THE MAGELLANIC STREAM AND THE MAGELLANIC CLOUD SYSTEM

M. FUJIMOTO
Uedayama 4-901, Tempaku, Nagoya 468, Japan
T. SAWA
Department of Physics and Astronomy
Aichi University of Education, Kariya 470, Japan
AND
Y. KUMAI
Faculty of Commerce
Kumamoto Gakuen University, Kumamoto 862, Japan

1. Introduction

A tidal model has been introduced to the triple system of the Galaxy, Large and Small Magellanic Clouds (the LMC and SMC hereafter) and successfully reproduced the Magellanic Stream (Murai and Fujimoto 1980; Lin and Lynden-Bell 1982; Gardiner et al. 1994; Gardiner and Noguchi 1995; Lin et al. 1995), a narrow band of diffuse atomic hydrogen gas emerging from the SMC region, passing by the South Galactic Pole along an overhead great circle spanning over 100° (Wannier and Wrixon 1972; Mathewson et al. 1974). The LMC and SMC have a hydrogen bridge and common envelope (Hindman 1964; McGee and Milton 1966) and, therefore, we can consider that they have been in a binary state for the Hubble time, revolving together around the Galaxy with a halo whose mass is larger than $10^{12} M_{\odot}$ if the flat rotation curve extends up to more than 100 kpc. The strong gravitational force due to this heavy halo attracts the Magellanic Stream and produces the high negative radial velocities (Murai and Fujimoto 1980).

The tidal model seems to be realistic when we view some characteristics of the SMC with two-peaked radial velocities separating each other with $\sim$40 km s^{-1}: The SMC is elongated and partially splitting over more than 15 kpc along the line of sight. (These famous phenomena have been found by many investigators. See their names referred to in a summary paper

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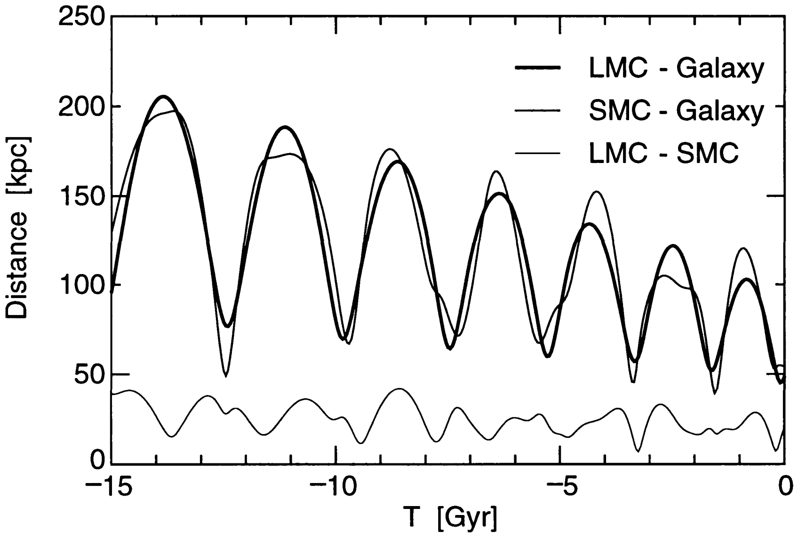

Figure 1. Time variation of the Galaxy-Magellanic Clouds distance and the LMC-SMC separation. The LMC and SMC have remained in a binary state for the past 15 Gyr.

by Mathewson and Ford 1983). The dynamics can be explained uniquely in terms of the tidal interaction that the SMC approached the LMC so closely a few 10^8yr ago and then the far-less-massive SMC suffered a deep tidal damage.

Since we support this tidal model for the Magellanic Stream, we are introducing in this paper more data that favor the past gravitational interaction between the LMC and SMC in a binary state.

2. The Magellanic Stream and the Binary Orbits of the LMC and SMC

The radial velocities of the LMC and SMC have been already measured, whereas their transverse velocities (proper motions) could not be measured until only three years ago (Section 3). As Murai and Fujimoto (1980) applied, we search for binary orbits of the LMC and SMC backward in time by assuming various values for their transverse velocities. For the following model for the Galaxy-LMC-SMC system, we take again $2\times10^{10}M_\odot$ and $2\times10^9M_\odot$ for the LMC and SMC masses, and 220 km s^{-1} for the velocity amplitude of the flat rotation curve of the Galaxy.

