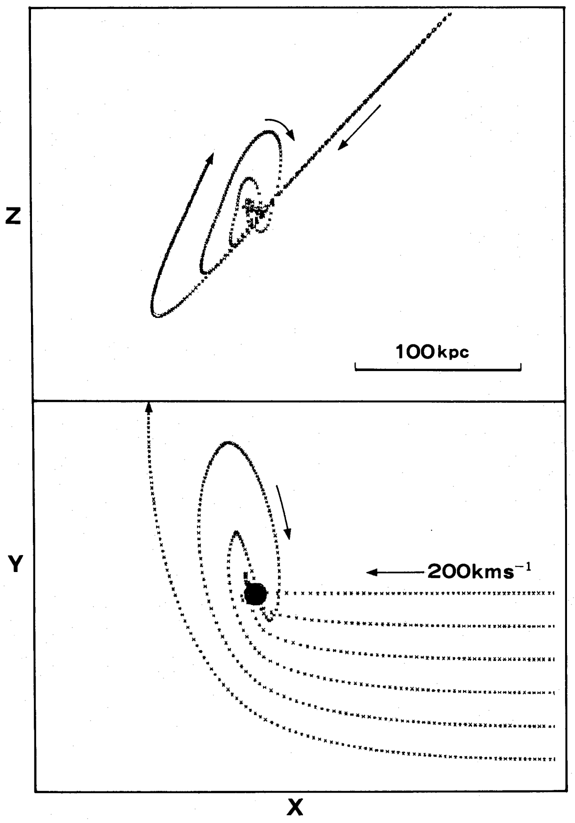

Fig. 4b. Retrograde encounter at 45°

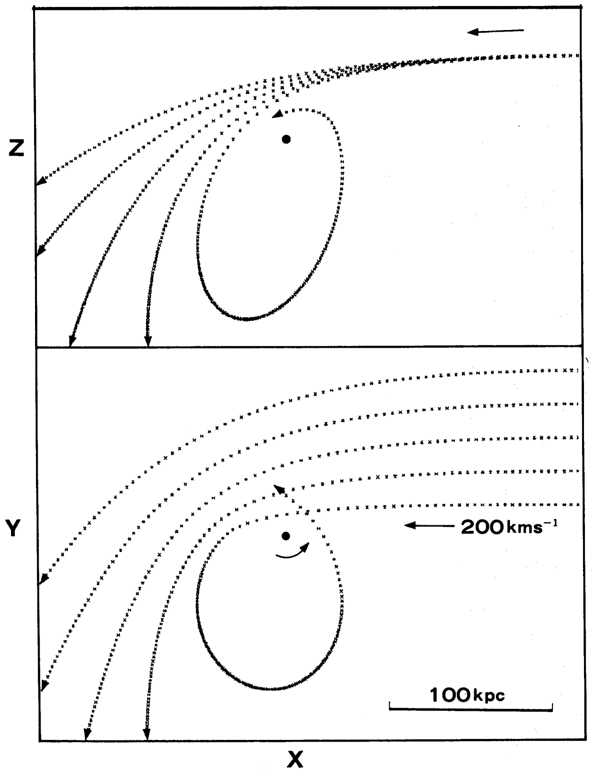

Fig. 4c. Direct encounter parallel to but off the galactic plane

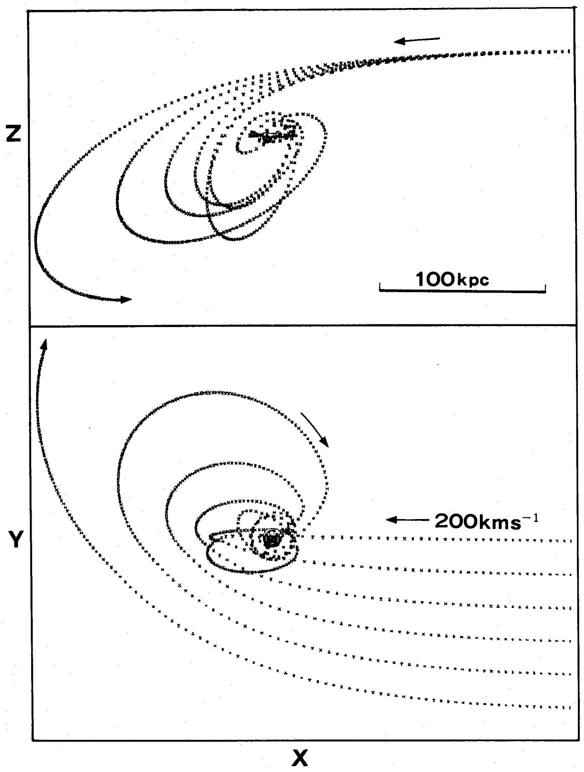

Fig. 4d. Retrograde encounter parallel but off-plane

Figure 4a shows orbits for direct encounters where the initial orbital plane is inclined to the galactic plane by 45°, while Fig. 4b shows retrograde cases. The capture is also asymmetric about the x-axis as was the case in Fig. 3. Conspicuous in this figure is that the retrograde clouds are rapidly accreted toward the central region, which occurs as follows: When a cloud crosses the galactic disk on the retrograde side, it is exerted strong drag and loses kinetic energy as well as angular momentum. Then the orbit changes to a semi-polar, whereby the halo gas in the polar region is rotating at much slower velocity than the disk. After half a rotation in a few 10^8 yr, the cloud crosses the galactic plane from the bottom, and again loses angular momentum. In a few crossings of the disk in this way, the cloud loses almost all the angular momentum and kinetic energy, and is attracted toward the central region. Finally the cloud is captured by the disk in the nuclear region. Figure 4c and d show, respectively direct and retrograde orbits of clouds injected parallel to but off the galactic plane. Again retrograde clouds are accreted toward the central region.

