THE MAGELLANIC STREAM: THEORETICAL CONSIDERATIONS

M. Fujimoto
Department of Physics
Nagoya University, Nagoya

ABSTRACT

The tidal and the primordial theories for the Magellanic Stream are examined in a frame of test-particle simulation for the interacting triple system of the Galaxy, the Large and Small Magellanic Clouds (LMC and SMC). Difficulties of the radial velocity of the Stream still beset these two theories. Several new models for the Stream and the Clouds are briefly discussed in relation to the bending of the galactic disk, the past binary orbits of the LMC and SMC and also the Local Group and the Local Supercluster of galaxies.

1. INTRODUCTION

The "tidal" theory considers that the Magellanic Stream (van Kuilenberg 1972, Wannier and Wrixon 1972, Mathewson et al. 1974) is hydrogen gas which has been pulled out of the Large and Small Magellanic Clouds (LMC and SMC) during their close approach to the Galaxy. This theory is based on a number of test-particle computations which successfully reproduced well-known filamentary bridges and tails in gravitationally interacting galaxies (see Toomre and Toomre 1972 and references therein).

The "primordial" theory has been proposed by Mathewson et al. (1974) and Mathewson and Schwarz (1976) to explain the high negative velocity at the tip of the Magellanic Stream which the tidal model could not reproduce. The Stream is considered as a band of primordial gaseous debris left from the formation of the Clouds and moving along a hyperbolic orbit unbound to the Galaxy.

In the present paper, we examine these two models for the Magellanic Stream on the basis of the test-particle computations, and compare our results with the observed geometry and motion of the Stream.

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2. TIDAL THEORY OF THE MAGELLANIC STREAM

2.1. Gravitationally-interacting triple system of the Galaxy, LMC and SMC

As preliminaries to the test-particle simulation, Fujimoto and Sofue (1976, 1977) obtained several series of orbits for the LMC and SMC passing the center of the Galaxy at 20, 30, 40 and 50 kpc, and along which the two Clouds were in a binary state for at least the past 5×10^9 years. The binary-orbit condition is based on the presence of the common envelope of diffuse gas and the systematic distribution of optical polarization planes of star-light and HII regions in and around the LMC and SMC (Hindman et al. 1963; Mathewson and Ford 1970; Schmidt 1970). Thereby the binary orbits of the LMC and SMC must satisfy at the present epoch the observed kinematical quantities listed in Table 1.

Table 1. Observed kinematical quantities of the LMC and SMC

	LMC	SMC
(l,b)	(280°,-33°)	(303°,-45°)
Distance from the Sun	52 kpc	63 kpc
Observed radial velocity (corrected for the galactic rotation and the motion of the Sun in the LSR)*	51 km s^{-1}	0
Mass (assumed in the text)	$1\text{-}2\times10^{10}M_\odot$	$2\times10^{9}M_\odot$

* V_θ=250 km s^{-1} and R_0=10 kpc are assumed: V_θ is the rotation velocity of the Sun at R_0 of the galactic center.

As shown in the next subsection, the orbit of the LMC is approximately on a plane perpendicular to the line joining the present position of the Sun and the galactic center. For such overhead orbits of $D\geq20$ kpc, the binary state of the LMC and SMC is guaranteed, at least, for the combinations of the masses of the Galaxy, LMC and SMC given in Table 2 where D is the perigalactocentric distance.

Table 2. Combinations of the masses of the Galaxy, LMC and SMC adopted in the present paper

m_G (Galaxy)	m_L (LMC)	m_S (SMC)
$1.2\times10^{11}M_\odot$	$2\times10^{10}M_\odot$	$2\times10^{9}M_\odot$
1.4	2	2
2.0	2	2
2.7	2	2
2.7	1	2

Three representative overhead orbits of the LMC are given in Fig.1, seen from the direction of l=180°, b=0°: the Sun is located on the galactic plane at 10 kpc on this side of the figure page. When the SMC's binary motion is taken into account, they are slightly waved. The bars at the present positions of the LMC and SMC, L and S, indicate the size of the tidal limit δr_L and δr_S, outside of which material would be pulled out easily.

When the LMC is at the perigalacticon, δr_L reduces to half of the present value, and the strong tidal disruption would be expected. If $m_G=2\times10^{11}M_\odot$ and D=20 kpc, the scale of the tidal limit becomes as small as $\delta r_L=4.6$ kpc.

