When was the Large Magellanic Cloud accreted onto the Galaxy?

Kenji Bekki

ICRAR M468 The University of Western Australia 35 Stirling Hwy, Crawley Western Australia, 6009

ABSTRACT

Using fully self-consistent N-body models for the dynamical evolution of the Large Magellanic Cloud (LMC) in the Galaxy, we show that if the LMC initially has an extended old stellar halo before its commencement of tidal interaction with the Galaxy, physical properties of the stars stripped from the LMC stellar halo can have fossil information as to when and where the LMC was accreted onto the Galaxy for the first time. If the epoch of the first LMC accretion onto the Galaxy from outside its virial radius is more than \( \sim 4 \) Gyr ago (i.e., at least two pericenter passages), the stars stripped from the stellar halo of the LMC can form an irregular polar ring or a thick disk with a size of \( \sim 100 \) kpc and rotational kinematics. On the other hand, if the LMC was first accreted onto the Galaxy quite recently (\( \sim 2 \) Gyr ago), the stripped stars form shorter leading and trailing stellar stream at \( R = 50-120 \) kpc. Also distributions of the stripped stars in phase space between the two cases can be significantly different. The derived differences in structure and kinematics of the stripped stars therefore suggest that if we compare the observed three-dimensional (3D) distribution and kinematics of the outer Galactic stellar halo along the polar-axis, then we can give strong constraints on the past orbit of the LMC. We also discuss whether the orbital properties of the LMC in successful formation models for the Magellanic Stream (MS) can be consistent with orbital properties of the LMC-type systems in Galaxy-type halos predicted from recent high-resolution cosmological simulations in a \( \Lambda \)CDM universe. We find that the orbital properties of the LMC in the successful formation models are consistent with those predicted from the cosmological simulations. We also find that the LMC can not merge with the Galaxy within the last \( \sim 6 \) Gyr in models consistent with predictions from the \( \Lambda \)CDM simulations. Given that the successful MS formation models predict at least two pericenter passages of the LMC in the Galaxy, we conclude that the LMC was accreted onto the Galaxy more than \( \sim 4 \) Gyr ago so that interaction between the LMC, the Small Magellanic Cloud (SMC), and the Galaxy could form the MS and its Leading Arms (LAs).

Key words: Magellanic Clouds – galaxies:structure – galaxies:kinematics and dynamics – galaxies:halos – galaxies:star clusters

1 INTRODUCTION

Recent proper motion measurements of the LMC and the Small Magellanic Cloud (SMC) have suggested that the LMC is now moving around the Galaxy with a velocity \( V_{\text{LMC}} \) of \( \sim 380 \) km s\(^{-1}\) with respect to the Galaxy (e.g., Kallivayalil et al. 2006, K06; Piatek et al. 2008). The latest observational studies on the proper motions of the Clouds (Vieira et al. 2010, V10) have however derived significantly different \( V_{\text{LMC}} = 343 \pm 47.8 \) km s\(^{-1}\)), which is significantly smaller than \( V_{\text{LMC}} \) derived by the above earlier studies (see also Costa et al. 2009, C09, which derived \( V_{\text{LMC}} \sim 300 \) km s\(^{-1}\)). Using N-body models of the LMC, Bekki (2011) has recently shown that if the total number of the LMC fields used for the derivation of the center-of-mass proper motion of the LMC, then the derived center-of-mass proper motion of the LMC can significantly deviate from the true one. These observational and theoretical studies imply that the proper motion of the LMC observationally derived so far does not allow us to construct a model for the very precise 3D orbit of the LMC.

The past 3D motions of the LMC and the SMC are the...
most important parameters in the construction of the formation model for MS and LAs (Murai & Fujimoto 1980). A recent “first passage” scenario has shown that MS was formed owing to LMC-SMC interaction well before the accretion of the Clouds onto the Galaxy for the first time (Besla et al. 2010). Although this model has failed to explain the observed bifurcated structure of the MS and the elongated leading arm, it is consistent with some of the observational results of the above-mentioned HST proper motions of the Clouds. On the other hand, classical tidal models can better explain physical properties of MS and LA (e.g., Gardner & Noguchi 1996, GN96; Yoshizawa & Noguchi 2003, YN03; Connors et al. 2006, C06), their models appear to be inconsistent with the above-mentioned HST proper motion results. Given that there are significant differences in orbital evolution of the Clouds between these previous models, it is observationally important to give more stringent constraints on the 3D motions of the Clouds, in particular, the LMC which gravitationally dominates the Magellanic system.

