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Note

Fate of the Magellanic Stream

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Abstract

We show that H I clouds in the Magellanic Clouds are stripped by the ram-pressure due to the halo and disk gases of the Galaxy. Molecular clouds are swept to the edge of the LMC, showing an eccentric distribution. The stripped H I clouds form a narrow band on the sky, and mimics the Magellanic Stream, when the LMC takes a polar orbit. We show that the Magellanic Stream will fall into the Galaxy, and will be finally accreted by the Galactic disk. The accretion may cause warping of the inner gas disk of the Galaxy. Some clouds are accreted by the nuclear disk, which could explain the peculiar distribution and kinematics in the central region. The stripping of the interstellar gas from the Magellanic Clouds will rapidly change their morphological type into dwarf ellipticals.

Key words: Galaxy — Halo — Interstellar gas — Magellanic Clouds — Magellanic Stream — Ram-pressure.

1. Introduction

The dynamical evolution of the triple system of the Galaxy, the Large and Small Magellanic Clouds has been extensively studied by test-particle simulations (Fujimoto, Sofue 1976, 1977; Murai, Fujimoto 1980; Gardiner, Fujimoto 1993). In these current gravitational models, the Magellanic Stream of H I gas (Mathewson et al. 1974, 1977; Mathewson, Ford 1984) has been treated as a tidal debris, which has been torn off from the LMC and SMC through the gravitational interaction. However, no hydro-dynamical effect has been taken into account.

The gas-dynamical interaction of the Magellanic Clouds with the intergalactic and halo gases has been discussed only by a few authors: A galactic-wake model was proposed by Mathewson et al. (1977), and was examined in a greater detail by Bregman (1979), who, however, found difficulty in obtaining a satisfactory modeling of the Stream, and favored the gravitational model. On the other hand, the ram-pressure effect on gas clouds in the Magellanic Clouds and Stream has not yet been thoroughly studied. In particular, the ram pressure would significantly affect the evolution of the Magellanic Stream during its orbital motion around the Galaxy embedded in an extended gaseous halo, after the stream has left the Magellanic Clouds.

We have proposed a ram-pressure accretion model of intergalactic gas clouds by galaxies with an extended gaseous halo, and have shown that gaseous debris from tidally disturbed galaxies are soon accreted by a nearby galaxy (Sofue, Wakamatsu 1991, 1992, 1993). We further performed a numerical simulation of the stripping-and-accretion process of gas clouds from a companion onto its host galaxy, and applied the result to the M31–M32–NGC 205 system (Sofue 1994).

In this paper, we attempt to examine the ram-pressure effect of the circum-Galaxy gas on the dynamics of gas clouds in the Magellanic Cloud by applying this model. We also aim to investigate the fate of the Magellanic Stream in the future during interactions with the galactic halo and disk gases as well as with the intergalactic diffuse gas.

2. Basic Assumptions and Equations of Motion

2.1. *H I and Molecular Clouds*

In this work we treat the ballistic orbits of H I and molecular clouds, which are initially distributed in the LMC in the presence of the ram pressure due to the intergalactic as well as halo gases around the Galaxy. Because of the larger effective cross section, compared to the mass, H I clouds are easily stripped from the companion than molecular clouds. Stripped gas clouds can remain as intergalactic clouds when they are sufficiently massive, while less massive clouds are dissipated into intergalactic space. In the simulation we assumed that H I clouds have dimensions sufficiently massive to be gravitationally bound, as shown in table 1, so that they are gravitationally balanced with its internal motion and/or rotation. Although it has not been clearly confirmed, and must be reconsidered in detail taking into account gas-dynamical effects, the assumption that the H I clouds are gravitationally bound has been a basic assumption in past test-particle simulations obtained after Fujimoto,

Table 1. Parameters for gaseous components.

Intergalactic gas	
ρ_0	$10^{-5} m_H$ cm^{-3}
Halo of the Galaxy	
ρ_H	$0.01\ m_H$ cm^{-3}
ϖ_H	15 kpc
z_H	10 kpc
Disk of the Galaxy	
ρ_D	$1\ m_H$ cm^{-3}
ϖ_D	10 kpc
z_D	0.2 kpc
Molecular cloud	
$\rho_{\rm cloud}$	100 H_2 cm^{-3}
R	30 pc
$m = (4\pi/3)R^3\rho_{\rm H\,I}$	$1.32 \times 10^5 M_\odot$
$\sigma_{\rm cloud}$	4.36 km s^{-1}
H I cloud	
$\rho_{\rm H\,I}$	$1\ m_H$ cm^{-3}
R	500 pc
$m = (4\pi/3)R^3\rho_{\rm H\,I}$	$3.05 \times 10^6 M_\odot$
$\sigma_{\rm H\,I}$	5.11 km s^{-1}

Sofue (1976, 1977); we also follow this assumption here. For molecular clouds, we assume a size and mass of the same order as those of a typical giant molecular cloud in our Galaxy (table 1) which are also gravitationally balanced with the internal motion and/or rotation.

