A POSSIBLE COMMON HALO OF THE MAGELLANIC CLOUDS

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Received 2008 June 17; accepted 2008 July 10; published 2008 August 28

ABSTRACT

Recent observational and theoretical studies on the three-dimensional (3D) space motions of the Large and Small Magellanic Clouds (LMC and SMC, respectively) have strongly suggested that the latest proper-motion measurements of the Magellanic Clouds (MCs) are consistent with orbital evolution models in which the MCs have arrived in the Galaxy quite recently for the first time. The suggested orbital models appear to be seriously inconsistent with the tidal interaction models in which the Magellanic Stream (MS) can be formed as a result of the mutual tidal interaction between the MCs and the Galaxy for the last ~2 Gyr. Based on orbital models of the MCs, we propose that if the MCs have a common diffuse dark halo with a mass larger than \( \sim 2 \times 10^{10} M_\odot \), the MCs can not only have the present 3D velocities consistent with the latest proper-motion measurements but also interact strongly with each other and with the Galaxy for the last 2 Gyr. These results imply that if the observed proper motions of the MCs are true ones of the centers of mass for the MCs, the common halo of the MCs would need to be considered in constructing self-consistent MS formation models. We discuss whether the origin of the possible common halo can be closely associated either with the past binary formation or with the MCs having been in a small group.

Subject headings: galaxies: dwarf — galaxies: evolution — galaxies: halos — galaxies: irregular — Magellanic Clouds

1. INTRODUCTION

Recent proper-motion measurements of the MCs by the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST) have reported that the LMC and the SMC have significantly high Galactic tangential velocities \((367 \pm 18\) and \(301 \pm 52\) km s\(^{-1}\), respectively) and thus suggested that the MCs could be unbound from each other (Kallivayalil et al. 2006, hereafter K06). Piatek et al. (2008) have independently analyzed the same data sets as those used by K06 and confirmed the proper motions of the MCs derived from K06. Besla et al. (2007) extensively investigated the long-term orbital evolution of the MCs by using the results of K06 and thereby suggested that the MCs have recently arrived in the Galaxy for the first time (“the first passage scenario”).

These observational and theoretical results on the 3D space motions of the MCs appears to be seriously inconsistent with the tidal interaction models in which the MS can be formed as a result of the strong tidal interaction between the MCs and the Galaxy (e.g., Gardner & Noguchi 1996, hereafter GN96): the MCs are required not only to keep their binary status but also to interact strongly with the Galaxy for at least the last ~2 Gyr in the models. Recently Bekki & Chiba (2008) have shown that the tidal interaction models consistent with the results by K06 cannot reproduce well the observed location of the MS on the sky, although they did not investigate all possible orbits consistent with K06. Given that the tidal interaction models of the MS formation can explain not only the fundamental properties of the MS but also the presence of the leading arm features (GN96), it is worth while to discuss whether the tidal interaction models consistent with K06 can be constructed by considering some new physical processes that have not been so far included in the previous models of the MC evolution.

The purpose of this Letter is to propose that if the MCs have a common diffuse dark halo, the halo can play an important role in the long-term orbital evolution of the MCs. Based on orbital models of the MCs with and without common halos, we investigate whether the MCs can keep their binary status at least for the last 2 Gyr for their present 3D velocities consistent with K06. We demonstrate that some models with common halos can keep the binary status of the MCs and thus show strong tidal interaction between the LMC and the SMC and also between MCs and the Galaxy for the last 2 Gyr. This work is inspired by recent numerical simulations which have clearly shown the concurrent accretion of multiple satellite systems onto galaxy-scale halos in a hierarchical galaxy formation scenario (e.g., Sales et al. 2007; Li & Helmi 2008; Ludlow et al. 2008; D’Onghia & Lake 2008).

2. THE MODEL

2.1. The Common-Halo Scenario

We investigate orbital evolution of the MCs with respect to the Galaxy within the last ~2.7 Gyr for a given set of initial parameters (e.g., velocities and masses of the MCs) by using a backward integration scheme (GN96). Since the present orbital model for the MCs is almost the same as those adopted in previous studies (GN96; Bekki & Chiba 2005), we briefly describe the model in the present study. A key difference between the present and the previous models is that the orbits of the MCs are influenced by the hypothesized common halo that is sinking into the inner region of the Galaxy via dynamical friction in the present study. We adopt the present velocities of the MCs by K06 for all models so that we can discuss whether we can construct orbital evolution models in which (1) the present velocities are consistent with K06 and (2) the MCs can keep their binary status for the last 2 Gyr.