Recently photometric and spectroscopic observations of stars in the surrounding regions of the LMC have revealed possible evidence for the presence of an extended stellar halo of the LMC (e.g., Minniti et al. 2003; Muñoz et al. 2006; Majewski et al. 2009; Saha et al. 2010). For example, Minniti et al. (2003) found that the velocity dispersion of the 43 RR Lyrae stars in the LMC region is 53 ± 10 km s⁻¹ and suggested that the LMC has a dynamically hot stellar halo. Muñoz et al. (2008) and Majewski et al. (2009) have revealed a possible presence of the LMC stars out to 22 − 23° from the LMC center (corresponding roughly 10 times the scale radius of the LMC stellar disk), which can possibly consist of the outer halo of the LMC. Subramaniam & Subramaniam (2009) found that the distribution of RR Lyrae stars in the inner region of the LMC has a disk-like distribution and suggested that the old RR Lyrae stars do not trace the extended metal-poor stellar halo of the LMC.

The possible extended stellar halo of the LMC can be much more strongly influenced by the Galaxy than the stellar disk during the LMC-Galaxy tidal interaction. Therefore the stellar halo can be stripped more efficiently by the Galaxy to become a part of the Galactic stellar halo. Thus, the outer part of the Galactic stellar halo can contain stars initially from the stellar halo of the LMC and therefore can have fossil records on the past orbital history of the LMC. However, the tidal stripping of the original metal-poor stellar halo of the LMC has not been investigated so far in previous numerical simulations. It is thus unclear what structural and kinematical properties of the stripped halo stars of the LMC have in the outer stellar halo of the Galaxy.

The purpose of this paper is thus to propose that if the LMC has an extended stellar halo before its commencement of the LMC-Galaxy tidal interaction, then the stripped halo stars in the outer Galactic halo can have fossil information as to when and where the LMC was first accreted onto the Galaxy. Using self-consistent N-body simulations of the LMC-Galaxy tidal interaction, we investigate how the tidal field of the Galaxy can influence the dynamical evolution of the stellar halo of the LMC. We show how the 3D spatial distribution and kinematics of stars stripped from the LMC stellar halo depend on the past 3D orbits of the LMC with respect to the Galaxy.

2 THE MODEL

We investigate how the LMC dynamically evolves after it is first accreted onto the Galaxy from outside the virial radius of the dark matter halo of the Galaxy. In the present model, both the LMC and the Galaxy are represented by N-body particles so that dynamical friction of the LMC against the Galactic dark matter halo can be self-consistently modeled. The present model is therefore more sophisticated than those used in recent models for the Magellanic system by Besla et al. (2010) and Diaz & Bekki (2011, DB11) which treated the Galaxy as a fixed gravitational field. Owing to

Table 1. Description of the model parameters for the representative models.

| Model | M_{dm,now} | a | r_{vir,now} | b | c | f_v | f_{v,z} | f_{v,y} | f_{v,x} | R_{h,LMC} | SMC | comments |
|-------|------------|---|------------|---|---|-----|-------|-------|-------|----------|-----|---------|
| M1    | 10^{12}    | 245 | 10     | 0.5 | 0.5 | 0.5 | 0.0   | 3     | 3       | No       | No | the standard FPS |
| M2    | 10^{12}    | 245 | 10     | 0.6 | 0.6 | 0.6 | 0.0   | 3     | 3       | No       | No | the standard SPS |
| M3    | 10^{12}    | 245 | 10     | 1.1 | 0.5 | 1.0 | 0.9   | 3     | 3       | No       | No |
| M4    | 10^{12}    | 245 | 10     | 0.6 | 0.6 | 0.6 | 0.4   | 3     | 3       | No       | No |
| M6    | 10^{12}    | 245 | 10     | 0.6 | 0.6 | 0.6 | 0.0   | 3     | 2       | No       | No | smaller size of the LMC halo |
| M7    | 10^{12}    | 245 | 10     | 0.6 | 0.6 | 0.6 | 0.0   | 3     | 3       | Yes      | R_iS = 8R_{h,LMC} |
| M8    | 10^{12}    | 245 | 10     | 0.6 | 0.6 | 0.6 | 0.0   | 3     | 3       | Yes      | R_iS = 6R_{h,LMC} |
| M9    | 2 \times 10^{12} | 9  | 0.5     | 0.0 | 0.0 | 0.0 | 3.0   | 3     | No       | more massive Galactic halo |
| M10   | 2 \times 10^{12} | 9  | 1.1     | 0.4 | 1.0 | 1.0 | 3.0   | 3     | No       | |
| M11   | 2 \times 10^{12} | 9  | 1.1     | 0.6 | 0.9 | 0.9 | 3.0   | 3     | No       | |

a The total dark matter halo mass of the Galaxy in units of M_⊙.
b The virial radius of the Galactic dark matter halo in units of kpc.
c The c parameter of the Galactic dark matter halo.
d The ratio of the velocity of the LMC (v_L) to the circular velocity (v_{cir}) at the initial position of the LMC.
e The initial tangential velocity of the LMC is given as f_{v,y}v_{cir}.
f The initial radial velocity of the LMC is given as f_{v,x}v_{cir}.
g The initial size of the stellar halo in the LMC in units of R_{h,LMC}, which is the size of the LMC stellar disk.
h Presence (“Yes”) or absence (“No”) of the SMC in the model.
i The initial distance between the LMC and the SMC is represented by R_{i,S} for the models with SMC.
the smaller mass of the SMC in comparison with the LMC mass, the SMC does not significantly influence the orbital evolution of the LMC. Also we focus exclusively on how the stellar halo initially in the LMC dynamically evolves during the LMC-Galaxy tidal interaction. Thus we do not investigate extensively the models with the SMC in the present study for clarity. However we briefly discuss whether the SMC can influence the evolution of the LMC stellar halo using two representative models with the SMC.