As can be seen from Figs. 3 and 4, we may conclude that the accretion of intergalactic clouds is significantly asymmetric with respect to the rotation axis: The capture frequency of retrograde clouds are much higher than that for direct clouds. It is conspicuous that *off-plane and retrograde* clouds are accreted toward the central region of the galaxy.

4. *N*-clouds simulation

We consider a case in which intergalactic H I clouds exist in an ensemble of many individual clouds, where each cloud satisfy the condition being a gravitationally bound system balancing with their internal motion as described in Sect. 2. In order to see the behaviour of such an ensemble during an encounter, we simulate motions of many (N) clouds, which are initially distributed in a sphere of radius $R_N = 5$ kpc. Within a cloud ensemble, which consists of N test clouds, the clouds are given velocity dispersion of 5 km s^{-1} around neither mean velocity. We hereafter call such an ensemble "N-clouds".

4.1. Elliptical and S0 galaxies

4.1.1. Circum galactic gas bands

Figure 5 shows a case for an elliptical galaxy without a gas halo but with an intergalactic diffuse gas of density $\rho_0 = 10^{-3} m_{\rm H}\,{\rm cm}^{-3}$. As the clouds approach the galaxy, they orbit around the galaxy one or more times before falling toward the nucleus. In this phase the clouds form a band surrounding the galaxy. This band of N-clouds mimicks a circum galaxy band of cool gas such as observed around the elliptical galaxy NGC 5128 (e.g. Sandage 1961). H I clouds and dark lanes found in many elliptical galaxies (van Gorkom et al. 1986; Kormendy & Djorgovski 1989) may be also such accreting clouds. On the other hand, if the clouds are heated and ionized, they may be observed as emission line rings or spirals. The present RPA model may thus explain the origin of gaseous bands surrounding galaxies, such as a cool gas ring of dark clouds in NGC 5128, an ionized gas ring of 30 kpc diameter in some radio galaxies as PKS 1216–10 (Danziger & Focardi 1988), and optical ring features often observed surrounding elliptical galaxies (Schweizer 1987; Wakamatsu 1991). It star formation occurs in the gas band during accretion, since the formed stellar component does not suffer from the ram deceleration any more, a circum elliptical ring of young stars may appear. This may explain such ring structures as detected in Hoag-type galaxies (Schweizer et al. 1987).

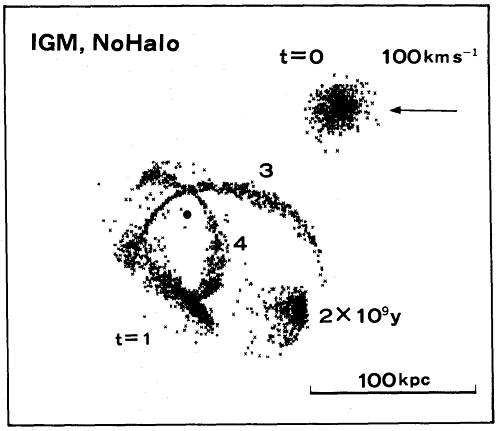

Fig. 5. Ram pressure accretion of "N-clouds" by an E galaxy embedded in a diffuse intergalactic gas at rest. Clouds are captured and gradually spiral into the galaxy. They form circum galaxian bands and arcs (Sofue & Wakamatsu 1991)

4.1.2. "Accretion spiral" in E galaxies

Figure 6 shows a result for an elliptical galaxy embedded in a hot halo as well as in intergalactic gas which is not rotating. In this case the accretion is much more rapid, and the clouds are accreted along open spiral orbits. As the N-clouds are accreted into the inner 10 kpc region, they are strongly stretched along the orbit. This "accretion spiral" is asymmetric and one-armed. Because their velocities increase and the hot gas density increases as well, the clouds will be likely heated and ionized. Therefore, we may expect a band of emission-line gas spiraling toward the nucleus. Very similar one-armed spiral features of Hα-line emission have been indeed observed in the elliptical galaxy NGC 4696, the radio galaxy PKS 0521–36 and in some other elliptical galaxies (Sadler 1987; Danziger & Focardi 1988; Kim 1990).

Our simulation cannot tell more about details within the central 0.5 to 1 kpc, because we have not taken into

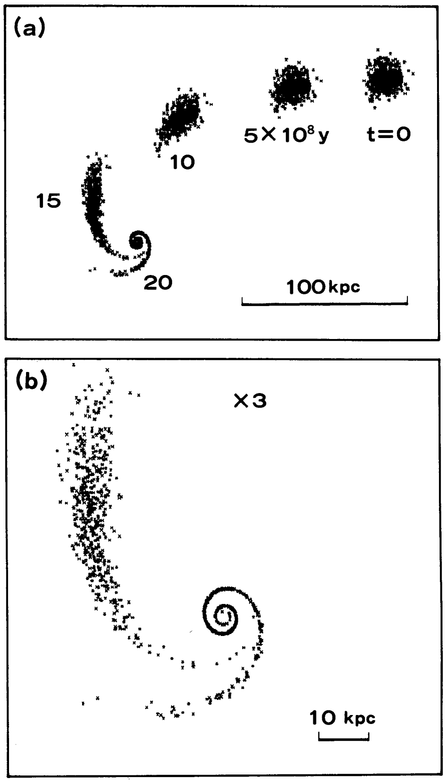

Fig. 6a. Ram pressure accretion of N-clouds in a hot halo at rest of an elliptical galaxy. Clouds spiral into the nuclear region in a few orbital rotations (Sofue & Wakamatsu 1991). **b** Same as **a** but the central region is enlarged, where the "accretion spiral" can be seen more clearly