We have $\delta r_L>\delta r_S$ for the present separation of the LMC and SMC, and δr_S is determined mostly by the LMC; the contribution from the Galaxy is only 20 percent or less. This is one of the reasons why Toomre (1973) predicted the presence of a long streak of gas emerging from the SMC or the vicinity of the Clouds region (see Mirabel and Turner 1973).

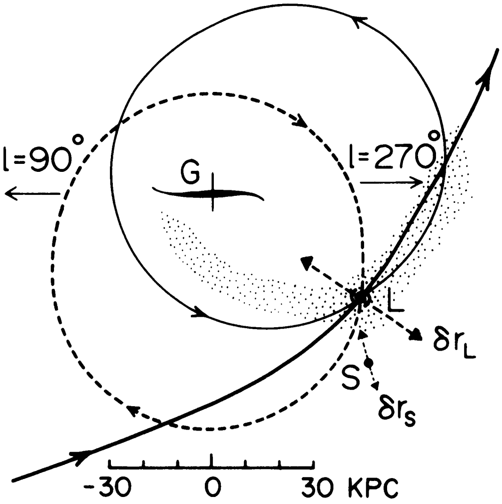

Fig.1. Three typical orbits of the LMC for D=30 kpc and 50 kpc. The direction of motion is indicated. The model Stream by Davies and Wright is given by numerous dots. $m_G=1.2\times10^{11}M_\odot$ and $m_L=2\times10^{10}M_\odot$ are assumed.

2.2. Tidal models for the Magellanic Clouds

About four hundred test-particles are distributed around the centers of the LMC and SMC within the radii of δr_L and δr_S, respectively. Numerical integrations of the motion of the test-particles began when the LMC was at the apogalacticon, and were performed toward the present. Fig.2 shows the post-interaction configuration of four hundred test particles, projected onto the plane of the sky. The binary orbits of the LMC and SMC are overhead and in a counterclockwise sense in Fig.1.

Two streaks—head and tail—are found to emerge from the Clouds region. When D=30 kpc, a good geometrical reproduction is obtained of the high-velocity-cloud (HVC) in the northern hemisphere and some HI gas complexes at l=260° to 330°, b=-20° to 30° on a great circle extrapolated from the Clouds to l=90°, b=-30°, passing near the south galactic pole (Fig.3). The radial velocities averaged over nearby particles are given (in km s^{-1}) relative to the Sun of the non-rotating Galaxy.

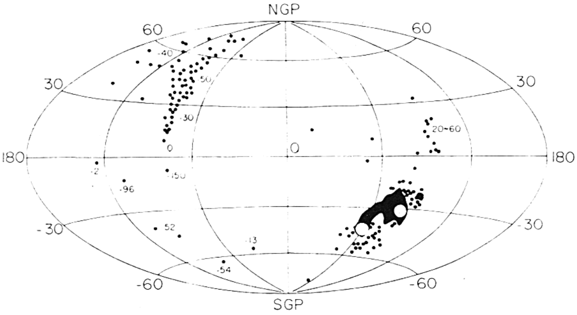

Fig.2. Present distribution of the test particles on the (l,b) plane in the overhead, D=30 kpc orbit of the LMC. Numbers show the radial velocities (km s^{-1}) to be observed at the Sun of the non-rotating Galaxy.

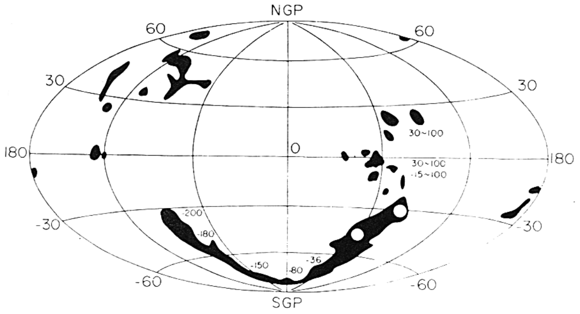

Fig.3. The Magellanic Stream of hydrogen gas, high-velocity HI clouds and some HI gas complexes at l=260° to 330°, b=-20° to 30°, after Mathewson et al. (1974). Numbers refer to the observed radial velocities relative to the Sun of the non-rotating Galaxy (in km s^{-1}).

When D=30 kpc the radial velocities of the particles in the HVC region are sufficiently high to regard the particles as the high-velocity gas clouds. The radial velocities of the test-particles corresponding to the Magellanic Stream are, although the sample number is small, much smaller than the observed values by about 100 km s^{-1}.

This discrepancy cannot be removed only by changing the parameters such as D, m_G and m_L, and it is exactly what Mathewson et al. (1974) stressed in their "primordial" theory of the Magellanic Stream.