Although the cloud properties would vary during the interaction with the halo and intergalactic gas, we here simply assume that their original properties remain unchanged during the simulation. Although detailed analyses of such hydrodynamical process within individual clouds are beyond the scope of this paper, we make the following comment. The internal motion, such as turbulence, within each cloud will be dissipated, causing the cloud to collapse. However, instabilities on the cloud surface due to an interaction with the intergalactic gas, such as the Kelvin-Helmholtz instability, would excite turbulence inside the cloud, and would thus act to maintain the internal motion.

2.2. *Equations of Motion and Potentials of the Galaxies*

We are mainly concerned with the accretion process of stripped clouds from the Magellanic Clouds. The accretion orbits of individual clouds after stripping are not strongly dependent on former internal motions of the clouds within the Magellanic Clouds. Hence, in order to simplify the simulation; we considered only the LMC; its satellite (the SMC) is regarded as being a part of the envelope. Since the potential of LMC is much deeper than that of SMC, the interstellar gas inside SMC and the gaseous envelope surrounding the both Clouds are regarded as being a single gaseous halo surrounding the LMC.

We adopt a simple ballistic model for "test clouds", as it was adopted in the previous simulations (Sofue, Wakamatsu 1993; Sofue 1994). The equation of motion for each cloud is written as

$$\frac{d^2\boldsymbol{r}}{dt^2} = \sum_{j=1}^{2} \frac{\partial \Phi_j}{\partial \boldsymbol{r}} - \frac{3\rho(\boldsymbol{r})}{4R\rho_c}\Delta v \boldsymbol{\Delta v}, \tag{1}$$

with

$$\Phi_1 = \sum_{i=1}^{3} \frac{GM_i}{\left\{\varpi^2 + \left(a_i + \sqrt{z^2 + b_i^2}\right)^2\right\}^{1/2}} \tag{2}$$

and

$$\Phi_2 = \frac{GM_C}{\sqrt{r^2 + b_C^2}} \tag{3}$$

being the gravitational potentials for the Galaxy ($j = 1$) and the companion galaxy ($j = 2$), which are approximated by the modified Miyamoto-Nagai's (1975) potential and Plummer's law, respectively. Here, $\varpi = (x^2 + y^2)^{1/2}$, and M_i, a_i, and b_i are the mass, scale radius, and thickness for the i-th galaxy, respectively. The vectors $\boldsymbol{v} = d\boldsymbol{r}/dt$ and $d\boldsymbol{r} = (x, y, z)$ represent the cloud's velocity and position with respect to the center of the Galaxy, and ρ_c and $\rho(\boldsymbol{r})$ are the densities of the cloud and the halo + disk gas of the Galaxy, respectively. $\boldsymbol{\Delta v} = \boldsymbol{v} - \boldsymbol{V}$ is the mutual velocity of the cloud and diffuse gas. For the Galaxy we assume three mass components: the central bulge ($i = 1$); disk ($i = 2$); and a massive halo ($i = 3$). The parameters are summarized in table 2.

We assume that the mass of the LMC is an order of magnitude smaller than the main body of the Galaxy: ($M_C = 0.1M_2$), and that the center of mass of the system coincides with the center of the Galaxy which is fixed to the origin of the coordinates. We take into account the dynamical friction on the companion's motion by the massive halo. The equation of motion of the center of the LMC is written as

$$\frac{d^2\boldsymbol{r}}{dt^2} = \frac{\partial \Phi_1}{\partial \boldsymbol{r}} - kM_C\frac{\boldsymbol{v}}{r^2 v}, \tag{4}$$

where M_C is the mass of the companion. The second term represents the dynamical friction due to the massive halo, which is assumed to be at rest. The density of the massive halo is assumed to be inversely proportional to the square of r, $\rho_{\rm MH}(r) = \rho_{\rm MH0}(r/100\ {\rm kpc})^{-2}$, with $\rho_{\rm MH0}$ being a constant. The variable k represents the coefficient of the dynamical friction. Although coefficient k is actually a slowly varying function of the velocity and mass (Tremaine 1976), we assume it to be constant. We used a value for $k\rho_{\rm MH0}$ so that the acceleration by the

Table 2. Parameters for the gravitational potentials of the Galaxy and LMC.

i	Mass component	$M_i (M_\odot)$	a_i (kpc)	b_i (kpc)
The Galaxy*				
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
Companions†				
LMC	Spheroid	$M_{\rm C} = 0.1 \times M_2$	0	2

* Miyamoto-Nagai's (1975) potential with a modified massive halo.