account changes in size, density and physical conditions of individual clouds, which had initial radii of about 1 kpc. We only conjecture that rapidly accreting clouds would finally reach the central region and fuel the nucleus. Thereby, it may be possible that individual clouds are more condensed and tidally streched along the orbits, so that cross section of the clouds reduces. This may reduce the effective ram pressure. Thus, before a final accretion onto the nucleus, the clouds would form a circum-nuclear accreting ring.

4.1.3. Counter-rotation of gas in S0 galaxies

We may also consider a similar case for S0 and oblate E galaxies, which have neither gas disk nor halo, but is embedded in an intergalactic medium. In this case the potential is oblate, but the accretion process is similar to the case for an elliptical galaxy case as above. Most remarkable in this case is that accretion band apparently rotates about the galactic center independent of the galaxy's rotation axis, where the sense of rotation depends on the initial orbital angular momentum. This is because exchange of the angular momentum of falling clouds occurs with the intergalactic gas at rest, but not with the stellar system in rotation. Hence, cool gas accreting onto S0 galaxies will often, perhaps in half of all cases, exhibit counter-rotation. In this regard we emphasize that a considerable number of early-type galaxies have been observed to have gases which are orbiting perpendicularly or in counter-rotating sense to the stellar system (Bertola 1987; Schweizer 1987; Bettoni et al. 1990), which could be explained by the present mechanism.

4.2. Spiral galaxies

4.2.1. "In-plane" encounters: spiral and ring formation

If we take into account rotation of the halo as well as the disk, quite different results are obtained. Here, the halo and disk are in a circular rotation around the z axis at velocities balancing the gravity at each radius, and the initial orbit of the cloud center is on the galactic plane (x, y plane). Figure 7a shows a case of a direct encounter within the plane, and Fig. 7b for a retrograde encounter. The N-clouds are distorted first into a one-armed spiral. Then they begin to co-rotate with the halo gas, and finally attain ring features. We may thus conclude that, when a galaxy with a rotating gas halo encounters intergalactic gas clouds, a circum galaxian ring of cool gas forms.

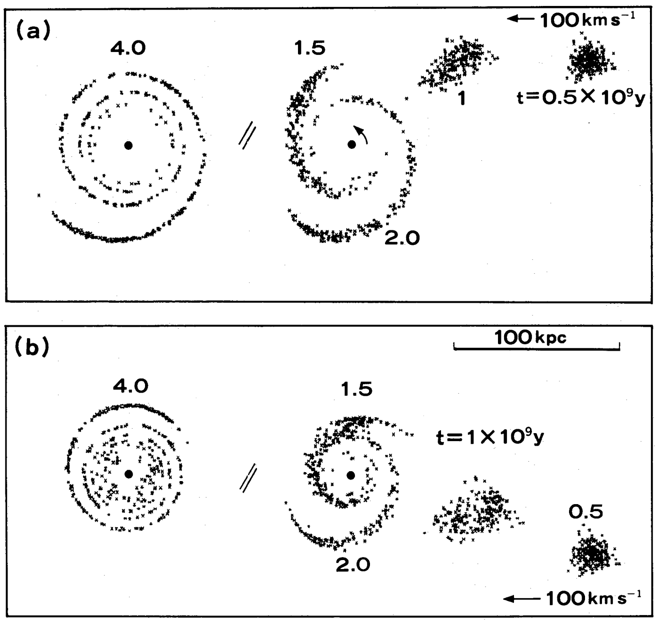

Fig. 7a and b. Ram pressure accretion of N-clouds by a rotating hot gas halo and disk. Here and hereafter the disk galaxy is rotating in a counter-clock wise in the x–y plane. **a** Clouds for a "direct (prograde)" hyperbolic encounter within the galactic plane. **b** Same as **a** but for a "retrograde" hyperbolic encounter

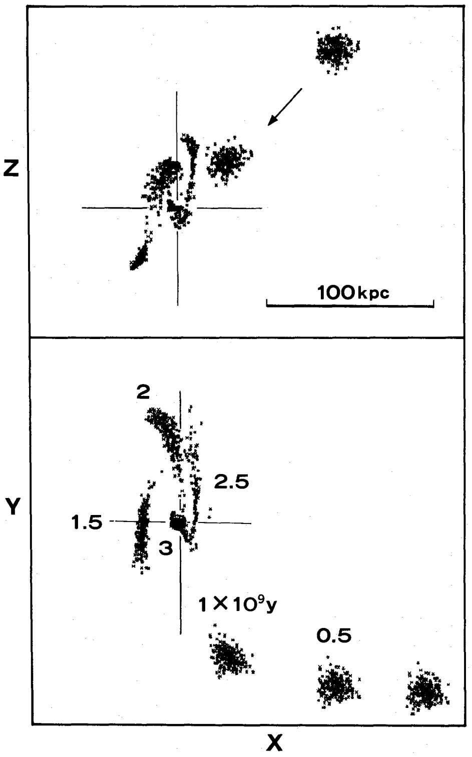

Fig. 8a. Ram pressure accretion of *N*-clouds for an inclined retrograde encounter at 45° at an injection speed of 141 km s^{-1}. Note that the clouds are accreted toward the nuclear region in a few rotation. The clouds are plotted every 5 10^8 yr

