THE MAGELLANIC STREAM AND ITS RELATED PROBLEMS

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ABSTRACT

A brief survey is made of recent 21-cm and optical observations of the Magellanic Stream(MS). The space orientation of the Magellanic Clouds is touched upon in relation to modelling the MS. After summarizing a variety of models for the MS, we show that if our Galaxy is massive with a huge dark halo, a tidal model is most suitable for reproducing its characteristic structure and high-negative radial velocity. Past orbits of the Large and the Small Magellanic Cloud (LMC and SMC) are determined uniquely for the last 2×10^9yr, if we postulate that the LMC and SMC are bound together for 10^{10}yr: Highly-noncircular motion of the SMC around the LMC could give a clue to understand some peculiar features associated with the Magellanic Clouds.

1. THE MAGELLANIC STREAM

The Magellanic Stream(MS) is a narrow band of neutral hydrogen gas extending along a great circle from the Magellanic Clouds past the South Galactic Pole to l=90°, b=-30°(Wannier and Wrixon 1972; Mathewson et al. 1974). The radial velocity of the gas varies systematically with angular distance along the MS, $V_r=-240\sin(\theta+2°)$ km s^{-1}, where θ is measured from the origin at l≈298°, b≈-69° toward the northern tip of the Stream.

As shown in figure 1 and references therein, recent high sensitive 21-cm surveys reveal large number of narrower filaments and elongated cloudlets of 0.5°×0.3° aligned along the MS proper. Two parallel sub-structures are found along the MS near the Magellanic Clouds. Large amplitude fluctuations of more than 50 km s^{-1} are superimposed locally on the smooth velocity features V_r(Haynes 1979).

Giovanelli(1980, 1981) and Mirabel(1981a and b) have observed and noted a wide-spread population of high-velocity clouds in the first and second quadrant in the southern galactic hemisphere. They consider that some

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of them are of the same origin as the MS: In fact, the radial velocity of the high-velocity clouds at the extension of or in the neighborhood of the MS connects smoothly with that of the MS.

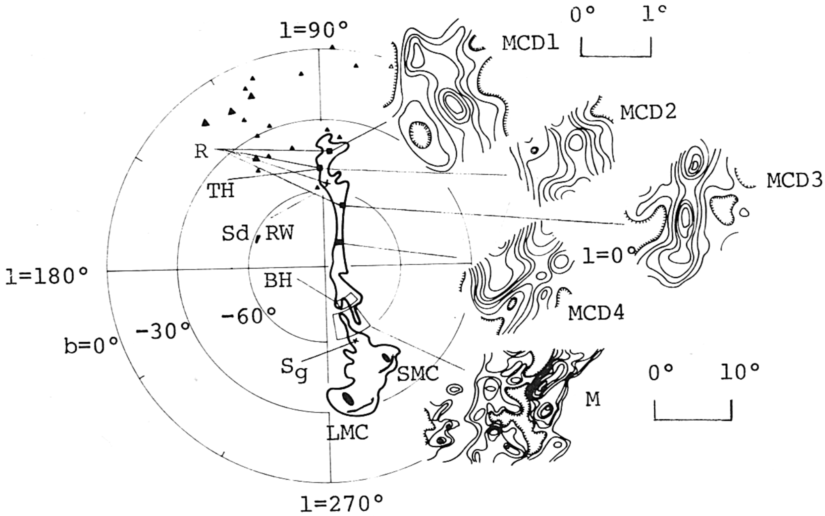

Fig. 1. Outline of the Magellanic Stream and some recent higher-sensitive 21-cm surveys. Six clouds MSI-VI by Mathewson et al. (1977) are not given, but the steep HI gradients are indicated closely along the leading edges of the LMC and SMC opposite to the MS. The selected areas for 21-cm and optical observations are shown: MCD1-4=Mirabel et al. (1979), M=Morras (1983), R=Recillas-Cruz (1982), TH=Tanaka and Hamajima (1982), Sd=Sanduleak (1980), BH=Brück and Hawkins (1983), Sg=Songaila (1981), RW=Richer and Westerlund (1983). The triangles ▲▲▲ are high velocity clouds near the northern tip of the Stream (Giovanelli 1980, 1981; Mirabell 1981a, 1981b). Other 21-cm observations by Haynes (1979) and Cohen (1982), not given here, also reveal that the MS consists of large number of small scale but large-amplitude fluctuations in the velocity and density.