Fig. 1 shows a typical result for the binary orbits of the LMC and SMC which have endured in the past 15 Gyr. On the basis of such binary orbits, we apply particle simulations to reproduce the geometrical as well as

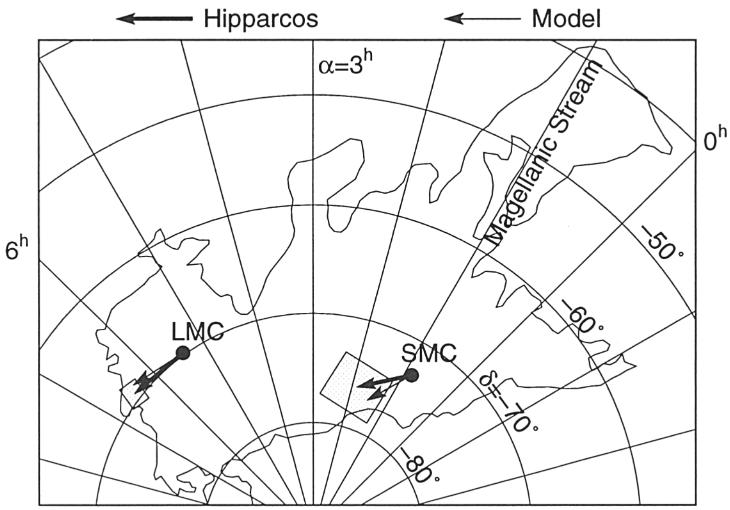

Figure 2. Observed and model proper motions of the LMC and SMC. The former data are due to Kroupa & Bastian (1997). The model proper motions are shown to fall well within the error boxes of observations.

dynamical structures which resemble quantitatively the Magellanic Stream. As discussed so far in many papers (see references in § 1), the Magellanic Stream can be modeled as a tidal debris torn off from the less-massive SMC and elongated due to the gravitational force of the Galaxy. We note that two diametrically-opposite structures are pulled out usually from the tidally perturbed object: One is heading, and the other is trailing. The present case for the SMC, the heading gaseous debris flowed into the LMC region and forms the common envelope of gas enclosing the LMC and SMC.

3. Observations Supporting the Tidal Model

3.1. PROPER MOTIONS OF THE LMC AND SMC

Jones et al. (1994) and Kroupa et al. (1994) have first obtained reliable data about the proper motion of the LMC by measuring extremely slight changes of stellar positions relative to the far background galaxies. The magnitude and direction of the proper motion are consistent with those predicted by Lin and Lynden-Bell (1982) and Gardiner et al. (1993): The LMC moves with $\sim$300 km s^{-1}, trailing the Magellanic Stream counterclockwise as seen towards the galactic center from the present position of the Sun (Murai and Fujimoto 1980).

Recently Kroupa and Bastian (1997) used the *Hipparcos* data and obtained the proper motions of both the LMC and SMC: $\mu_\alpha = 1.94 \pm 0.29$ mas

y^{-1}, $\mu_\delta = -0.14\pm0.36$ mas y^{-1} for the LMC, and $\mu_\alpha = 1.23\pm0.84$ mas y^{-1}, $\mu_\delta = -1.21 \pm 0.75$ mas y^{-1} for the SMC. We recognize in Fig. 2 that these data are nearly coincident with our model proper motions. Furthermore, as Kroupa and Bastian (1997) pointed out, the observed proper motions of the LMC and SMC are qualitatively the same in magnitude and direction, implying that these two dwarf irregulars are in a binary state and revolve around the Galaxy with similar high velocities, as leading the Magellanic Stream. If we adopt the above mean values of μ_α and μ_δ for the LMC, the last pericenter distance of the LMC is 48 kpc, and its orbital plane is approximately perpendicular to the line joining the Galactic center and the present position of the Sun, but the northern part is inclined toward us by 7°.