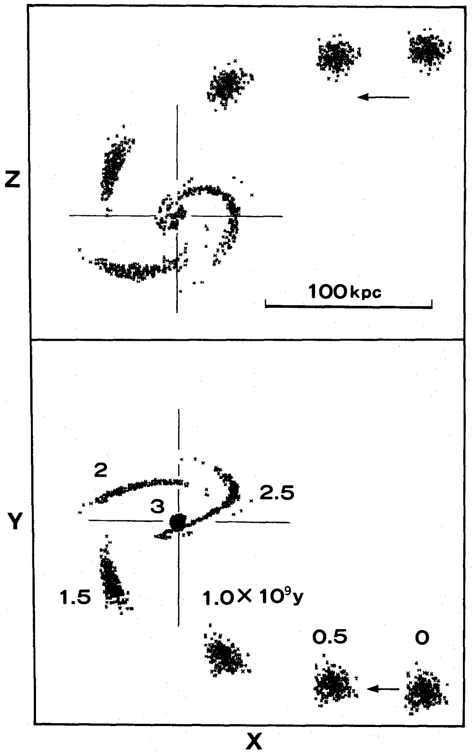

Fig. 8b. The same but for a retrograde encounter parallel to but off the plane at an injection speed 100 km s^{-1}. Note that the clouds are accreted to the nuclear region

4.2.2. "Off-plane" encounters: polar orbits and nuclear fueling

Figure 8a shows a result for a 45° encounter on a retrograde orbit. As described in the previous section, orbits of individual clouds change drastically when they cross the galactic plane, and attain polar orbits in its later stage. It is conspicuous that almost all clouds are accreted toward the central few kpc, where they form a rotating disk of small radius. Similar accretion of clouds toward the center occurs for a wide range of impact parameters: Almost the same result is obtained, if the orbit crosses the galactic plane in the retrograde side. This applies for a wide range of injection angle ($0 \sim 60°$), and for a wide range of impact velocity (100–300 km s^{-1}). The same happens even for parallel orbits to the galactic plane, provided that they are off-plane. Figure 8b shows a case of parallel-off plane encounter on the retrograde side. Here we can see again an efficient accretion onto the nuclear region.

Hence we may conclude that, if they approach a spiral galaxy on off-plane orbits from the retrograde side, intergalactic gas clouds are accreted to the central region within one or two polar orbitings. The accreted clouds form a rotating disk of small radius, say a few kpc. We suggest that such an accretion of intergalactic gas clouds will fuel the nuclear region and probably trigger starburst. Final fueling on the nucleus will happen with the aid of such a mechanism as the bar-shock accretion process (Sørensen et al. 1976). In fact many galaxies are suggested to have a stellar bar in the inner few kpc, and is actually the case for the starburst galaxy NGC 253 (Scoville et al. 1985).

4.2.3. Peculiar kinematics and counter rotation of gas clouds

As the simulation indicates, accreting clouds that hit the nuclear region must exhibit peculiar kinematics distinguished from the disk rotation, and this may explain some observations of inner peculiar motions. For example, the apparent counter rotation of gas observed in the spiral galaxy NGC 2217 (Bettoni et al. 1990) would be due to an accretion of external gas clouds accreted in this way. The present model could also explain the peculiar and even counter-rotating motion of some molecular clouds in our galactic center (Bally et al. 1987). Our Galaxy is surrounded by numerous high-velocity H I clouds (e.g. van Woerden et al. 1985), and it may happen that their considerable fraction was accreted to the nuclear region, exhibiting the peculiar kinematics.

4.2.4. One-armed H I spiral and plume

During the accretion, the clouds exhibit a stretched plume feature, which points to the galactic disk in a one-armed spiral. The feature is transient, lasting for about half a billion years. The plume has a regular spiral feature in distant regions from the galactic disk, while it exhibits a complicated polar feature over the disk in the central region when clouds approach the nucleus. Such a one-armed spiral feature around a disk galaxy has been indeed found by recent VLA observations: a giant intergalactic H I plume has been detected near the peculiar galaxy NGC 2782 = Arp 215 (Smith 1991). The plume extends for more than 50 kpc from the disk, as massive as $10^9 M_{\odot}$, and is certainly an intergalactic feature. Smith (1991) interprets this feature as debris of a gas rich galaxy which was already merged by NGC 2782. The feature can be naturally understood as an accreting spiral on the disk by the present RPA model. In fact the shape and extent of the observed H I plume resembles very much the simulated clouds feature in Fig. 8. In particular the stretched one-arm spiral as obtained in Fig. 8b at $t = 2.5\ 10^9$ yr mimicks the observation. Furthermore NGC 2782 processes pronounced polar dust lanes across the almost face-on disk (Arp 1966), and its nuclear region shows an active star formation (Sakka et al. 1973). The polar dark lanes and nuclear star formation activity seem to be relevant phenomena to be accretion of H I gas according to the RPA model. Detailed discussion of NGC 2782 will be given in a separate paper (Wakamatsu et al. 1992).