2. OPTICAL OBSERVATIONS OF THE MAGELLANIC STREAM

Songaila (1981) detected visual absorption lines, Ca K and Na D, on the background continuum of the Seyfert galaxy, Fairall-9, at Sg in MS in figure 1. The metalicity of the MS gas is determined as 0.01 to 1.78, depending on the calcium depletion. Although it ranges still widely from metal-poor globular cluster values to those of the LMC and SMC, Songaila's observations may shed some light on the origin of the MS material.

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Following negative searches for faint stars in the MS by Philip (1976a and b) and by Mathewson et al. (1979), Sanduleak (1980) found a carbon star at Sd in figure 1, suggesting that it might belong to the MS. Although it seems to await confirmation, the distance to the MS is estimated as 15 kpc or 50 kpc depending on its absolute magnitude M_V=0.4 or -2.5. In their near-infrared survey of carbon stars in galaxies of the Local Group, Richer and Westerlund (1983) identified a carbon star at the same place as Sanduleak. If it belongs to the MS, the distance to the northern tip of the MS is 38 kpc, but its radial velocity differs from that of the MS by 150 km s^{-1}.

Faint A type stars of apparent magnitude around m_V=18.5 are searched in several selected areas in the directions R in figure 1 (Recillas-Cruz 1982). The number of stars of this magnitude is a factor 10 lower than what we should expect if the tip of the Stream is located as close as 10 kpc from the sun. A similar search is made by Tanaka and Hamajima (1982) by means of three-colour photometry whose limiting magnitude is 17.5 (TH in figure 1). Again no candidates for A type star have been found associated with the MS. These two results suggest strongly that the distance to the MS is far greater than 15 kpc and comparable to that to the Magellanic Clounds.

Brück and Hawkins (1983) performed star counts to 20.5 in B magnitude on an extended area in the MS. The amplitude of excess of stars is not so large as expected and their positional correlation with the maximum HI density is not present or just marginal. Since the excess stars to 20.5^m in B were expected to consist of intermediate age objects, Brück and Hawkins (1983) consider that the age of the MS is older than 2×10^9yr or the distance to the MS is greater than that to the Clouds.

To sum up, the optical search for faint stars in the MS has been negative, suggesting that the distance to the MS is far greater than 15 kpc.

3. SPACE ORIENTATION OF TRANSVERSE MOTION OF THE MAGELLANIC CLOUDS

The angular size of the LMC is finite that a small fraction of its transverse motion would be seen as radial velocity superimposed on the intrinsic rotational motion. Taking into account this and the apparent distribution of HI, supergiants etc., Feitzinger et al. (1977) concluded that the transverse component of the LMC motion is about 275 km s^{-1} relative to the LSR, toward the galactic plane and parallel to the MS. Lin and Lynden-Bell (1982) applied a similar kinematics to the LMC-SMC system whose angular separation is so large as 21° that one quarter of the transverse motion of the Magellanic Clouds would be seen as a part of radial velocity of the SMC. Assuming a circular motion of the SMC around the LMC, Lin and Lynden-Bell (1982) derived the same transverse motion of the Magellcnic Clouds as Feitzinger et al. (1977).