† Plummer's potential. For a convenience to trace the global behavior of stripped gas clouds, we consider the LMC+SMC system as a single object represented by LMC.

second term becomes equal to 0.005 times the gravitational acceleration by the first term when the companion galaxy is at a distance of 100 kpc from the center.

2.3. Models for Gaseous Disk, Halo, and Intergalactic Gas

A hot tenuous halo of extended gas around the Galaxy has been theoretically predicted (Spitzer 1956), and was discovered by IUE observations (de Boer, Savage 1983). In this paper, we consider three components of extended gas around the Galaxy: the disk gas, the halo, and the intergalactic diffuse gas. We assume a simple density distribution around the Galaxy, as represented by

$$\rho(\mathrm{r}) = \rho(\varpi, z) = \rho_0 + \frac{\rho_{\rm H}}{(\varpi/\varpi_{\rm H})^2 + (z/z_{\rm H})^2 + 1} + \frac{\rho_{\rm D}}{(\varpi/\varpi_{\rm D})^2 + (z/z_{\rm D})^2 + 1}, \quad (5)$$

where ϖ and z are cylindrical coordinates; the values of the parameters are given in table 2. The first term represents a low, constant-density intergalactic gas. The second term represents a gaseous halo with a round-shaped distribution with a large z scale height, which dominates in the high-z halo region. The third is for a dense gaseous disk, which has a flattened distribution and dominates in the galactic plane.

Although little is known about the rotation of the halo gas, we assume here that the halo gas is rotating around the z-axis with its centrifugal force balancing the galaxy's gravity toward the z-axis, following the assumption taken by Sofue, Wakamatsu (1993). We assume that the gas is in hydrostatic equilibrium in the z-direction, so that $V_z = 0$, and the pressure gradient in the ϖ direction can be neglected. This assumption would be too simplified and neglecting the pressure gradient in the ϖ direction would result in an over-estimation of the rotation speed of the halo gas.

2.4. Orbits of the LMC and the Initial Conditions

The orbit of the Magellanic System has been extensively investigated by numerical integrations of the orbits toward the past, so that the present binary state has been guaranteed for the past ten Gyr as well as that the Magellanic Stream can be reproduced by the tidal debris (Fujimoto, Sofue 1976, 1977; Murai, Fujimoto 1980; Gardiner, Fujimoto 1993). These computations have indicated that the LMC is rotating around the Galaxy along a polar orbit that is counter-clockwise as seen from the Sun. In this study we adopted the polar and semipolar (high-inclination) orbits, and examined both the clockwise and counter-clockwise orbits. The perigalactic distance was taken to be 40 to 50 kpc.

We solved the differential equations by using the Runge-Kutta-Gill method. The time step of integration was taken to be smaller than 0.005-times the dynamical time scale of each test cloud. The initial position of the LMC was taken at a sufficiently large distance on the z- or x-axis, and the initial velocity was given so that it takes a (semi-)polar orbit. The initial velocity was given so that the distance and radial velocity at the present position approximately coincide with the observed distance (52 kpc) and galactocentric radial velocity (51 km s^{-1}) of the LMC (Allen 1973). The initial values of the coordinates and velocity of the LMC are given in the figure captions for the individual results (figures 2–5).

$N(= 50)$ interstellar clouds were initially distributed at random in the companion within a radius of R (= 10 kpc) with a velocity dispersion of $\sigma_v (= 50$ km s$^{-1})$, so that the ensemble of test clouds would remain a spherical system. This might be replaced with a rotating disk of similar size. Since the initial distribution within the companion would only slightly affect the accretion process after stripping (Sofue 1994), we adopt here simply a spherical distribution.

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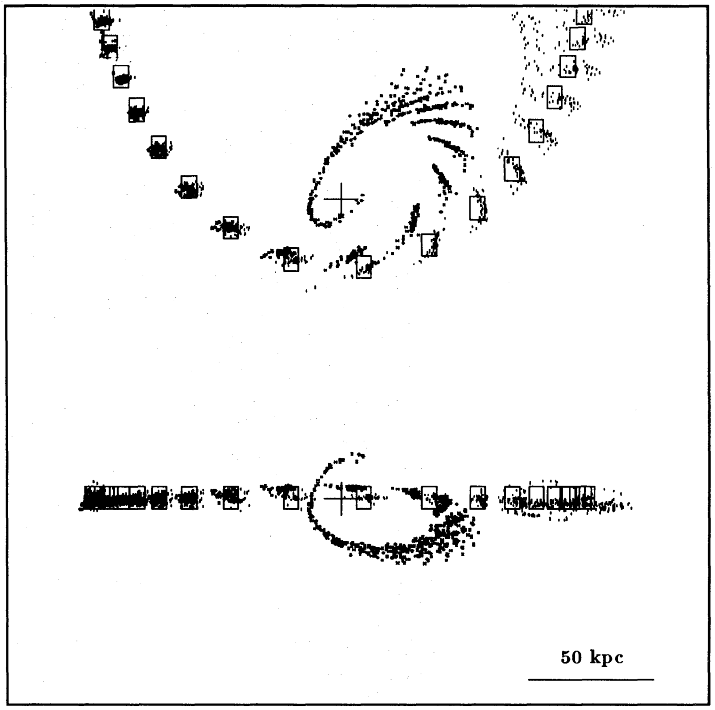