4.2.5. Outer stochastic spiral arms

In the above simulation we put only one ensemble of N-clouds. However, it is also likely that the galaxy encounters more such ensembles. Therefore we then consider a case in which a "cluster" of N-clouds ensembles are distributed in a wider area, and the galaxy moves through this cluster. Figure 9 is a result for 20 such N-clouds randomly distributed in a 40 kpc-diameter sphere. As the cluster approaches the galaxy, individual clouds fall toward the galaxy plane on spiral orbits. The clouds form a number of "spiral arms", which are rather asymmetric with respect to the galactic center. In particular, if the injection is inclined with the galactic plane, most of the spirals are shown to become off-plane and exhibit warped spiral features. In the outermost region open spirals develop while in the inner region they make a tightly wound spiral pattern.

We point out that there have been observed distant H I spiral arms in our Galaxy, which are largely warped (Verschuur 1975). Moreover, such distant arms at 20–30 kpc from the galactic center are beyond the corotation radius of the pattern speed, and cannot be explained by the density wave theory. In this context, the interpretation by Verschuur (1975) of the high-velocity clouds should be revisited in the scope that HVC and distant arms are related objects and might be due to infall of intergalactic gas clouds. We emphasize that the spiral pattern formed in the RPA model is stochastic, depending on the distribution and motions of intergalactic clouds. In this respect, we could compare our model to the spiral pattern formation by stochastic star formation and its propagation through the disk (Seiden & Gerola 1979).

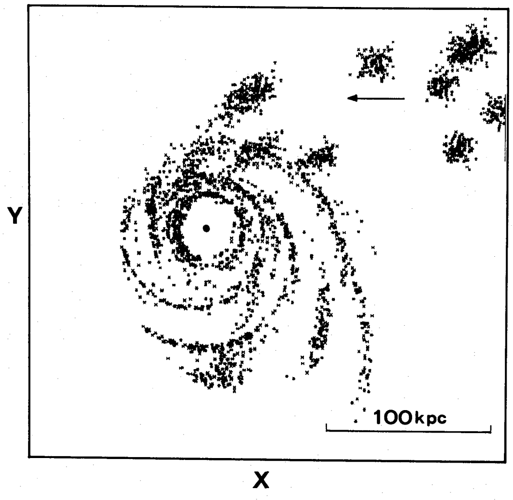

Fig. 9. Encounter of a rotating galaxy with a "cluster" of N-clouds. The clouds are captured, accreted and make a stochastic spiral pattern in the outer region of the galaxy. They further make a ring and tightly wound spiral pattern in the inner region. The cluster is initially centered at $(x, y, z) = (150, 80, 0)$ kpc spread over a 30 kpc radius sphere, and moves at 100 km s^{-1} in a direct sense

4.2.6. Exotic cases

In cases of retrograde encounters, the clouds are more or less accreted toward the central region and make a small-radius ring. On the other hand, those encountering on direct orbits form spirals. If the direct encounter takes place off the plane, spirals show sometimes a peculiar features. An example of such an exotic case is shown in Fig. 10, where the initial condition was settled arbitrary except for direct encounter condition. Before attaining a final ring in the disk, the clouds exhibit complex behaviour, showing a complicated arm.

4.2.7. Continuous flow

In the intergalactic space, it might happen that H I clouds are not localized as the N-clouds, but a large number of H I clouds are distributed more spread, resembling a continuous gas distribution with a density fluctuation. Such a situation might happen in an early epoch of the universe, where a number of proto-galactic clouds existed. It may also happen in such a circumstance that a galaxy moves through a large-scale tidal H I tail or debris from other disturbed galaxies.

We here simulate such a "continuous" cloud flow, where numerous clouds are uniformly distributed at random and a spiral galaxy moves through at a velocity of 100 km s^{-1} at an inclination of 45° (or the clouds are flowing toward the galaxy). Figure 11 shows the result.

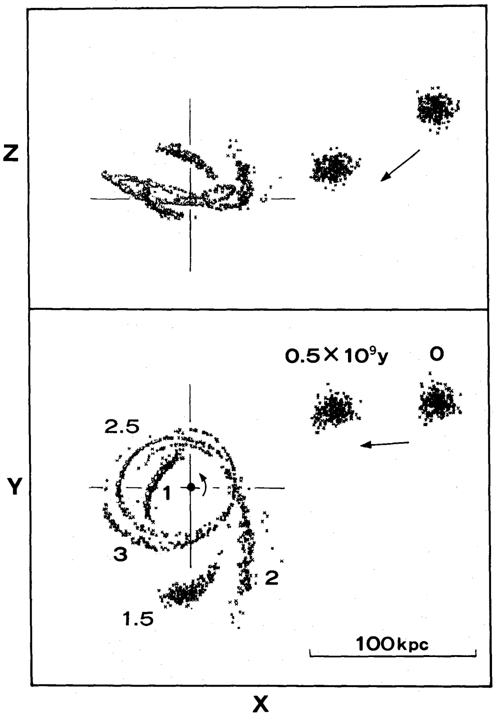

Fig. 10. A case of N-clouds direct encounter with an initial condition $(x, y, z) = (200, 50, 50)$ kpc and $(v_x, v_y, v_z) = (-100, 0\text{–}60)$ km s^{-1}. Before attaining a ring in the disk, clouds show various exotic features. Clouds are plotted every 5 10^8 yr