The LMC is modeled as a bulge-less disk galaxy embedded in a massive dark matter halo. Since the LMC is assumed to fall onto the Galaxy from outside the dark matter halo of the Galaxy, it is highly likely that the LMC initially has an extended dark matter halo (i.e., not truncated at the tidal radius of the LMC). The total mass and the virial radius of the dark matter halo of the LMC are \( M_{\text{dm,L}} \) and \( r_{\text{vir,L}} \), respectively. We adopted an NFW halo density distribution (Navarro, Frenk & White 1996) suggested from CDM simulations:

\[
\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2},
\]

where \( r \), \( r_0 \), and \( r_s \) are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. We adopted \( c = 12 \) (= \( r_{\text{vir,L}}/R_0 \)) and the mass ratio of \( M_{\text{dm,L}} \) to \( M_{\odot} \) was fixed at 16.7.

The stellar disk with the size \( R_{3D} \) and mass \( M_{\text{disk}} \) is assumed to have an exponential profile with the scale length \( (a_{\text{disk}}) \) of 1.5 kpc and the truncation radius of 7.5 kpc (= \( R_{\text{disk}} \)). In order to investigate the models which have the maximum rotation speed of \( \sim 120 \) km s\(^{-1}\) as suggested by recent observations by Piatek et al. 2008, we assume that the total mass of the LMC (\( M_{\text{L,1}} \)) is \( 9.6 \times 10^10 \) M\(_{\odot}\) and \( r_{\text{vir,L}}/R_0 = 10.0 \). The LMC has a stellar halo with the mass \( M_{\text{halo}} \) and the size \( R_{\text{halo}} \) and the radial density profile is assumed to follow the power-law one with the power-law index of \( -3.5 \) (\( \rho(r) \sim r^{-3.5} \)). We mainly investigate the models with \( M_{\text{halo}}/M_{\odot} = 0.01 \) and \( R_{\text{halo}} = 3R_{\text{disk}} \). Gas dynamics, star formation, and chemical evolution modeled in our previous models (Bekki & Chiba 2005, 2009) are not included in the present model, because we focus exclusively on the dynamical evolution of the stellar halo of the LMC.

Observational studies for 1047 edge-on disk galaxies in the Sloan Digital Sky Survey (SDSS) revealed almost ubiquitous presence of stellar halos around disk galaxies (Zibetti et al. 2004). Their Fig. 2 clearly shows that the stellar halos extend at least \( 10a_{\text{disk}} \), where \( a_{\text{disk}} \) is the scale length of a stellar disk. The Galaxy is observed to have the stellar halo which extends at least 30 kpc corresponding to \( \sim 9a_{\text{disk}} \) (\( \sim 12R_{\text{halo}} \)) for the stellar scale length of 3.5 (2.5) kpc (e.g., Chiba & Beers 2000) and has a mass that is about \( \sim 1\% \) of the Galactic stellar disk (Freeman & Bland-Hawthorn 2002). Thus the present models with \( M_{\text{halo}}/M_{\odot} = 0.01 \) and \( R_{\text{halo}} = 3R_{\text{disk}} (= 15a_{\text{disk}}) \) are quite reasonable. However we investigate models with different \( R_{\text{halo}} \) in order to make more robust conclusions of the present numerical simulations.

The Galaxy is assumed to consist of the NFW dark matter halo, exponential stellar disk, and Hernquist bulge. The dark halo has a mass \( M_{\text{dm,mw}} \), a virial radius \( r_{\text{vir,mw}} \), and a \( c \) parameter. We investigate two dark halo models in which the maximum circular velocity can be \( \sim 220 \) km s\(^{-1}\) that is observed for the Galaxy. One has \( M_{\text{dm,mw}} = 10^{12} \) M\(_{\odot}\), \( r_{\text{vir,mw}} = 245 \) kpc, and \( c = 10 \) and the other has \( M_{\text{dm,mw}} = 2 \times 10^{12} \) M\(_{\odot}\), \( r_{\text{vir,mw}} = 347 \) kpc, and \( c = 9 \). The stellar disk has a mass of \( 6 \times 10^{10} \) M\(_{\odot}\), a size of 17.5 kpc (scale-length of 3.5 kpc), and the Q-parameter of 1.5. The bulge has a mass of \( 10^{10} \) M\(_{\odot}\) and a size of 3.5 kpc (scale-length of 700 pc). Like the LMC model, the Galaxy is assumed to have no gas and no star formation. The disk plane of the Galaxy is set to be the \( x-y \) plane in the present study (i.e., the \( z \)-axis is the polar direction of the Galaxy).