Fig. 1a. Ram-pressure stripping of H I (large dots) and molecular (small dots) clouds from the LMC, and their accretion onto the Galaxy for a counter-clockwise (as seen from the Sun) polar orbit. The initial condition is $(x, y, z) = (-100, 0, 100)$ kpc and $(v_x, v_y, v_z) = (0, 0, -80)$ km s^{-1}with the peri-G distance of 30 kpc. The upper panel is the projection onto the (x, z) plane (the Galaxy is edge on), and the lower panel onto the (x, y) plane (Galactic plane). The Galaxy is rotating clockwise on this (x, y) plane. The large cross indicates the center of the Galaxy. The square represents the position of the LMC plotted every 0.1 Gyr. The linear scale is indicated by a bar. Stripped H I clouds reproduce the Magellanic Stream, while molecular clouds show an eccentric distribution within the LMC.

3. Results

Figure 1a shows the result of a numerical integration for a counter-clockwise polar orbit, which mimics the orbit taken by Fujimoto, Sofue (1976, 1977). Figure 1b is the same, but in a stereo-gram, and figure 1c is an enlargement of figure 1a. The upper panel shows the (x, z) plane, where the Galaxy lies edge-on; we can obtain a rough idea about the distribution of clouds when they are projected on the sky in the (l, b) coordinates. The lower panel is a projected view on the (x, y) plane (the Galactic plane). Figures 2, 3, and 4 show the cases for clockwise orbits, where figure 2 is for a polar orbit, figure 3 is for a semi-polar prograde (direct) orbit, and figure 4 is for a semi-polar retrograde orbit with respect to the galactic rotation. Figure 5 plots the results on the sky as seen from the Sun.

The simulation shows that the orbits of the individual gas clouds change drastically when they cross the galactic plane, where the clouds suffer from the strongest ram-braking due to the rotating disk. In all cases, the H I test clouds are entirely stripped, and the molecular clouds are partly stripped. The "efficiency" of the stripping of H I clouds may be too high compared to the observations; this is because the individual clouds suffer from the ram pressure, even when they are distributed in the LMC. In reality, however, clouds within the LMC are "shielded" from the halo and intergalactic gas by many other clouds and by the diffuse component, so that the effective ram would be smaller. Therefore, the real stripping of clouds would be more gentle than the simulation shows. The decrease in the apogalactic distance due to dynamical friction is gradual, and is negligible during the period of the present simulations.

3.1. *Eccentric Distribution of Clouds in the LMC*

During the passage of the galactic plane, H I clouds in the LMC suffer from the strongest ram pressure. The clouds attain an eccentric distribution, being accumulated in the down-stream side of the LMC, and are swept away from the central region. After the passage, the H I clouds are almost entirely stripped. On the other hand, stripping of molecular clouds occurs more gently, and many clouds survive the stripping: most of the molec-

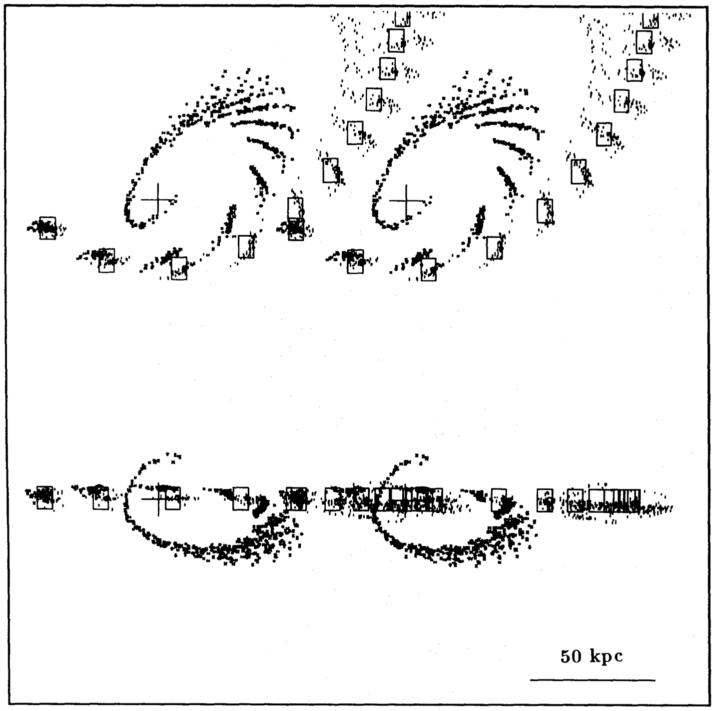

Fig. 1b. Same as a, but in a stereogram.