If the orbital plane of the LMC is inclined to the galactic plane, the pulled-out particles do not lie on a great circle defined by the Magellanic Stream. This is the reason why the orbital plane of the LMC is considered as approximately perpendicular to the line joining the Sun and the galactic center.

Davies and Wright (1977) have made similar test-particle simulations for the LMC orbits circling in a clockwise and overhead sense seen from the Sun (see Fig.1). The leading and trailing streaks of the particles emerge from the LMC when it reaches the perigalacticon (Lynden-Bell 1976). The leading part, which is on the side towards the Galaxy, becomes a bridge between two galaxies and its tip is captured to the Galaxy when the LMC approaches the present position. Davies and Wright claimed that the high-negative velocities can be produced at the northern tip of the Stream.

As shown schematically in Fig.1, the narrow bridge of the test-particles seems to be clear and realistic seen from outside of the Galaxy-LMC system. However, when we plot the positions of these particles on the plane of the sky, they cover a considerable area of the sky because of the very large parallaxes involved for the particles which fall down so close as to hit the galactic plane in the solar neighborhood. If we choose a narrower and more likely Stream from their results, the radial velocity is much smaller than the observed values by 100 km s^{-1}.

3. PRIMORDIAL-GAS MODELS FOR THE MAGELLANIC STREAM

We examine in our scheme of test-particle simulation the behavior of primordial gaseous debris left from the condensation to the Clouds and moving along a hyperbolic orbit unbound to the Galaxy, with a special regard to the high-negative-velocity difficulties besetting the tidal theory.

3.1. A line of test-particles

Following the primordial models of the Mathewson et al. (1974), we placed two hundred particles in a line on the same hyperbolic orbit of the LMC, with the LMC and SMC at the extreme end near the Galaxy. The LMC, SMC and each particle were given velocities sufficient to move along the orbit whose perigalactocentric distance is 50 kpc and whose plane is perpendicular to the line joining the Sun and the galactic center.

The integration commenced when the LMC was at 550 kpc distant from the Galaxy. The particle distribution at the present epoch is shown projected onto the plane of the sky in Fig.4. From a comparison with Fig.3, we find a good reproduction of the linear distribution of gas and a good fit to the high negative velocity at the tip of the Stream. Moreover, if such initial linear distribution of gas is realistic, the hydrogen gas clouds at 270° to 330°, b=-20° to 30° could be regarded as primordial gas; they overtook and passed the Magellanic Clouds from behind, and now in a disordered state. The radial-velocity distribution of these particles is rather dispersed, 70 to 100 km s^{-1}, which is not inconsistent with observations.

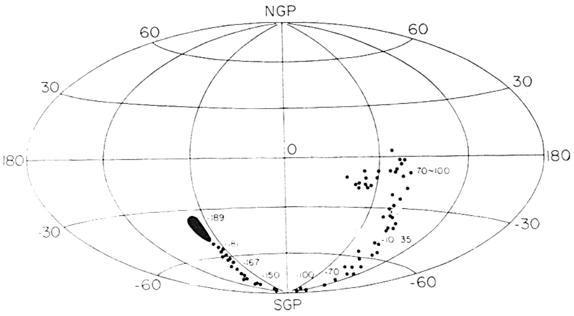

Fig.4 Present distribution of test particles for the initial linear case.

3.2. A spherical cloud of test-particles

Since the above initial configuration is too specific, Fujimoto and Sofue (1976, 1977) considered an elongation of a spherical gas cloud due to a drag force of intergalactic gas: the primordial gas cloud would be decelerated relative to the LMC and SMC and be stretched to become a narrow band of gas.

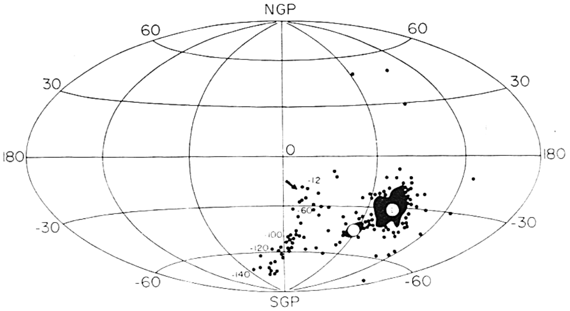

Fig.5. Present distribution of the test particles on the sky. $1/k=2\times10^{10}$ years is assumed. Note a hump in the particle distribution (arrow). The particles do not fall on the Magellanic Stream region adjacent to the south galactic pole.