The gravitational potential of the Galaxy is assumed to have the logarithmic potential (i.e., the isothermal density distribution) with the constant rotational velocity of 220 km s\(^{-1}\). The LMC is assumed to have the Plummer potential,

\[
\Phi_L(r_L) = -M_L(r_L^2 + a_L^2)^{0.5},
\]

where \( M_L, r_L, \) and \( a_L \) are the total mass of the LMC, the distance from the LMC, and the effective radius, respectively. The SMC
is also assumed to have the Plummer potential with the mass of $M_{\odot}$ and the effective radius of $a_{\odot}$. We adopt the same values of $a_{\odot} (=3 \text{ kpc})$ and $a_{S} (=2 \text{ kpc})$ as previous numerical studies (e.g., GN96). Although we investigated the models with $10^{10} M_{\odot} \leq M_{b} \leq 2 \times 10^{10} M_{\odot}$ and with $3 \times 10^{9} M_{\odot} \leq M_{b} \leq 6 \times 10^{9} M_{\odot}$, we mainly show the results of the models with $M_{b} = 2 \times 10^{10} M_{\odot}$ and $M_{b} = 3 \times 10^{9} M_{\odot}$, which were extensively discussed in previous models (GN96; Bekki & Chiba 2005).

The common halo is assumed to have a mass of $M_{b}$ and the Plummer potential with the effective radius of $a_{b}$. This mass of the halo does not include the masses of individual halos in the MCs. We consider the dynamical friction due to the presence of the Galactic dark matter halo for the common halo and adopt the following expression (Binney & Tremaine 1987):

$$F_{\text{fric},G} = -0.428 \ln \Lambda_{G} \frac{G M_{b}^2}{r^2},$$

where $r$ is the distance of the common halo from the center of the Galaxy and $M = M_{b}$ for the halo. We adopt the reasonable value of 3.0 for the Coulomb logarithm $\Lambda_{G}$ (GN96). Although we investigated models with different initial 3D velocities of the common halo, we only show the results of the “successful models” in which the common halo can play a role in keeping the binary status of the MCs for the last 2 Gyr. The initial positions $(x, y, z)$ and velocities $(v_{x}, v_{y}, v_{z})$ with respect to the Galactic center for the MCs and the common halo are summarized in the Table 1.

The present velocities of the common halo of the MCs adopted in the successful models correspond to those for the center of mass of the LMC and the SMC used in GN96; the total velocity $|v|$ of the common halo is 291 km s$^{-1}$, which is significantly smaller than $|v| = 378$ km s$^{-1}$ derived by K06 for the LMC. We choose these values so that we can show how the common halo controls the orbital evolution of the MCs, if the common halo has a significantly smaller $|v|$ than the LMC. For convenience, the MCs with their mutual distance $(R_{Ls})$ less than 50 kpc for the last 2 Gyr are defined as a binary (thus the models are regarded as successful). We confirm that in the 5000 models with $-87 \leq v_{z} \leq 40$ (km s$^{-1}$), $-268 \leq v_{x} \leq -185$ (km s$^{-1}$), and $149 \leq v_{y} \leq 252$ (km s$^{-1}$) for the common halos with $M_{b} \leq 8 \times 10^{10}$ $M_{\odot}$, the number fraction of the successful models is 0.43. For comparison, we also investigate models without common halos in which $M_{b}$ is set to be 0.0.

In order to mimic the orbital evolution of the MCs in the first passage scenario (Besla et al. 2007), we investigate “the truncated halo models” in which the density of the isothermal halo of the Galaxy become zero beyond the truncation radius at which the total mass becomes $10^{12}$ $M_{\odot}$ consistent with the observed total mass of the Galaxy (Wilkinson & Evans 1999). For this truncated halo model, the LMC can arrive in the Galaxy quite recently ($\sim 0.1$ Gyr ago) for the first time. We try to understand how the common halo can change the orbits of the MCs by investigating truncated halo models with and without common halos. In the present models, the orbital evolution of the MCs depends much more strongly on $M_{b}$ than on $a_{b}$ for models with and without truncation of the Galactic halo. We thus mainly show the results of models with $a_{b} = 10$ kpc and different $M_{b}$. The time $T = 0$ and $T = -2.7$ Gyr correspond to the present and the start (i.e., past) of orbital calculation, respectively.