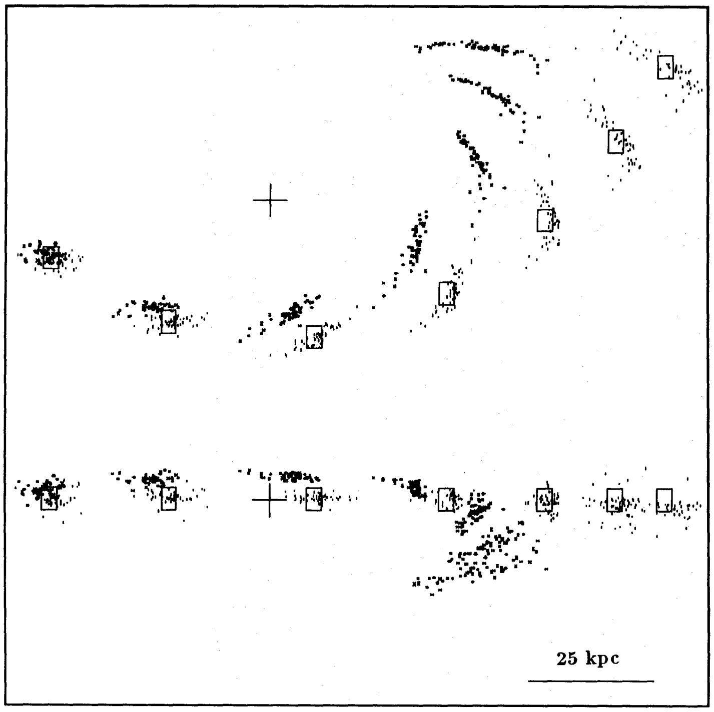

Fig. 1c. Same, but the scale is doubled.

Fig. 2. Same as figure 1, but for a clockwise polar orbit with the initial condition of $(x, y, z) = (-100, 0, 0)$ kpc and $(v_x, v_y, v_z) = (0, 0, 100)$ km s^{-1}, and the peri-G is 40 kpc. The lower-right bar indicates 50 kpc. The H I tail also resembles the Magellanic Stream.

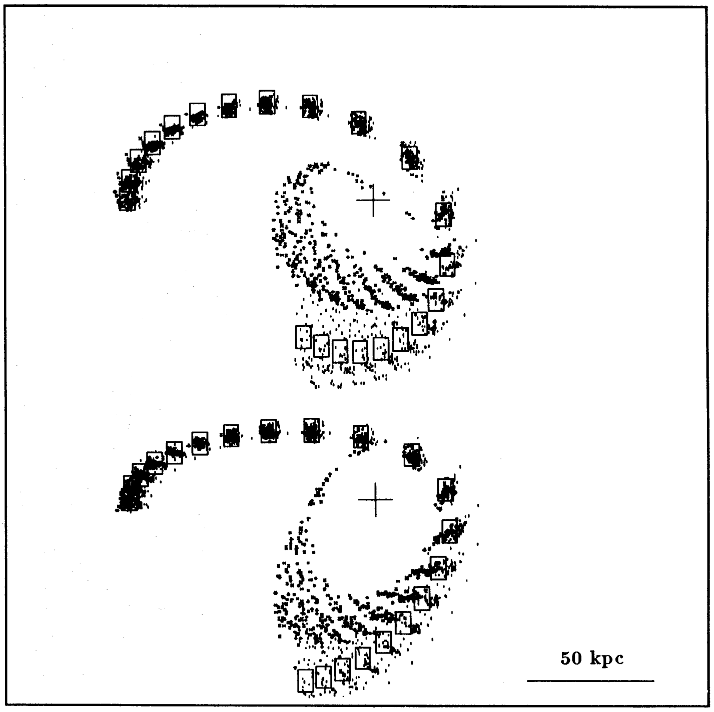

Fig. 3. Same as figure 3, but for a prograde orbit with respect to the galactic rotation. The initial condition is $(x, y, z) = (-100, 0, 0)$ kpc and $(v_x, v_y, v_z) = (0, 50, 80)$ km s^{-1}. The bar indicates 50 kpc.