Mathewson et al. (1977) suggested already the above motion in their

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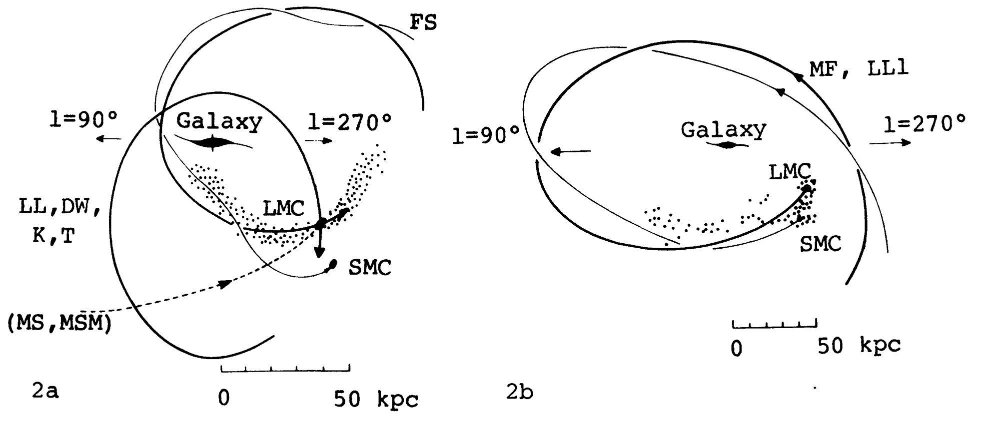
hydrodynamical model for the MS (section 4). As shown schematically in figure 1, the steep HI gradients along the leading edges of the LMC and SMC are considered as due to the ram pressure of the galactic halo gas through which the Magellanic Clouds pass toward the galactic plane and in pararell with the MS.

4. MODELS FOR THE MAGELLANIC STREAM

Three kinds of models — tidal, primordial and hydrodynamical — have been proposed for the MS. They attempt to explain the narrow and long-extended structure of the MS, together with its smooth sinusoidal and highly-negative radial velocity features.

4.1. Tidal Interaction Models

Figures 2a and 2b summarize the tidal models for the MS, with references and adopted parameters. Orbits of the Magellanic Clouds are approximately on a plane perpendicular to the sun-galactic center line: They are seen from the direction of l=180°, b=0°. The Magellanic Stream is simulated by some hundreds of test particles. [See Toomre(1972) for earlier studies on the tidal disruption of the Magellanic Clouds at their close approach to the Galaxy. The present paper deals with the tidal models published after the discovery of the Magellanic Stream.]



Figs.2a and 2b. Tidal models for the Magellanic Stream. FS=Fujimoto and Sofue(1976, 1977), LL=Lin and Lynden-Bell (1977), DW=Davies and Wright(1977), K=Kunkel(1979), MF=Murai and Fujimoto(1980), T=Tanaka(1981), LL1=Lin and Lynden-Bell (1982). The thin lines of FS and MF indicates the SMC orbits bound to the LMC. In figure 2a, the perigalactic distance of the orbit is 10 to 20 kpc and the total mass of the Galaxy is 1.2-2.8×$10^{11}M_\odot$. In figure 2b, the perigalactic distance is

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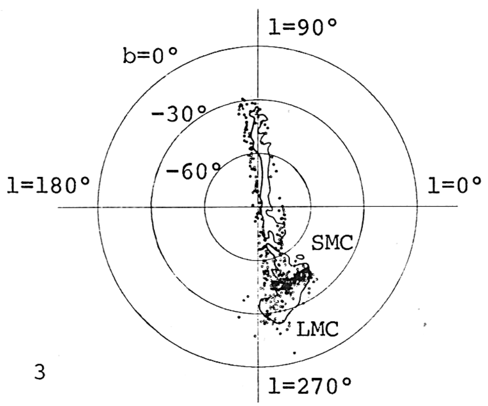
50 kpc, and the Galaxy is assumed to be massive with a huge dark halo. The total mass of the Galaxy within a radius of 50 kpc is $7\times10^{11}M_{\odot}$. The dashed lines, MS and MSM, are due to Mathewson and Schwarz(1979) and Mathewson et al.(1978) for the LMC orbit of the primordial and the hydrodynamical model.