The LMC is initially located at \( R_t \) from the center of the Galaxy and has a velocity \( (v_t) \) from the Galactic plane (i.e., the \( x-z \) plane). \( R_t \) is fixed at \( 1.07r_{\text{vir,mw}} \) for all models so that the LMC can be accreted from outside the virial radius of the Galaxy. Previous best models for the MS formation predicted that the orbital plane of the LMC is almost coincident with the \( y-z \) plane (e.g., YN03). We thus assume that \( \Theta_{\odot} = 90^\circ \): the spin vector of the initial orbital angular momentum of the LMC is the same as the \( x \)-axis. The initial velocity components of the LMC are given as \( (0, f_{x,y}v_t, f_{x,z}v_t) \), where \( f_{x,y} \) and \( f_{x,z} \) of the velocity correspond to initial tangential and radial velocities, respectively. The spin vector of the stellar disk of the LMC is inclined by 45 degrees with respect to the orbital plane of the LMC for all models.

By changing \( f_{x} \) (also \( f_{x,y} \) and \( f_{x,z} \)), we can determine the time (referred to as \( T_p \) from now on) when (i) the LMC-Galaxy distance can become the observed 50 kpc and (ii) the LMC is moving away from the Galaxy. We mainly investigate the dark matter model of the Galaxy with \( M_{\text{dm,mw}} = 10^{12} \) M\(_{\odot}\). If we adopt \( f_{x} = 0.5 \) for the above dark matter model, then \( T_p \) is just after the first pericenter passage: this model corresponds to the first passage scenario (referred to as “FPS” and the model M1). If we adopt \( f_{x} = 0.6 \), then \( T_p \) is just after two pericenter passages: this corresponds to the second pericenter passage scenario (“SPS” and M2).

We mainly discuss the results of these standard FPS and SPS in order to more clearly show whether stars stripped from the LMC stellar halo have fossil information of the past orbital history of the LMC: we however investigate different models and discuss the results briefly in §3.2. The parameter values for the representative 11 models investigated in the present study are shown in the Table 1.

If we adopt models with larger \( v_t \) (\( \geq 0.7 \)), then \( T_p \) can be after the third or fourth pericenter passage of the LMC. The simulated distribution of the stripped LMC halo stars in these models are essentially similar to that in the SPS. The aim of this paper is to more clearly show how the spatial distribution of the stripped halo stars depends on the past orbit of the LMC. Accordingly we focus on the differences in physical properties the stripped halo stars between the FPS and SPS in the present paper. Also it should be stressed that the present models cannot reproduce exact locations of the LMC in the Galactic coordinate (i.e., \( x, y, z \) for the LMC): we adopt the present models in order to point out the possible differences in physical properties of the stripped LMC stellar halo between the two scenarios. Fully self-consistent 3D models which can explain the present 3D locations and
velocities of the LMC and the SMC will be discussed in forthcoming papers.

We estimate the velocity of the LMC when (i) the LMC passes the pericenter around the Galaxy and (ii) the pericenter distance \( R_p \) is close to \( \sim 50 \) kpc that corresponds to the present distance of the LMC from the center of the Galaxy. We confirm that the velocity at \( R_p \) \( (V_p) \) is in good agreement with the observed one \( (300 - 380 \) km s\(^{-1}\); K06; C09; V10) for all models except the model M11 with \( R_p = 91 \) kpc (which is therefore unreasonable for the LMC). For example, \( V_p \) is 323 km s\(^{-1}\), 300 km s\(^{-1}\), 342 km s\(^{-1}\), 347 km s\(^{-1}\), and 355 km s\(^{-1}\) for models M1, M2, M3, M4, and M9, respectively. For all models, the LMC can not merge with the Galaxy within \( \sim 6 \) Gyr after the first passage of the Galactic virial radius. These results demonstrate that the present LMC model is reasonable and realistic in discussing dynamical evolution of the LMC.

Numerical computations were carried out both on the latest version of GRAPE (GRavity PipE, GRAPE-DR) – which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990) at University of Western Australia (UWA) and on the HP 390S blade machine with three GPU cards (NVIDIA Tesla M2070) with CUDA G5/G6 software package being installed for calculations of gravitational dynamics at iVEC in UWA. The total number of particles used for dark matter halo, stellar disk, and bulge of the Galaxy in a simulation are 800000, 200000, and 33400, respectively. The total number of particles used for dark matter, stellar halo, and stellar disk in the LMC are 100000, 100000, and 50000, respectively. The adopted gravitational softening length is fixed at 200 pc for all models. The time \( T \) represents the time that has elapsed since the simulation starts. The polar axis of the Galactic disk does not change during a simulation in the present study owing to the adopted LMC orbit. The LMC disk particles are not stripped owing to the adopted large initial mass of the LMC \( (M_{t,L} = 9.6 \times 10^{10} M_\odot) \).