3.2. TIDAL DAMAGE OF THE SMC

When we examine in details the separation between the LMC and SMC in Fig. 1, we find a close approach of the SMC to the LMC 2×10^8 yr ago with impact parameter of 5 kpc or so, comparable to their sizes. Murai and Fujimoto (1980) have found that such dynamics occur in quite high probability in their model construction and concluded that the LMC and SMC collided and/or grazed recently in the near past. As mentioned already in the Section 1, the less-massive SMC is actually damaged due probably to this close encounter (Mathewson et al. 1986)

3.3. SPORADICALLY ENHANCED CLUSTER FORMATION

It is now widely known that massive star-clusters are easily generated in environments where interstellar gas clouds are in large-scale unorganized motion, such as in heavily interacting and merging gas-rich galaxies (Ashman and Zepf 1992, Holtzman et al. 1992, Whitmore et al. 1993, Schweizer et al. 1996). Fujimoto and Noguchi (1990) first pointed out that greatly disordered motion of interstellar gas produces young massive clusters in the LMC, and Kumai et al. (1993) found that galaxies associated with young massive clusters generally have interstellar gas in large-scale turbulent motion with velocity amplitude more than 50 km s^{-1}, based on the study of nearby galaxies including the Magellanic Clouds (see also Fujimoto and Kumai 1991).

According to the idea that disordered motion of interstellar gas (through high-velocity collisions between gas clouds) forms massive clusters, the tidal model predicts sporadic cluster formation history of the LMC and the SMC since serious disturbance is caused in their interstellar gas at their every close encounter. For example, Fig. 1 reveals that the LMC and SMC made close encounters 2×10^8 yr and $3 \sim 4 \times 10^9$ yr ago, with the impact param-

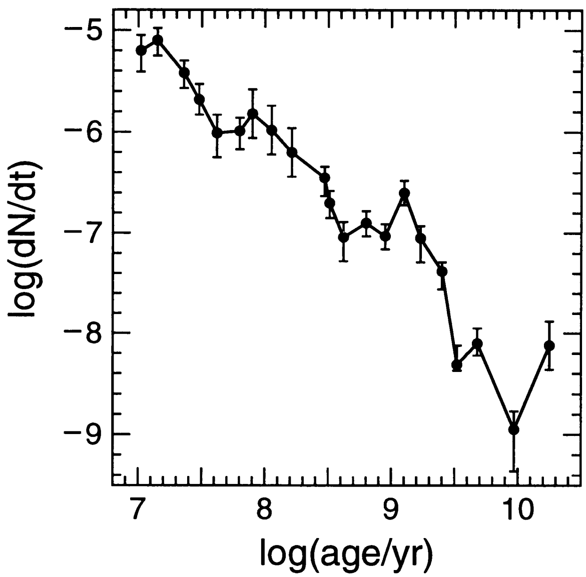

Figure 3. Age distribution of the LMC clusters, reproduced from Girardi et al. (1995). Salpeter initial mass function (with exponent = 1.35) is assumed for stars in a cluster, and correction is made for incompleteness due to magnitude bias. The error bars indicate the statistical uncertainties of cluster counts. The overall distribution is not smooth but has distinct humps at ages $\sim 10^8$ yr and $\sim 10^9$ yr, consistent with the prediction of the tidal model.

eters of $5 \sim 7$ kpc and relative velocity of more than 100 km s^{-1}. Then, the Magellanic Clouds gas were violently disturbed and we expect that numerous star clusters were formed associated with these events.

With such an expectation, we refer to a paper by Girardi et al. (1995) in which age distribution of more than six hundred LMC star cluster is obtained (for the SMC, unfortunately, there are no available data sample which contains significant number of clusters of known ages). Actually in Fig. 3, we recognize two humps in the age distribution, which approximately correspond to the above-mentioned epochs of close encounter of the Magellanic Clouds. Since the number of data clusters in Girardi et al. (1995) are large enough, this characteristic feature can be regarded as statistically significant, and this coincidence lends a strong support to the reality of the tidal model; the binary orbit chosen as in Fig. 1 where the LMC and SMC have revolved together around the Galaxy for the past, at least, $3 \sim 4$ Gyr, are likely the case.