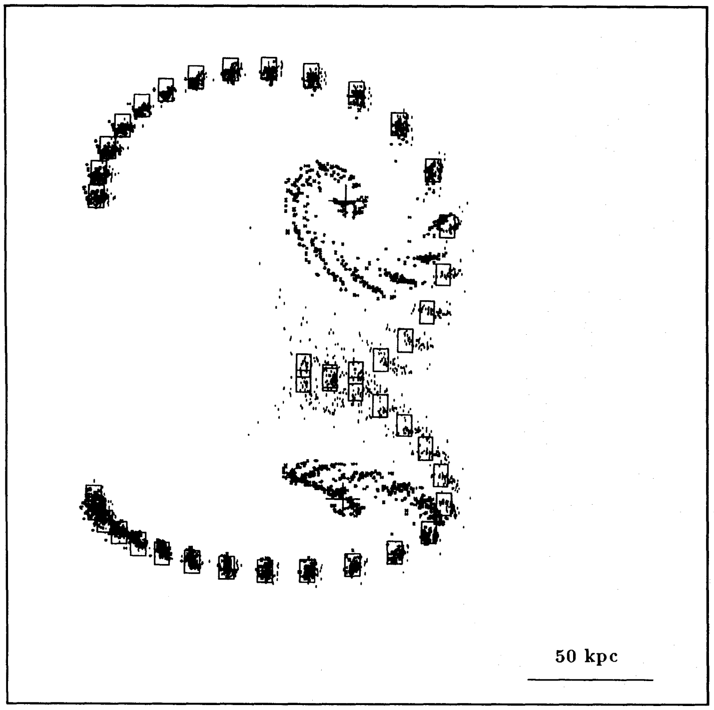

Fig. 4a. Same as figure 3, but for a retrograde orbit. The initial condition is $(x, y, z) = (-100, 0, 0)$ kpc and $(v_x, v_y, v_z) = (0, -50, 100)$ km s^{-1}. The bar indicates 50 kpc. The accreted H I clouds hit the central region of the Galaxy.

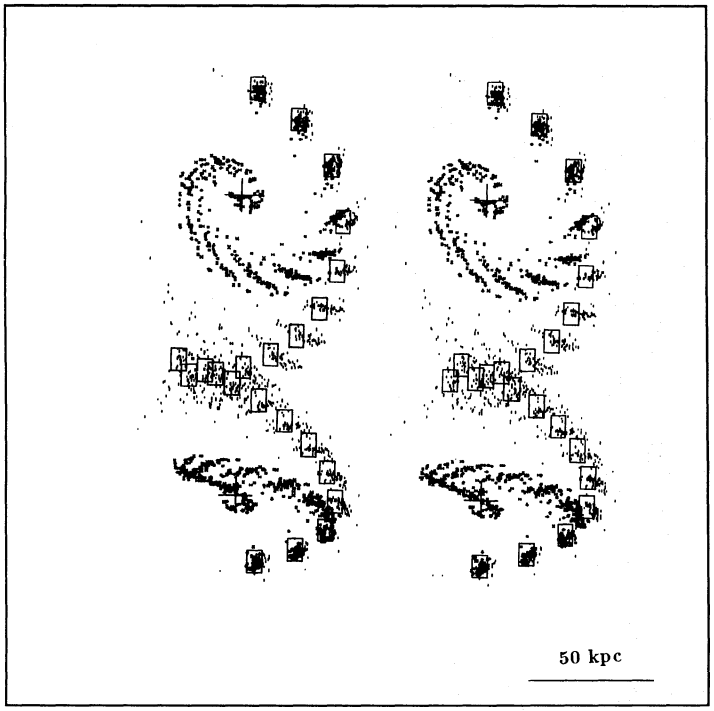

Fig. 4b. Same as figure 4a, but in a stereogram.