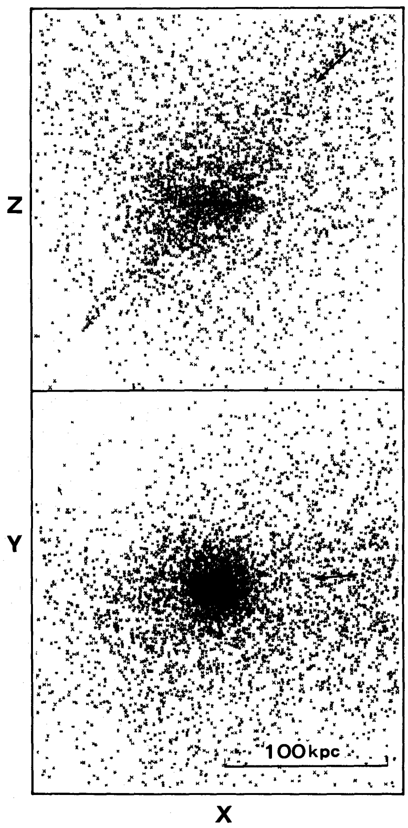

Fig. 11. Accretion of a "continuous flow" of N-clouds encountering a spiral galaxy at 45° inclination

A considerable portion of the encountering clouds from the retrograde side are accreted toward the central region, while those from the direct side are captured and are distributed in the outer disk, forming a broad disk. No clear spiral feature appears.

5. Discussion

5.1. Feeding AGN in E and S0 galaxies

Our simulation indicates that trapped gas clouds by elliptical galaxies are accreted toward the central region along the spiral orbits. However, the simulation cannot tell more about details within the central 1 kpc, because we have not taken into account changes in size, density and physical conditions of individual clouds, which had initial radii of about 0.5 to 1 kpc. We could only conjecture that the rapidly accreting clouds would finally reach the central region and fuel the nucleus. Thereby, it may be possible that individual clouds are more condensed and tidally stretched along the orbits, so that cross section of the clouds reduces. This may reduce the effective ram pressure. Thus, before a final accretion onto the nucleus, the clouds would form a circum-nuclear accreting ring due to their angular momentum support.

In the above simulation we have not taken into account the flow motion of halo gas within elliptical galaxies. However, it is known that the central region of hot gas halo in elliptical galaxies have a cooling flow (Fabian et al. 1991). Obviously such an inflow will promote the accretion of clouds in the central regions.

Feeding of the AGN (active galactic nuclei) of E and S0 galaxies has been extensively discussed based on correlation analyses of X-ray luminosity, which represents the hot gaseous halo, and radio emitting power of the nuclei (e.g. Fabbiano et al. 1989, and the literature therein). The authors find a significant correlation between the X-ray and radio powers, and suggest that the cooling flow may be the feeding source. They also point out the large scatter in the correlation, and claim that more than one mechanism may at play in feeding AGN. In this context, we stress that the external accretion of cool gas onto the nuclei by the present RPA mechanism could be an additional feeding source: Namely, *external cool clouds plus X-ray halos*, which are connected via the RPA, would lead to more powerful AGN. In fact, NGC 5128 (Cen A), which is the most scattered one to radio-loud sense in their correlation diagram (Fabbiano et al. 1979), is famous for its cool gas band (Sandage 1961). On the other hand, NGC 4406 (M 86) is the other most extreme case of radio-faint galaxy with a luminous X-ray halo, which is known to be moving fast through the intergalactic gas (Forman et al. 1979) and the accretion condition may not be satisfied, so that the RPA does not apply. Hence, we comment that a correlation analysis between the radio power and circum-galactic cool gas clouds *plus* X-ray halo of E/S0 galaxies would be an interesting subject.

5.2. Angular momentum loss and disk contraction in spiral galaxies

We have assumed that the disk and halo gases in spiral galaxies have angular momentum large enough compared to that of falling gas clouds. However, if we take into account the finite amount of angular momentum of the disk and halo gases in the galaxy, their rotation should be significantly influenced by an encounter with intergalactic gas clouds. If the encounter is direct, the disk gas gains angular momentum, so that the disk radius will increase. If the encounter is retrograde, the gas disk loses angular momentum, and the disk radius decreases. It is likely that a galaxy experiences a number of encounters through its life with intergalactic gas clouds which are distributed at random. As has been shown above, the capture frequency of a cloud is higher for a retrograde encounter, while it is less for a direct one. Therefore, it happens that more retrograde captures occur as a net, and hence the total angular momentum of the gas disk is lost significantly.

Suppose that direct and retrograde clouds are captured, when their impact parameters are smaller than P_D and P_R, respectively. Then the variation (loss) of angular momentum, A, of the disk is estimated by

$$\frac{dA}{dt} \sim -\rho_I \Delta S P_R v_0^2 \cos j, \tag{15}$$

where

$$\Delta S \sim \pi (P_R^2 - P_D^2)/2 \sim \pi P_R^2/2 \tag{16}$$

is an excess cross section of capture of retrograde clouds over the direct and head-on ones, j is the injection angle of clouds with respect to the disk plane, and ρ_I is an averaged density of intergalactic gas clouds with which the galaxy is encountering.