### 2.2. Test-Particle Simulations

The main purpose of this Letter is to demonstrate that the MCs can not only keep their binary status but also interact strongly with the Galaxy for the last $\sim 2$ Gyr owing to the presence of the common halo. We however consider that it is also important to show that the formation of the MS is possible for some orbital models by using idealized test-particle simulations in which self-gravity of particles is not included. We therefore investigate the last 2.7 Gyr evolution of an exponential disk of the SMC that has the scale length of 2.5 kpc and is composed of 50,000 particles: the MS is here considered to be formed from the SMC as demonstrated by GN96.

For a given set of initial positions and velocities of the MC system at $T = -2.7$ Gyr derived from the backward integration scheme described in § 2.1, we integrate the equation of motion forward between $T = -2.7$ and $T = 0$ (i.e., the present) for the MC system so that we can investigate dynamical evolution of the SMC disk. We here illustrate the results of a simulation based on the orbital model with $M_{b} = 3 \times 10^{9}$ $M_{\odot}$, $M_{b} = 10^{10}$ $M_{\odot}$, $M_{b} = 8 \times 10^{9}$ $M_{\odot}$, and $a_{b} = 15$ kpc, because this model shows the formation of the MS. It should be stressed here that this model is used just for an illustrative purpose: fully self-consistent numerical simulations of the MS formation under the common-halo scenario will be done in our future studies.

### 3. RESULTS

Figure 1 shows that the MCs in the model with the common halo can not only keep their binary status (i.e., $R_{Ls} < 50$ kpc) for more than 2 Gyr but also have orbital periods of $\sim 1.5$ Gyr. The model without the common halo, on the other hand, shows that (1) the MCs can start their tidal interaction only quite recently ($T = -0.2$ Gyr) and (2) they are orbiting the Galaxy independently from each other for $T < -0.6$ Gyr. These results clearly demonstrate that the common halo can play a role in keeping the binary status of the MCs through its gravitational influence. The derived results of the small $R_{Ls}$ at $T = -1.6$ and $-0.2$ Gyr in the model with the common halo are strikingly similar to those of the successful MS model by GN96, which implies that the common halo may well also play a key role in the formation of the MS and the Magellanic Bridge.

Figure 2 shows that the models with $M_{b}$ equal to or larger than $4.0 \times 10^{10} M_{\odot}$ can keep the binary status of the MCs owing to the presence of the common halos. The models with $2.0 \times 10^{10} M_{\odot}$ and a smaller $a_{b}$ of 5 kpc can also keep the binary status,
although models with \( M_{ch} = 10^{10} M_\odot \) cannot keep the binary status independent of \( a_{ch} \). These results suggest that the common halo of the MCs needs to be at least as massive as \( 2.0 \times 10^{10} M_\odot \) in order for the MCs to keep their binary status for the last 2 Gyr. As shown in Figure 2, the detail of the time evolution of the binary orbit \( (R_{ch}) \) is quite different between the two models with \( M_{ch} \geq 4.0 \times 10^{10} M_\odot \); formation processes of the MS, which depend on the evolution of \( R_{ch} \), can be controlled by \( M_{ch} \).

Figure 3 shows that the truncated halo model with the common halo of the MCs can keep the binary status, although the orbital period becomes significantly longer (~2.5 Gyr) both for the LMC and for the SMC. The truncated halo model without the common halo of the MCs shows that the LMC can arrive in the Galaxy only quite recently \((T = -0.1 \text{ Gyr})\) for the first time, which is consistent with the result by Besla et al. (2007). The SMC can interact strongly with the LMC at \( T = -0.2 \text{ Gyr} \) for the first time, which is essentially the same as the result obtained in the model without the common halo shown in Figure 1. These results shown in Figures 1 and 3 thus suggest that the MCs can interact with each other and with the Galaxy for the last more than 2 Gyr owing to the presence of the common halo, even if they have the high present 3D velocities.

Figure 4 shows that tidal streams from the SMCs can be formed as a result of strong interaction between the MCs and the Galaxy for the last 2.7 Gyr. The locations of the streams are similar to the observed MS (e.g., Putman et al. 1998, hereafter P98) so that the stream may well be observationally identified as the MS. It should be however stressed that (1) the distribution of the stripped particles in this model appears to be too dispersed in comparison with the successful MS model by GN96 and (2) leading-arm features observed by P98 and shown in GN96 cannot be so clearly seen in this model. Therefore, this model should be regarded not as being a successful MS model but as suggesting a possibility that successful MS models may well be constructed by including the common halo in the models for reasonable values of \( M_{ch} \) and \( a_{ch} \). It is our future work to discuss whether the observed fundamental properties of the MS (e.g., P98) can be explained by the MS models with the MCs having common halos based on fully self-consistent \( N \)-body simulations of the MS formation.