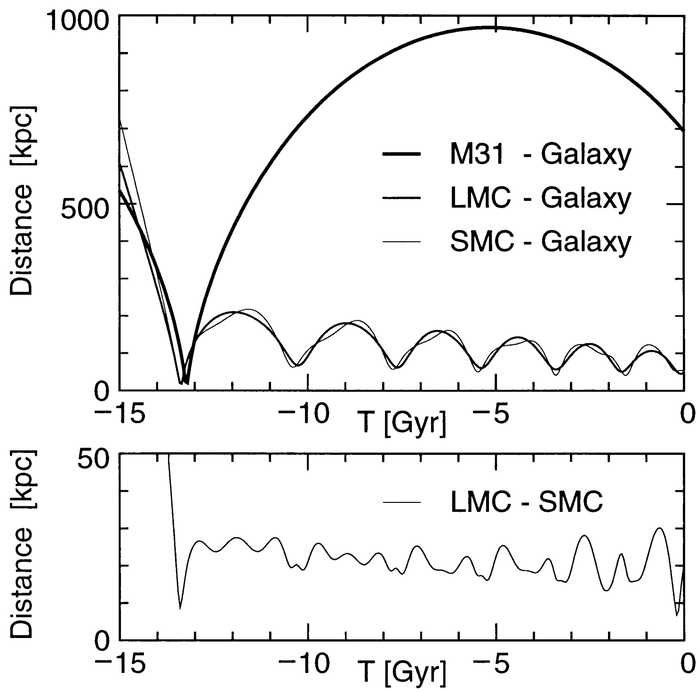

Figure 4. Time variation of the Galaxy-M31 distance and the Galaxy-Magellanic Clouds separation. The LMC-SMC separation is given in the lower diagram.

4. The Andromeda Galaxy and The Triple System of the Galaxy, LMC and SMC

When we explore the origin of the LMC and SMC, and their early dynamical relations to the Galaxy, it is inevitable to ask the gravitational influence from the Andromeda galaxy (M31) which must have been very close to the Galaxy in the expanding early universe. In a similar way to the timing arguments made by Kahn and Woltjer (1960), we trace back in time the motions of the M31 and the Galaxy, and, in this Section, the LMC and SMC as well.

M31 approaches the center of the Galaxy with a velocity of 117 km s^{-1} at present from the direction l = 121°, b = −22° (Tully 1988). We assume the sum of the masses of the Galaxy and M31 to be $4{\times}10^{12}M_{\odot}$ with the flat rotation curves respectively of 220 km s^{-1} and 250 km s^{-1}, both truncated at 150 kpc from the center. The upper diagram of Fig. 4 shows the evolutions of the distances between M31 and the Galaxy, and that between the Galaxy and the LMC-SMC binary. The lower diagram shows the LMC-SMC separation. We find that the binary state of the LMC and

SMC are stable, and disrupted only when M31 and the Galaxy overlapped completely ~13 Gyr ago. When they are closely located by about 300 kpc apart or when their halo outer fringes touch each other, the binary structure of the LMC and SMC seem to be unaffected by the M31's gravity.

We have also traced back in time the motion of the four bodies (M31, the Galaxy, LMC and SMC) in some other cases that the unknown transverse motion of M31 is assumed. The orbits of the Galaxy and M31 are not radial but elliptical, avoiding their complete overlapping in early phase. It is obvious that M31's tidal force on the Galaxy is reduced compared with the previous case and therefore the binary structure of the LMC and SMC is more stable.

The LMC and SMC seem thus to have been formed together attracting each other, and bound gravitationally to the Galaxy, suggesting it unlikely that the Magellanic Clouds migrate via the M31 region initially and then to the Galaxy (Shuter 1992).

5. Conclusions

A tidal model for the Magellanic Stream is reexamined by postulating that the LMC and SMC have been in a binary state for the Hubble time and the high negative radial velocity of the Magellanic Stream is due to the strong gravitational attraction of the massive halo of the Galaxy.

All the data that we have discussed, the proper motions of the LMC and SMC, and the sporadic enhancement in formation history of the LMC clusters, are not only consistent with the tidal model but also strongly support the dynamics of the LMC and SMC in binary structure. These phenomena are rather difficult to understand, if we do not take into account the occasional close encounters between the LMC and SMC rotating around each other with time-variable radius.

The introduction of M31 to our tidal model offers a new key to explore the dynamical origin of satellite galaxies. Although more data are necessary, we could say primarily that the satellite dwarf irregulars, at least the LMC and SMC, were formed not isolated but closely related to their nearest-neighboring massive galaxies.

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