We made similar computations for a sphere of two hundred particles, having the LMC and SMC at its center and moving on the hyperbolic orbit in Fig.1. A drag force is assumed on each particle in the form $-k\underset{\sim}{V}$. Figs.5 and 6 show the post-interaction configurations at the present epoch for $1/k=2\times10^{10}$ and 2×10^{9} years, or 10^{-5} and 10^{-4} hydrogen atoms per cm^3 of intergalactic gas, respectively. A trailing structure is naturally produced.

From a comparison with the Stream in Fig.3, however, we find some unsatisfactory results such as a gap and hump in the particle distribution and its large deviation from a great circle defined by the Stream. Since such behavior of the particles is intrinsically associated with our scheme of computation of particles in the gravitational potential and the drag force $-k\underset{\sim}{V}$, we could not remove them from the primordial model of the Stream.

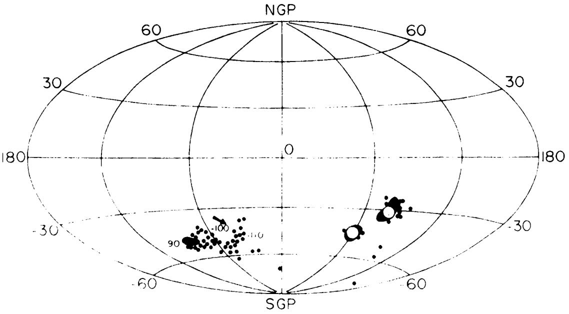

Fig.6 Same as Fig.5, but $1/k=2\times10^{9}$ years

4. PROBLEMS RELATED TO THE MAGELLANIC STREAM

The tidal and primordial models for the Magellanic Stream have been examined in sections 2 and 3 for the masses of the Galaxy, LMC and SMC assumed in Table 1. Parallel with this computation, Fujimoto and Sofue (1976, 1977) obtained the bending of our galactic disk for various binary orbits of the Clouds, and concluded that the bending is reproduced when D=20 to 30 kpc, $m_G\lesssim2.0\times10^{11}M_\odot$ and $m_L=2$ to $3\times10^{10}M_\odot$. For the theoretical analysis of the bending, see Hunter and Toomre (1969) and references therein, and Spight and Crayzeck (1977). In other words, if the bending of our galactic plane is due to the tidal force, the total mass of the Galaxy within the radius of 50 kpc is not so large as suggested by Ostriker and Peebles (1973). We stress that the current controversy concerning the mass of our Galaxy is but part of a much larger problem involving the mass of the LMC, the mechanism of the bending of the galactic disk and also dynamical state of the Magellanic Clouds — whether they are a steady binary circling round the Galaxy or are accidental passers-by on hyperbolic orbits.

Mathewson et al. (1977) considered that the primordial models in section 3 is not enough to explain the geometry and high negative velocities of the Stream, and proposed a new theory for the origin of the Stream in which the observed six discrete gas clouds were formed from thermal instability arising behind the Magellanic Clouds passing through the hot halo of our Galaxy (see Mathewson at the present symposium). The high negative velocities are considered to be achieved from the work done by the gravitational potential of the Galaxy. When $m_G=2.8\times10^{11}M_\odot$, they are reproduced for only 44 kpc of the closest distance of approach to the galactic center. The past binary state of the Clouds are guaranteed, but the origin of the bending is left undiscussed.

Tremaine (1976) has shown that the present proximity of the Clouds can be explained by the decay of the orbit due to dynamical friction in an extended massive halo of our Galaxy. Since he could take 40 and 190 kpc as the peri- and apogalactocentric distance of 10^{10} years ago, the initial state of the triple system of the Galaxy, LMC and SMC seems to be related to the Local Group and perhaps to the Local Supercluster of galaxies (de Vaucouleurs and Corwin 1975). The total mass of the Galaxy is assumed as 5 to $7\times10^{11}M_\odot$, within 50 kpc of the galactic center, which is much greater than that we have adopted so far, and which makes it difficult to maintain the Clouds in a gravitationally bound state for the last 5×10^9 years.

In various attempts to understand the Magellanic Stream, many models of the Magellanic Clouds have been introduced. It becomes more difficult to explain the Stream in detail in a simple way such as our test-particle computations. We consider that these difficulties must be resolved not by examining only one or two aspects separately, but by synthesizing the whole situations that would be associated with the Galaxy-LMC-SMC system. At the same time we must search for other possible mechanism which may produce the galactic bending structure.