4. DISCUSSION AND CONCLUSIONS

The present study has first shown that if the MCs have a common halo, they can not only have the present 3D velocities consistent with K06 but also keep their binary status within the last more than 2 Gyr in some models. It should however be stressed that the common diffuse halo needs to have (1) a present velocity \(|\mathbf{v}|\) significantly smaller than that of the LMC and (2) a mass larger than \( \sim 2 \times 10^{10} \) in order for the MCs to keep their binary status for the last ~2 Gyr. These two requirements would be very hard to be confirmed directly by observations: differences in velocities between the center of the common halo and those of the MCs and the mass of the halo can be inferred from numerical simulations on the binary halo.
formation of the MCs. Then, how could they have formed a common halo in the histories of the MCs?

We here suggest the following two scenarios for the common-halo formation. The first is that the MCs might have dynamically coupled recently (<4 Gyr) to form a common halo: dynamical relaxation processes of the two preexisting halos of the MCs during binary galaxy formation can be responsible for the common-halo formation. The orbital evolution models including dynamical friction between the MCs by Bekki & Chiba (2005) showed that the MCs could become dynamically coupled for the first time about 3–4 Gyr ago. Recent cosmological N-body simulations in the common-halo scenario. For the binary state of the MCs at the epoch of their binary formation: their original masses are significantly larger than the present ones.

The second scenario is that a small group of galaxies including the MCs in its central region fell onto the outer region of the Galaxy and then lost most of the halo and the group member galaxies via tidal stripping by the Galaxy: the MC system with the common halo is the remnant of a destroyed group. Li & Helmi (2008) have investigated merging histories of subhalos in a Milky Way–like halo using high-resolution simulations based on a ΛCDM model and thereby demonstrated that about one-third of the subhalos have been accreted in groups (see also Sales et al. 2007; Ludlow et al. 2008). The demonstrated higher incidence of the group infall appears to suggest that the MCs can originate from a group thus that the second scenario is also viable. It is currently unclear which of the two scenarios are more consistent with other observations.

If the MCs really have a common halo, then the common halo would have the following possible dynamical effects on the Galaxy and the LMC. First, the MC system embedded in the common halo, which is more massive than the LMC, can more strongly influence the outer part of the Galaxy than the LMC alone is demonstrated to be able to do (e.g., Tsuchiya 2002) so that the observed HI warp of the Galaxy (e.g., Diplas & Savage 1991) can be more naturally explained in terms of the common-halo scenario. Second, the common halo can weakly influence the disk of the LMC so that the combined tidal effect of the Galaxy, the SMC, and the common halo could form an off-center bar that is more pronounced than the simulated one in the last LMC-SMC interaction about 0.2 Gyr ago (Bekki & Chiba 2007). Third, the common halo enables the LMC and the SMC to have their stellar halos extended much beyond their optical radii.

The present study suggests that it would be difficult to observationally determine the 3D velocities of the MC system solely from proper-motion measurements of the MCs in the common-halo scenario. Furthermore, it would be even more difficult for theoretical and numerical works to predict precisely the long-term orbital evolution of the MCs with a common halo owing to two (or more) additional parameters for physical properties of the halo. If the observed proper motions of the MCs (K06) are really true ones of the centers of mass for the MCs can occur at z < 0.33 corresponding to less than 3.7 Gyr ago for a canonical set of cosmological parameters (Ishiyama et al. 2008). These results imply that the common-halo formation of the MCs might have happened recently (4 Gyr ago). We suggest that the required larger mass of the common halo (i.e., $M_{ch} > 2 \times 10^{10} M_\odot$) for the binary state of the MCs in the last ~2 Gyr can come from the stripped dark matter halos of the MCs at the epoch of their binary formation: their original masses are significantly larger than the present ones.

I am grateful to the anonymous referee for valuable comments, which contributed to improving the present Letter. I acknowledge the financial support of the Australian Research Council throughout the course of this work.

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Fig. 4.—Present distribution of particles of the SMC projected onto Galactic coordinates ($l$, $b$) in the test-particle simulation based on the orbital model with $M_p = 1.0 \times 10^{10} M_\odot$, $M_b = 3.0 \times 10^9 M_\odot$, $M_l = 8.0 \times 10^9 M_\odot$, and $a_\odot = 15$ kpc. The particles stripped from the SMC as a result of the LMC-SMC-Galaxy interaction can form streams and the locations of the streams appear to be similar to the observed location of the MS (e.g., P98). This result implies the possibility that successful MS models can be constructed by our future self-consistent N-body simulations in the common-halo scenario.