In order to see the variation of the disk size, we must take into account the variation of the disk mass. We approximate a disk by a ring of radius r and mass M, which are both variable, and assume that accreted gas makes the ring. We have equations

$$A(t) = M(t)\, V(t) r(t), \tag{17}$$

and

$$dM/dt = \rho_I S v_0. \tag{18}$$

If the ring loses angular momentum and gains mass, its radius decreases until its rotation velocity balances the gravity of the galaxy. Namely, the rotation velocity may be taken to be equal to the rotation velocity of the galaxy. We consider here two simple cases: (a) a flat rotation curve with $V(t) \simeq V_{rot} \simeq V_0$; and (b) a Keplerian rotation case in which $V(t) = V(r) \sim V_0 (r/r_0)^{-1/2}$. Then we can integrate Eqs. (15), (17) and (18), and get

$$r = r_0 \frac{1 - t/t_A}{1 + t/t_M}, \tag{19}$$

for case (a), and

$$r = r_0 \left(\frac{1 - t/t_A}{1 + t/t_M}\right)^2, \tag{20}$$

for case (b), where r_0 is the initial ring radius. Here t_M and t_A are time scales for the mass gain and angular momentum loss, respectively, and are given as

$$t_M = \frac{M}{\rho_I S v_0}, \tag{21}$$

and

$$t_A = t_M \frac{S}{\Delta S} \frac{r_0}{P_R} \frac{V_0}{v_0} \frac{1}{\cos j}. \tag{22}$$

Angular momentum loss by this mechanism would be significant if the density of intergalactic cool gas is high enough. Such a circumstance might happen in the early universe or in the early epoch in the central regions of rich clusters. For an extreme case, we here tentatively take $\rho_I \sim 10^{-4 \sim -5} m_H\,\mathrm{cm}^{-3}$, $S/\Delta S \sim 2$, $r_0/P_R \sim 0.1$, $V_0/v_0 \sim 1$, $\cos j \sim 0.5$, and $M \sim 10^{10} M_\odot$. Then we have $\rho_I S v_0 \sim 1 M_\odot\,\mathrm{yr}^{-1}$, and obtain $t_M \sim 10^{10}$ yr, and $t_A \sim 4\ 10^9$ yr. The disk radius decreases and gets to zero within 4 Gyr.

From this estimate, we could conjecture that gas disks of galaxies rotating in denser-gas environment lose their angular momenta rapider than those in less gas density regions. Furthermore, the angular momentum loss in the gaseous disk would result in contraction of the gas toward the nucleus, resulting in loosing gas in the disk region. This might be related to the fact that galaxies near rich clusters tend to have poorer gaseous disks.

It is also interesting to note that the angular momentum decreases further to negative value, or that the rotation sense of the disk reverses after shrinking to zero radius. Then, the disk radius increases, as it gets counter angular momentum from the falling gas. Therefore, it is possible that the inner disk starts to rotate in a counter sense to the initial galaxy rotation, and expands again. In fact some galaxies have been observed to have gaseous disks in counter rotation with respect to the stellar system (e.g. Bettoni et al. 1990).

We here assumed that the falling gas comes from the retrograde encounter, and that the outer halo rotation is still in the same rotation sense as the initial one. In reality, however, the situation including the halo and disk will change simultaneously. One the disk and halo become counter-rotating, they will be exerted by injection of angular momentum in the opposite sense to the previous one, and the disk will again begin to contract. Such an overshooting oscillation of the counter- and direct-sense rotation and corresponding contraction and expansion of the disk size will last for a while in an oscillatory manner.

5.3. Stochastic ignition of starburst in isolated galaxies

It has been pointed out that tidal interaction among galaxies plays an essential role in triggering accretion and fueling starburst (e.g. Noguchi 1987, 1988). In this scenario the gravitational disturbance and induced bar-stock accretion of interstellar gas is essential. This idea has been successful to explain such galaxies as M 82, which is interacting with the giant galaxy M 81 [see review by Sofue (1987)]. However, starburst is not a particular phenomenon seen only in interacting galaxies, but is observed also in isolated galaxies. NGC 253 is the most typical example of such an isolated burst galaxy (Rieke et al. 1980). The galaxy has neither companion nor any apparent nearby galaxy massive enough. Hence, starburst in such isolated galaxies must be triggered by some mechanism other than tidal interaction.

In this respect we suggest that our ram-pressure accretion of intergalactic clouds may be a promising mechanism to fuel and ignit starbursts in isolated galaxies. In Sect. 4.2 we have shown that gas clouds approaching the galaxy on off-plane and retrograde orbits are efficiently accreted to the central region. In addition, as discussed in the previous subsection, if we take into account the transfer of angular momentum with the disk, the rotation of gaseous disk is significantly decelerated, and the disk gas contracts toward the center. This effect would further enhance the feeding and starburst. Furthermore, if the galaxy has already an inner bar structure, which is likely for any spiral galaxy, gases occasionally supplied by the capture of intergalactic clouds may be more rapidly accreted toward the nucleus by the bar-shock mechanism (Sørensen et al. 1976).

We stress that the starbursts triggered in this way must not be regular at all, but will be sporadic and stochastic, depending on the frequency of "bombing" of clouds. We stress that even if the bombing is at random, which is likely for intergalactic clouds, clouds hit the nucleus rather accurately, provided that their orbits are retrograde and off-plane. The most important aspect of the present result is that this accretion process applies to any galaxies, even though they are isolated: Only clouds, and probably even fluctuations in the intergalactic gas, through which the galaxy is moving, are sufficient to cause starburst in the central region. Hence, this would give a hint to answer the long-standing question, why some isolated galaxies show starburst.