**Figure 1.** The time evolution of the LMC-Galaxy distance in the standard FPS (solid, model M1) and SPS (dotted, M2). Filled circles represent the present LMC-Galaxy distances in these two models.

**Figure 2.** The time evolution of the distribution of the LMC stellar halo projected onto the \( y-z \) plane in the SPS. The solid line represent the past 5.6 Gyr orbit of the LMC in the SPS.

**Figure 3.** The distributions of the stripped LMC stellar halo particles projected onto the \( x-y \) plane (left) and the \( y-z \) plane (right) for the FPS (upper two) and the SPS (lower two). Only particles outside \( R = 3R_{d,L} \) (where \( R_{d,L} \) is the initial stellar disk size and 7.5 kpc) are regarded as those stripped from the initial LMC stellar halo. The thick solid line in each frame represents the initial halo size \( (R_{h,L} = 3R_{d,L}) \).
3 RESULTS

3.1 FPS versus SPS

Fig. 2 shows how the LMC stellar halo is stripped by the strong tidal field of the Galaxy to form a disk-like or ring-like stellar structure with a long diffuse stellar stream in the outer Galactic halo (\( R < 200 \) kpc) in the standard SPS (M2). After the first pericenter passage (\( T \sim 3 \) Gyr), the outer part of the LMC stellar halo is partially stripped to form diffuse leaning and trailing stellar stream (\( T = 3.8 \) Gyr). These stripped stars can be then trapped by the Galactic potential to form a smaller ring-like structure with the radius of \( \sim 50 \) kpc (\( T = 4.5 \) Gyr), while the LMC stellar halo continues to be stripped. Finally an irregular ring-like stellar structure connected to the LMC and the outer diffuse stellar stream can be formed after the second pericenter passage (\( T = 5.6 \) Gyr). Owing to the initially extended structure of the LMC stellar halo, the stripped stars do not form narrow tidal streams.

Fig. 3 shows how the 3D distributions of the stripped LMC stellar halo particles depend on the past orbits of the LMC. Here stripped stars are those outside the original stellar halo size (\( R_{b,L,M} = 3R_{d,L} = 22.5 \) kpc) at \( T = T_p \). Clearly, a thick disk structure along the polar axis (i.e., z-axis) can be seen for \( |z| < 50 \) kpc in the SPS whereas such a disky structure cannot be seen in the FPS. Furthermore, diffuse leading and trailing stellar streams can be seen in the y-z projection for the FPS whereas a closed irregular ring can be seen in the SPS. Since it is almost impossible for any models based on the FPS to show a closed ring just after the last pericenter passage, the derived clear differences in distributions of stripped LMC halo stars projected onto the y-z plane between the two scenarios can be used for distinguishing the two scenarios.

Fig. 4 demonstrates that the tidally stripped LMC stellar halo can show a characteristic distribution in the \( L_z - L_{xy} \) plane, where \( L_z, L_x, \) and \( L_y \) are the angular momentum component in the \( z, (x, y) \) direction and \( (L_z^2 + L_y^2)^{1/2} \), respectively. Distributions of halo stars on this \( L_z - L_{xy} \) plane have been discussed in the context of the formation of the Galactic stellar halo due to accretion of dwarf galaxies (e.g., Chiba & Beers 2000). It should be stressed that only the stripped stars (\( R > R_{b,L,M} \)) shown in Fig. 3 (i.e., not all stars) are plotted in this Fig. 4. Owing to the diffuse and wide stellar distributions in the tidal streams and the polar ring, the stellar distribution in phase space does not show any strong concentration in the FPS and SPS. However, there is a clear difference between the two in the sense that the FPS shows a much larger number fraction of stars with \( L_{xy} \) larger than \( 2 \times 10^4 \) kpc km s\(^{-1}\) in comparison with the SPS. The presence of stars with larger \( L_{xy} \) in the FPS is due to the fact that the LMC is moving faster in the FPS. Thus this appreciable difference in phase space can be used to distinguish the two scenarios.

The present study predicts that the stripped dark matter halo of the LMC can form a polar thick disk with a central hole (“dark polar ring”) in the SPS. A “ripple” (of “shell”) structure can be clearly seen at \(-100 \) kpc \(< z < -40 \) kpc and \(-100 \) kpc \(< z < 100 \) kpc in the x-z plane. If dark matter particles outside \( R > R_{b,L,M} \) are regarded as those consisting of the dark polar ring, then the total mass of the
ring is $5.5 \times 10^{10} M_\odot$ (i.e., about 61% of the original dark halo mass) which corresponds to 5.5% of the total mass of the Galactic dark matter in the present model. Although this dark polar ring would be currently impossible to be detected by observational studies, it could dynamically influence orbital evolution of dwarf satellite galaxies around the Galaxy, in particular, those in polar orbits (e.g., Carina dwarf galaxy).