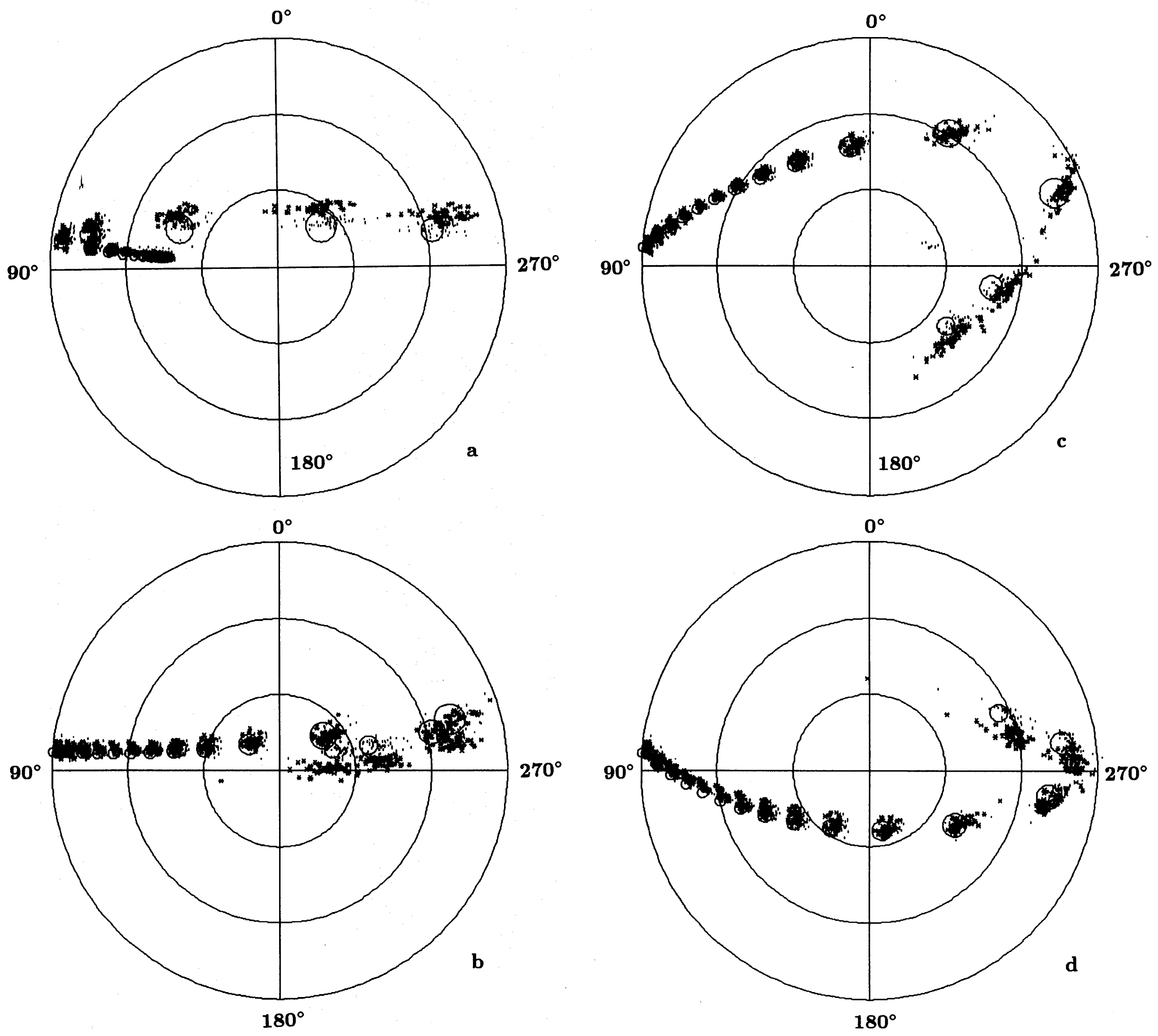

Fig. 5. Plots of the results in figure 1 to 4 on the (l, b) coordinates, respectively in panels (a) to (d). Note that the ram force for H I clouds in (a) is assumed to be half that assumed for figure 1. The northern and southern hemispheres are projected on the Galactic plane. The Galactic poles are at the center, and the outer circle represents the galactic equator. The small circles represent the LMC's position, and the diameter is inversely proportional to the distance from the Sun.

ular clouds are only accumulated in the edge of the LMC without being stripped, except for outer clouds, which are stripped. They attain an eccentric distribution, and begin to oscillate in the potential of LMC. Such an eccentric distribution is indeed observed both for CO (Cohen et al. 1988) and H I (Mathewson, Ford 1984). We stress that the eccentric distribution of gas displaced from the stellar body cannot be reproduced by the gravitational model.

3.2. The Magellanic Stream

The stripped H I clouds are distributed in the intergalactic space as a long and thin tail. Soon after the stripping, the clouds form a tail trailing from the LMC. As they leave the LMC and are attracted by the Galaxy's potential, they become more elongated. Since they begin to rotate around the Galaxy at a higher angular velocity than the LMC, the clouds form a "leading stream" on the sky. The calculated stream for the counter-clockwise orbit reproduces the observed Magellanic Stream (Mathewson, Ford 1984), when the LMC reaches the present position (figure 1). It is conspicuous that the stream becomes as narrow as about 4 kpc across, becoming narrower and longer as they approach the Galaxy. This stream is, however, finally accreted by the galactic disk.

In order to compare the simulation with the observed H I stream (Mathewson, Ford 1984), we plotted the calculated results in the galactic coordinates in figure 5. The simulation for figure 5a reproduces qualitatively the observed Stream, where the ram pressure is assumed to be half that assumed for figure 1. However, the details are not well reproduced, which would be due to the too simplified assumption regarding the size and mass of the clouds, as well as due to ignoring the shielding effect of clouds inside the LMC by other clouds and the diffuse component. If we take into account these effects, yielding a wider range of effective-ram force on the clouds, the stream would be more elongated, and would better reproduce the observations. We point out that not only the tail, but also "pre-stream" clouds, which are observed at $(l, b) \sim (300°, -10 \text{ to } 0°)$, are simulated. It is also interesting to note that the simulated stream is not perfectly aligned along the LMC's projected orbit, but is displaced toward the direction of the SMC by about 10°, which is indeed observed in the H I gas distribution.