5.4. Interacting galaxies

Obviously the RPA model applies also to interacting galaxies. Galaxy-galaxy collision and tidal interaction are general phenomenon in multiple systems, where tidal debris of disturbed galaxies is either orbiting around the galaxies or escapes from the galaxies to form intergalactic clouds. Usually the orbiting velocities of the debris is more or less comparable to the escaping velocity (Gottesmann et al. 1977; Weliachew et al. 1978; Haynes et al. 1979; Mathewson et al. 1979; Sancisi et al. 1987; Smith 1991). The debris will be therefore easily captured by one of the galaxies with gaseous halo due to the RPA mechanism within a time scale of one or two orbitings, or within about 1 Gyr. The life time for the gaseous debris being "floating" clouds is therefore short compared to the Hubble time. Thereby, a considerable fraction of the accreting clouds fall toward the nuclear region to cause starburst. Hence, it may happen that starbursts of RPA origin are likely to be more often seen in interacting systems than isolated galaxies. This would play some essential role in triggering starbursts in interacting systems in addition to such an "internal" burst mechanism as the bar-shock accretion, which has been extensively investigated by Noguchi (1988).

5.5. High-velocity H I clouds

The origin and principal characteristics of high-velocity H I clouds in our Galaxy are still controversial, despite extensive surveys and investigations for the last three decades. Interpretations of the clouds are widely spread: whether they are very local clouds bubbled out from the galactic disk by a fountain mechanism; or tidal debris of the Magellanic Clouds; or intergalactic clouds falling toward the Galaxy (e.g. van Woerden et al. 1985). Recently Uemura & Tosa (1991: private communication) modeled HVCs as primordial gas clouds in the Galaxy-M 31 group, where HVCs are falling toward the Galaxy orbiting in the potential of M 31 and our Galaxy. We point out that the ram pressure due to the intergalactic and halo gases may play an essential role in promoting the accretion of HVCs, if we take a standpoint that they are external or outer galactic objects. In fact the Galaxy is embedded in a diffuse hot halo extending for a few kpc above the disk with a density of about $10^{-3} m_H$ cm^{-3} (de Boer & Savage 1983). If HVCs are orbiting the Galaxy, they will be accreted by the RPA mechanism through this halo and fall into the central region within 10^{8-9} yr. Such falling clouds would be related to the counter rotating motion of molecular clouds near the nucleus (e.g. Bally et al. 1987) as discussed in the previous section. Thus, it might be possible to link such distant HVCs in the outer Galactic region with molecular clouds in the galactic center by the present ram pressure model. Alternatively, if the halo rotation is large enough and the friction with the disk gas is also effective, accreting HVCs may attain corotation with the disk gas, tending to form an outer disk ring in the galactic plane. It would be an interesting subject to search for such an outer ring structure in the H I line emission in our Galaxy.

5.6. Early universe

Although we have increasing evidence for the presence of intergalactic H I clouds such as those mentioned in the literature cited in Sect. 1, they are still not commonly observed in usual intergalactic space. The apparent absence of intergalactic clouds is, perhaps, partly due to sensitivity problems in observations of H I and molecular clouds. However, it is also argued that intergalactic H I or cold clouds and debris were rather thoroughly captured by nearby galaxies: it is difficult for them to survive for the Hubble time, as the simulations indicated.

In this context, we point out that the intergalactic space may have been richer in cold gas clouds in the early universe, particularly in the epoch of galaxy formation. In such an early epoch, the gas-dynamical process of accretion of intergalactic gas clouds, besides the gravitational effect, would have played an important role in the evolution and dynamics, particularly the change of angular momentum and gaseous content.

5.7. Limitation of the model

Finally we comment on the limitation of application of the present RPA model. We have regarded intergalactic gas clouds to be test particles ("test clouds"), and their motion has been traced by the ballistic method as described in Sect. 3. This assumption may be valid, when the ratio of densities between a cloud and intergalactic gas is large enough. This condition is satisfied almost in all circumstances in our model: in galaxy halos and intergalactic space, the density ratio is about 10^3–10^5, respectively. Only when the cloud approaches the nuclear region or crosses the galactic plane, this ratio may become about unity. If the cloud velocity is high enough as is the case in the present circumstances, the model will still give reasonable results. However, if the cloud velocity becomes small to be comparable to the turbulent velocity within the galactic disk, such as when a cloud has been almost merged by the disk, we may need a hydrodynamical treatment. In particular, if there exists steep pressure gradient in the ambient gas, which may happen in the transient zone between the disk and halo, a slowly moving cloud may be significantly affected by the pressure term instead of the ram-pressure term in equations of motion. Also we mention that our ballistic method does not apply to a case of a continuous gas inflow, as in already discussed in Sect. 4.

In our model, we have assumed that the motion of clouds is subsonic in high-temperature intergalactic and halo gases, and have assumed that the ram drag is simply proportional to the cross section of a cloud. However, when the cloud crosses the disk of a spiral galaxy, its velocity is more likely supersonic against the interstellar gas. Then the effective ram will be increased by a factor due to the shock wave, and therefore the ram-pressure term in the equation of motion should be enhanced. We note that this is equivalent either to an increase in the gas density of the disk component or to an increase in the disk thickness. In fact, we took the thickness of the gas disk to be 200 pc (Table 2), which is slightly larger than the thickness usually observed for spiral galaxies. Also we note that the time duration for a cloud being moving through the low-temperature interstellar gas is very short compared to that moving in the halo and intergalactic space. Hence, the global behaviour of motion and orbit will not change significantly, even if we take into account the effect of shock and thinner, therefore more realistic, disk, although a detailed treatment taking into account shock waves is desired.

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