3.2 Dependence on model parameters

3.2.1 Orbit

Fig. 6 shows the orbital evolution of the LMC in the four representative models with different $f_v$ and $M_{\text{in}, \text{nw}}$. Clearly, the LMC can not merge within the last 6.8 Gyr in these four models, which demonstrates a possibility that the LMC was accreted onto the Galaxy long time ago but has not merged with the Galaxy yet. Although the LMC initially has a larger total mass ($M_{\text{t}, \text{L}} = 9.6 \times 10^{10} M_\odot$), it can lose a significant fraction of the mass owing to tidal stripping by the Galaxy. This mass loss can make the time scale of dynamical friction significantly longer for the LMC. As a result of this, the LMC can not so quickly merge with the Galaxy as it otherwise could if it keeps the large initial mass. The LMC in the model M4 with $f_v = 1.1$ can finally show $R_p \sim 50$ kpc corresponding to the present distance of the LMC from the center of the Galaxy. The LMC can not merge with the Galaxy within $\sim 10$ Gyr in this model.

Given that the adopted $f_v = 1.1$ in the model M4 is predicted to be typical in recent ΛCDM cosmological simulations (e.g., Wetzel 2011), this means that the LMC orbit needs not be unusual one in a ΛCDM universe. Only the model with lower $f_v$ for $M_{\text{in}, \text{nw}, \text{dm}} = 2 \times 10^{12} M_\odot$ can show $R_p \sim 50$ kpc within the last 6 Gyr. Such a lower $f_v$ is not typical in the ΛCDM simulations, which implies that the LMC could be an unusual object if the Galaxy is as massive as $M_{\text{in}, \text{nw}, \text{dm}} = 2 \times 10^{12} M_\odot$.

Fig. 7 shows the distributions of the stripped LMC stellar halo particles around the Galaxy projected onto the $y-z$ plane for six representative models. Since the distributions of the stars projected onto the $x-z$ plane are less significantly different between FPS and SPS, we here focus on the distributions projected onto the $y-z$ plane. Clearly, the model M3, which is regarded as FPS, does not show a ring-like distribution for the stripped LMC stellar halo stars. This means that irrespective of orbital models, FPS can not show a ring-like distribution of the stripped stars whereas the model M10 (FPS) does not. This clear difference between FPS and SPS in models with larger masses of the Galaxy ($M_{\text{in}, \text{nw}, \text{dm}} = 2 \times 10^{12} M_\odot$) strongly suggests that the stripped LMC stellar halo stars can be used for distinguishing FPS and SPS.

3.2.2 $R_{\text{h}, \text{L}}$

The model M6 has a smaller size of the LMC stellar halo ($2 R_{\text{h}, \text{L}} = 15$ kpc) so that the halo can not be so strongly influenced by the tidal field of the Galaxy in comparison with the model M2. Fig. 7 shows that there is no significant difference in the distribution of the stripped LMC stellar halo stars between M2 and M6 (i.e., the two models with the same orbit of the LMC). This result combined with that derived for the model M2 suggests that as long as the LMC has an extended stellar halo ($R_{\text{h}, \text{L}} \geq 2 R_{\text{d}, \text{L}}$), the stripped halo stars can have fossil record of the past orbit of the LMC. If the LMC stellar halo has $R_{\text{h}, \text{L}} \leq R_{\text{d}, \text{L}}$, then the stripping of the halo stars become less efficient. However, such models with $R_{\text{h}, \text{L}} \leq R_{\text{d}, \text{L}}$ are inconsistent with observations of galactic stellar halos by Zibetti et al. (2004).

3.2.3 SMC

In order to discuss how the LMC-SMC interaction can influence the final distribution of the stripped LMC halo stars in the outer halo of the Galaxy, we construct a N-body model for the SMC. The SMC has an initial total mass of $4.8 \times 10^{6} M_\odot$ and is modeled as a bulge-less disk galaxy embedded in a massive dark matter halo. The structural and kinematical properties of stellar disks and dark matter halos are assumed to be self-similar between the LMC and the
SMC. The SMC has an exponential stellar disk with the mass of $2.8 \times 10^8 M_\odot$ and the size of 2.0 kpc. The initial distance of the SMC from the center of the LMC is a free parameter and denoted as $R_{i,S}$. The initial velocity of the SMC with respect to that of the LMC is given by $v_{circ,L}$, where $v_{circ,L}$ is the circular velocity of the LMC at $R_{i,L}$. The orbital evolution of the SMC depends not only on the orbital parameters of the LMC but also on $R_{i,S}$. We here describe the results for the models M7 ($R_{i,S} = 8 R_{i,L}$), because the LMC and the SMC do not merge so quickly with each other in this model. Although we have investigated a number of models with different $R_{i,S}$, the models with smaller $R_{i,S}$ like M8 with $R_{i,S} = 6 R_{i,L}$ show a short time scale of LMC-SMC merging (within $\sim 4$ Gyr). They are not so useful for discussing physical properties of the present LMC-SMC system which has not completely merged yet.