The orbits, LL, DW, and K, are clockwise as seen from the sun in an opposite direction to that derived in section 3. The MS is a gaseous (test particles) bridge torn from the LMC and leading toward the Galaxy. The apparent features and the high-negative radial velocity of the MS are reproduced qualitatively. However, the northern part of the model Stream covers too large an area of the sky because the test particles approach the sun so close as 10 kpc. Although its amplitude is reasonable, the radial-velocity distribution does not resemble the observed one V_r. It is also to be noted that these models do not take into account the SMC: A tail or a counterpart to the bridge appears unavoidably in the two body system, the Galaxy and the LMC. As seen in figures 1 and 3, the MS misses the tail and is asymmetric with respect to the Magellanic Clouds. The model T considers the LMC and SMC which are bound together for 10^{10}yr. The radial velocity at the tip of the model Stream is, however, -140 km s^{-1}, too large by 80 km s^{-1} compared with the observed value -220 km s^{-1}.

The parameters adopted for the model FS in figure 2a are the same as T except for the direction of the revolution around the Galaxy. It is counterclockwise as seen from the sun. A narrow band of test particles can be obtained on the sky, but the observed radial velocity V_r can not be reproduced. This model FS is open to drastic improvement.

In order to overcome these difficulties, a model Galaxy with a massive halo is introduced, in which the LMC and the SMC are postulated to be bound together for 10^{10}yr. The binary state like MF and LL1 in figure 2b is realized when the perigalactic distance is 40-50 kpc. A good



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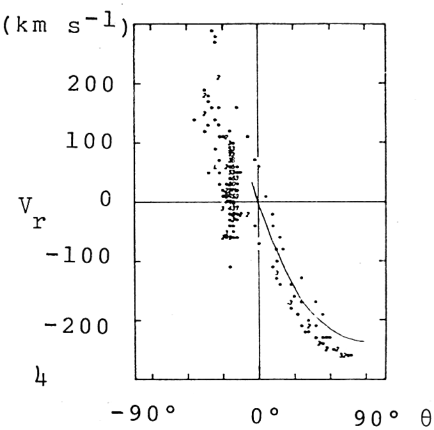

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Figs. 3 and 4. The model Stream and its radial velocities are superimposed on the observed ones.

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example of our particle simulations is given in figures 3 and 4, where the apparent feature and radial-velocity distribution of the MS is reproduced, much better than the models in figure 2a. The Magellanic Clouds revolve around the Galaxy in the direction consistent with that in section 3. The asymmetric structure of the Stream, a tail with no bridge, is understood by taking into account the SMC: A bridge from the SMC enters into the LMC and captured by it.

Since the massive halo assumption of the Galaxy is very reasonable (Rubin et al. 1978; Blitz 1979), the tidal models, MF and LL1, in figure 2b can be regarded as most realistic at present. It is interesting to note that such a similar orbit and a similar picture for the origin of the Stream have emerged through various investigators who have previously different opinions like LL and FS in figure 2a.

4.2. Other Theoretical Models

The primordial and the hydrodynamical (or wake) model have been introduced to produce the high-negative radial motion of the MS, without disrupting tidally the LMC-SMC system at its close approach to the Galaxy (Mathewson and Schwarz 1976; Mathewson et al. 1977). They explained also the observed inhomogenities in the density and velocity which can not be treated by the particle simulation in the tidal theories. Fujimoto and Sofue(1977) tried to find a mechanism to stretch a primordial gas cloud left from the condensation of the LMC and SMC. A drag force is assumed between the intergalactic gas and this gas cloud. However, it is not yet successful to reproduce a long-extended and gapless structure of the MS.