3.3. *The Fate of the Magellanic Stream: Accretion onto the Galaxy*

In all cases of the simulations, stripped H I clouds are finally trapped by the Galaxy, and infall toward the galactic disk along polar "spiral" orbits. The accretion occurs within $\sim 10^9$ yr after the clouds left the LMC's gravity. For the polar and prograde orbits, regardless of being clockwise or anti-clockwise, H I clouds are finally accreted by the galactic disk, and form a ring having a radius of about 10 kpc. For the retrograde orbits, on the other hand, the infalling clouds enter the central region of the Galaxy, and form a compact disk (ring) of a few kpc radius around the nucleus.

The accretion of molecular clouds is much slower, and they remain as intergalactic or intra-halo gaseous debris for a longer time than H I. Finally, however, they are also accreted by the Galaxy in several 10^9 yr. During the accretion, some molecular clouds take peculiar polar orbits, and enter the central region of the Galaxy.

4. Discussion

We have shown that gas clouds in the LMC are stripped due to the ram-pressure of the halo gas of our Galaxy, and that the Magellanic Stream will be accreted by the Galaxy in a few Gyr. We discuss some implications of these results for the gas dynamics in the Galaxy and for the evolution of the Galaxy-Magellanic System.

4.1. *Infalling Streams and High-Velocity Clouds*

We may suppose that the stripping-and-accretion of H I and molecular clouds occurred recurrently during the past tidal as well as gas-dynamical interaction of the LMC and the Galaxy, particularly when the LMC crossed the galactic plane. We may, therefore, expect that a larger number of Magellanic-Stream-like clouds have fallen into the Galaxy in the past, which would be observed as high-velocity H I clouds (e.g., van Woerden et al. 1985). As the simulation indicates, the directions and velocities of the infalling clouds near to the galactic plane are not apparently related to the orbit of the LMC, because of the larger friction of the disk gas of the Galaxy.

4.2. *Warp and Peculiar Kinematics of the Inner Galactic Disk*

The falling gas clouds hit the central region of the Galaxy when the LMC's orbit is retrograde. If we take into account the finite amount of the angular momentum of the original gas disk in the Galaxy, particularly of the inner disk, the infall would cause a significant change in the angular momentum of the gas disk (Sofue, Wakamatsu 1993). It is quite possible that such infalling streams have hit the central region of the Galaxy in the past, which caused a significant change in the rotation characteristics of the inner disk. This could explain the tilt of the inner 1-kpc H I disk, which is warping by about 10° from the galactic plane (Burton, Liszt 1978). The angular momentum of of the inner disk of 1 kpc radius is on the order of $A \sim MrV \sim 1.2 \times 10^{65}$ g cm^2 s^{-1} for $M \sim 10^8 M_{\odot}$, $r \sim 1$ kpc, and $V \sim 200$ km s^{-1}. If the infalling stream had a mass of $\sim 10^7 M_{\odot}$ and has hit the inner disk at a velocity of 200 km s^{-1}perpendicular to the disk, the additional angular-momentum, $A \sim 10^{64}$ g cm^2 s^{-1}, would be sufficient to change the angular momentum vector of the inner disk by about ten degrees.

The infall of clouds into the more central region would further cause a peculiar kinematics and distribution of the molecular gas in the nuclear disk. Indeed, the molecular gas in the central few hundred pc of our Galaxy exhibits a highly eccentric (asymmetric) distribution, and shows even "forbidden" velocities (e.g., Bally et al. 1987). We point out that the infalling high-velocity clouds would produce "sprays" of gas, which vertically expand from the nuclear disk toward the halo, as well as shock waves inside the disk. These appear to have been observed in the central few-hundred pc region of the Galaxy in the form of various exotic features seen in radio and molecular lines (e.g., Sofue 1989).

4.3. *Evolution of the Magellanic Clouds into Early-Type Galaxies*

The stripping of gas clouds from a companion and their accretion onto the Galaxy apply generally to any multiple-galaxy systems, and should play a significant role in the evolution of smaller-mass galaxies. In particular, a selective and one-way transfer of gas would result in a rapid evolution of the companion. The companion becomes more gas-deficient, and, therefore, redder (early type), whereas its host galaxy becomes gas-richer and bluer (later type). We stress that the gas transfer between interacting galaxies occurs much more rapidly than the stellar mass transfer due to the gravitational effect, such as dynamical friction. We, therefore, predict that the LMC and SMC will evolve from the present young and blue irregular type into gas-poor dwarf ellipticals in the future, as long as the two Clouds are bound to the Galaxy. Moreover, the binary state of the LMC and SMC will be destroyed by the stronger tidal force as they approach the Galaxy, due to dynamical friction. Hence, the future state of the Magellanic Clouds will mimic that of the dwarf elliptical companions (M32 and NGC 205), which are already gas deficient, around M31 (Sofue 1994).

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