Fig. 8 shows the orbital evolution of the SMC with respect to the Galaxy and the LMC in the model M7. This is the first orbital model of the SMC based on a fully self-consistent N-body simulation in which all of the three galaxies are represented by N-body particles. Dynamical friction between the Galaxy, the LMC, and the SMC is self-consistently included so that the orbit of the SMC can be more precisely predicted in this model. Clearly, the Clouds can keep their binary status for the last 5 Gyr, if they were initially strongly bound. Owing to dynamical friction between the LMC and the SMC, the Clouds appear to be almost merged at $T \sim 6$ Gyr. Fig. 7 shows that the stripped LMC halo stars in this model has a ring-like distribution along the polar axis of the Galaxy and the distribution is quite similar to that in the model M2. Thus the SMC can not change significantly the spatial distribution of the stripped LMC halo stars in the outer Galactic halo owing to its low mass.

4 DISCUSSION

4.1 Relation to cosmological N-body simulations

Recent theoretical studies based on high-resolution collisionless N-body simulations have investigated orbital properties (e.g., eccentricities and pericenter distances) of satellite galaxies around luminous ones like the Galaxy (e.g., Benson 2005; Lux et al. 2010; Boylan-Kolchin et al. 2011, B11; Wetzel 2011). One of their results relevant to the present study is distributions of normalized total velocities ($V_{tot}$ in Fig.2 by Wetzel 2011) which correspond to $f_\ell$ in the present study. The predicted $f_\ell$ distribution in Wetzel (2011) has a peak value of 1.15 and shows only a small fraction of satellites with $f_\ell \leqslant 0.6$. This means that the orbits used in models with low $f_\ell \leqslant 0.6$ are less common in the $\Lambda$CDM model: the present models with $f_\ell \sim 1$ would be more appropriate for describing the orbit of the LMC. Given that both low and high $f_\ell$ models show clear differences in 3D distributions of stripped LMC halo stars between FPS and SPS, the above less consistent models do not become a problem in the present study.

The LMC in the models with $f_\ell \sim 1$ and $R_i \sim 260$ kpc can finally have $R_p \sim 50$ kpc (at $T \sim 6$ Gyr) owing to the orbital decay of the LMC caused by dynamical friction against the Galaxy. Given that $f_\ell \sim 1$ is typical in recent cosmological simulations (Wetzel 2011), this result means that if the LMC has a typical orbit for satellites in the Galaxy, then it should have been accreted onto the Galaxy more than $\sim 6$ Gyr ago. This also suggests that successful formation models of MS and LAs will be able to be constructed by using results of cosmological N-body simulations on orbital properties of LMC-type satellites in Galaxy-type halos. The LMC even in the models with lower $f_\ell$ ($\sim 0.5$) can not merge with the Galaxy within the last 6 Gyr. This demonstrates a possibility that the LMC was accreted onto the Galaxy more than $\sim 6$ Gyr ago and has been interacting with the Galaxy since then.

It is well known that the observed locations, kinematics, fine-structures (e.g., bifurcation) in MS and LAs can give very strong constraints on the orbital evolution of the LMC and the SMC for a given mass model of the Galaxy (e.g., GN96; YN03; C06; DB11). Previous models that reproduced very well the observed bifurcated MS and long LA predict that the LMC and SMC have passed their pericenter about the Galaxy at least twice for the last 2–3 Gyr (C06; DB11). Previous dynamical models for the formation of MS based on FPS have reproduced neither the observed location of MS (Fig. 21 in Bekki & Chiba 2009) nor the bifurcated structure of MS (Besla et al. 2010). These models also failed to reproduce the observed properties of the LAs so far: their models can not be regarded as successful MS formation models. These results imply that the LMC arrived within the virial radius of the Galaxy (for the first time) more than 4–5 Gyr ago. The question is whether this earlier arrival of the LMC is consistent with the latest results of dissipationless cosmological N-body simulations on accretion processes of LMC-type satellite galaxies onto Galaxy-type halos.

Using the results of the Millennium II simulation, B11 investigated the epochs ($t_{ec}$) of first accretion onto Galaxy-mass galaxies and orbital properties for the “LMC analogs” that have masses ranging from $8 \times 10^8 M_\odot$ to $3.2 \times 10^{11} M_\odot$ at the accretion epochs. They showed that (i) only $\sim 30\%$ of LMC analogs have $t_{ec} < 2$ Gyr (their Fig.1), (ii) LMC analogs with $t_{ec} > 4$ Gyr have lower angular momentum ($\tilde{j}$) in GN96 by adopting the same method as used in B11, (iii) LMC analogs with $t_{ec} > 4$ Gyr are more likely to be strongly bound (Figs. 3 and 4), and (iv) about 50% of LMC analogs with $t_{ec} > 4$ Gyr have orbital eccentricities ($e$) smaller than 0.6 (Fig. 5). These results are consistent with the previous successful MS models (e.g., GN96; YN03; and DB11) that predict bound orbit of the LMC with $e \sim 0.4$ and at least two pericenter passages of the LMC in the Galaxy (i.e., $t_{ec} > 4$ Gyr). If we estimate the specific angular momentum of the LMC ($\tilde{j}$) in GN96 by adopting the same method as used in B11, then $\tilde{j} = 0.26$ for $v_{circ,mw} = 245$ km/s. The results in Fig. 2 in B11 show that about 60% of early-accreted LMC analogs with $t_{ec} > 4$ Gyr have $\tilde{j} < 0.26$. This means that the predicted orbit of the LMC in GN96 is a common one in B11. We thus conclude that the orbital properties in the above successful MS formation models based on the early accretion of the LMC are consistent with those of LMC analogs predicted from recent cosmological simulations by B11.