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DISCUSSION

Giovanelli: What happens with your models if you take a mass on the order of 10^{12} $M_\odot$ for the Galaxy instead of $1\text{-}2\times10^{11}$ $M_\odot$ as you used?

van Woerden: Are stability of the Magellanic Cloud pair and the formation of a warp in our Galaxy also excluded if 10^{12} $M_\odot$ would be distributed over a volume 60 kpc in radius?

Fujimoto: Yes. More exactly, if the mass within 30 to 50 kpc of the galactic center exceeds 3×10^{11} $M_\odot$, the overhead binary orbits of the Clouds are easily disrupted.

Mathewson: I believe that you have touched too lightly on the Turbulent Wake Theory of the Magellanic Stream. It explains rather nicely: (1) the near great circle of the Stream which suggests that it is at least at a distance of 50 kpc. There is then no difficulty in keeping the Magellanic Clouds bound to each other; (2) the looped structure of the six clouds which make up the Stream; (3) the extremely constant velocity field of each Stream cloud which places rigid constraints on the translational velocity of the clouds and suggests that their motion is purely radial; (4) the fact that the Stream clouds have all blue shifts; (5) the ease with which one can explain the high negative velocity of MS VI at the tip of the Stream; (6) the direction of motion of the Magellanic Clouds implied by the steep HI gradients on one side of the gas envelope containing the Magellanic Clouds; (7) the large velocity discontinuity between the nearest part of the gas envelope containing the Magellanic Clouds to the start of the Stream and MSI.

The main difficulties with the Turbulent Wake Theory are: (1) that it needs a hot gaseous halo around our Galaxy which we are not sure exists and (2) the question of whether or not the passage of the Magellanic Clouds will produce the thermal instabilities in the halo necessary to condense out the cold clouds.

I would like to point out that if this is the correct explanation of the Magellanic Stream then HI clouds of $10^7\text{-}10^8$ $M_\odot$ will fall into the galactic center at intervals separated by about 10^8 years.

Felten: If I understood Dr. Fujimoto's presentation, the great-circle geometry of the Magellanic Stream arises provided the clouds in the stream all originate in the orbital plane of the Magellanic Clouds. But I believe this geometry would be destroyed if the clouds were to have appreciable random velocities. Dr. Toomre's skepticism about the tidal models moves me to ask whether this planar geometry is telling us which models are correct. Would we necessarily get this geometry in non-tidal models?

Haynes: This geometry is obtained, for example, in the non-tidal, galactic-wake model of Mathewson.

Lynden-Bell: It is possible to compute away and to fit the lie of the Magellanic Stream on the sky exactly. All tidal models produce streams roughly in a plane and the parallax due to the Sun's offset is not too large. Thus rough great circles arise from all theories in which the clouds move in a planar orbit that does not come closer to the Galaxy than say 20 kpc. The fact that the stream is on a large small circle is not really very surprising.

Kerr: It is important for people who speak of a Galactic Standard of Rest (GSR) or of "velocities corrected to the center" to define quite carefully what they mean. Several systems are in use now, and others are possibly in the future.

van Woerden: Magellanic-Stream and intergalactic-hydrogen workers may be using various formulae to correct velocities to the galactic standard of rest. Most extragalactic observers use a velocity vector of 300 km s^{-1} towards ℓ = 90°, ℓ = 0° (even if this is not the correct motion of the Sun with respect to the galactic center) to refer their observations to an extragalactic standard of rest, intended to be (the center of gravity of?) "the Local Group".

van Woerden: Do I remember correctly that three years ago there were reports about stars in the Magellanic Stream clouds?

Humphreys: I am curious to know the magnitudes, colors, and spectral type of the stellar objects you have identified in the gas between the clouds. Finding charts would be very useful.

Mathewson: I would like to point out how tricky it is to define an intergalactic gas cloud. For example, Murray and I found HI emission in the Centaurus Group a few degrees to the north of NGC 5236 with a velocity characteristic of the Group. The Palomar Sky Atlas showed no optical emission at this position. However, a deep SRC Schmidt plate showed a faint smudge of emission which Louise Webster, using the AAT, showed to be an HII region. It then becomes a matter of definition whether you call this an intergalactic gas cloud or a low surface brightness galaxy.

While Toomre's tidal theories have had outstanding success in explaining many astrophysical phenomena, one should be careful in using the tidal theory to explain all phenomena. Rather than going into a long-winded discussion as to why I do not believe Magellanic Stream has been produced by tidal forces, I would just like to point out that Alar Toomre has never attempted to model the Stream.