Bregman(1979) studied vortices in the wake which arise behind the Magellanic Clouds passing through a tenuous and high-temperature halo gas. The viscosity, thermal conduction and radiative cooling are considered in a realistic unstable gas. Bregman concluded, also through his hydrodynamical simulation, that the cooling time is not much less in the wake than the surroundings and consequently too large an amount of cooled (neutral) gas must be found downstream after the Magellanic Clouds. This feature is not observed in the MS.

The present authors consider that these non-tidal models await more extensive theoretical work, and also that the presently available data is not so well understood as to support them more strongly than the tidal models.

5. PAST ORBITS OF THE LMC AND SMC

When we postulate a bound state between the LMC and SMC in the tidal models, their past orbits are rather uniquely determined for the last, say, 2×10^{9}yr (Murai and Fujimoto 1980; Fujimoto and Murai 1984).

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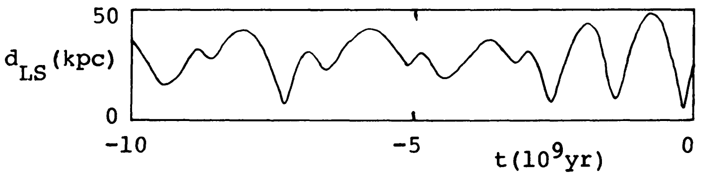

Fig. 5. The distance between the LMC and SMC, $d_{LS}(t)$, for the model MF in figure 2a.

Figure 5 shows a binary orbit of the LMC and SMC in the form of the separation (in kpc) between them, $d_{LS}(t)$. One finds that d_{LS} is not constant but varies with time from 2-7 kpc at $t \approx -2\times10^8$, -1.5×10^9 and -2.6×10^9yr to 50 kpc at $t \approx -8\times10^8$ and -2×10^9yr and so on.

Since this tendency in $d_{LS}(t)$ is found in most cases of our computed binary orbits of the LMC and SMC, we consider that the "collision" such as d_{LS}=2-7 kpc is not an accident but a dynamical event repeated in the history of the Magellanic Clouds. The last collision occurred 200 million years ago. Thereby the LMC and SMC must have been much disturbed and its aftereffect could be seen in some peculiar features in the Magellanic Clouds. In order to see them, we would like to refer to the spatial distributions of HI gas(Hindman et al. 1963), of H_α nebulosities(Johnson et al. 1982) and of planes of optical polarization of stars(Mathewson and Ford 1970; Schmidt 1970 and 1976). As shown in figure 6, they are observed along the relative orbit of the SMC to

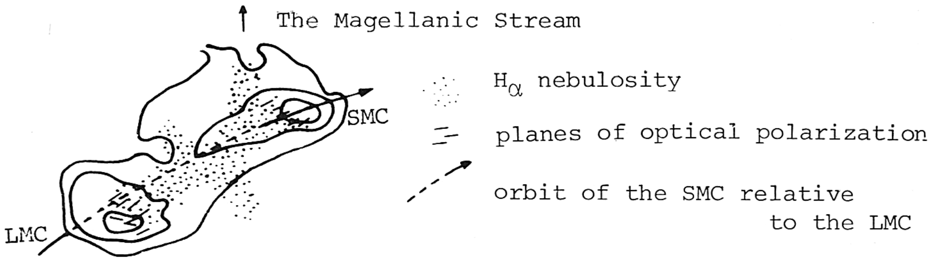

Fig. 6. Spatial distributions of HI gas, H_α nebulosity and planes of optical polarization of stars. The relative orbit of the SMC is given to the LMC.

the LMC, as if the SMC has stretched and stimulated the common magnetized gas as it departed from the LMC after the collision.

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DISCUSSION

Fall: How close does the LMC-SMC pair get to the Milky Way in your simulation? When was the last perigalactic passage?
Fujimoto: 200 million years ago the Galaxy and the Magellanic Clouds approached each other to about 50 kpc.

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