Our conclusion above therefore appears to be at odd with B11 which concluded that the LMC was accreted within the past four Gyr and is currently making its first pericenter passage about the Galaxy. Clearly, their Fig. 4 shows that about 60% of LMC analogs are accreted onto the Galaxy more than 4 Gyr ago (i.e., $t_{ec} > 4$ Gyr). This
result appears to be inconsistent with the above conclusion by B11. This apparent inconsistency is due to the fact that B11 used only observations by K06 and thereby estimated orbital energy and angular momentum of the LMC in order to find LMC analogs that have orbital properties similar to the observed ones: their conclusions depend on the adopted assumptions on the orbital angular momentum and energy of the LMC. New observational results on the proper motion of the LMC (e.g., C09; V10) have shown that the orbital energy and angular momentum of the LMC are significantly different from those by K06. These significant differences between different observations imply that it would be worthwhile for cosmological N-body simulations to find the best LMC analogs separately for each of observations by K06, C09, and V10.

4.2 Fossil records in the outer Galactic halo

The present study has first shown that the outer regions of the Galactic stellar halo (R > 50 kpc), in particular, those along the Galactic polar axis, can have fossil information on the past 3D orbit of the LMC. If the LMC has already experienced the pericenter passage at least two times, then the stars stripped from the LMC stellar halo can have a thick disk or ring-like distribution along the z-axis in the Galactic coordinate. This polar disk (or ring) has a mass of \( \sim 10^7 M_\odot \) (\( \approx 0.2 M_\odot \text{L}_\odot \)) and thus can consist of \( \sim 0.5\% \) of the entire Galactic stellar halo mass. The rotating kinematics of the polar disk and the spin vector of the polar disk (i.e., the z-direction) would be distinguished from those of other possible stellar substructures formed from tidal destruction of dwarf galaxies in the Galactic stellar halo. Therefore, if the polar disk really exists in the outer stellar halo, then it would be feasible for ongoing and future observations to detect them along the Galactic polar axis.

Previous models showed that the MS along the polar axis of the Galaxy can be formed from efficient stripping of gas from the SMC due to tidal interaction between the LMC, SMC, and the Galaxy (YN03). Their models also predicted that there should be no/little stars along the MS, because tidal stripping is efficient only for gas that is initially located in the outer part of the SMC in comparison with stars (See Fig. 8 in YN03). Therefore, if observations discover stars in the MS region, then the stars are unlikely to originate from the polar disk/ring. Future observational surveys such as the Southern Sky Survey by the SkyMapper telescope (Keller et al. 2007) would be ideal for the detection of the polar disk/ring.

It should be stressed that the present results depend strongly on whether the LMC has an extended stellar halo well before its commencement of tidal interaction with the Galaxy: if the LMC initially does not have the halo, then the outer stellar halo of the Galaxy would not have valuable information on the past 3D orbit of the LMC. Extensive observational studies on physical properties of the outer part of the LMC based on photometric properties of stars (e.g., color-magnitude diagrams) are currently ongoing (e.g., Saha et al. 2010). The physical extension and projected 2D distribution of the possible LMC stellar halo revealed by these studies will assess the viability of the present new idea to give constraints on the past orbit of the LMC.

4.3 Other possible evidence for early accretion of the LMC?

Using the results of numerical simulations on dynamical properties of substructures in a Milky Way-like halo in a \( \Lambda \)CDM model, Li & Helmi (2008) showed that accretion of a small group of galaxies on to the Galaxy about 8 Gyr ago can explain the polar distribution of satellite galaxies in the Galaxy. Bekki (2008) suggested that if the LMC was a central galaxy of a group being accreted onto the Galaxy (i.e., with other small galaxies, like the SMC, Carina, and Fornax), then the LMC now can have a “common halo” that surrounds both the LMC and the SMC. If this is the case, the stripped low-mass dwarfs from the LMC group might well have a polar distribution like the stripped LMC stellar halo. The observed thin disk-like distribution of the Galactic satellite galaxies along the Galactic polar axis (e.g., Metz et al. 2009) could be thus possible evidence of early accretion of the LMC onto the Galaxy, if the LMC was accreted onto the Galaxy as a group.

Yoon & Lee (2002) revealed an intriguing distribution of seven metal-poor ([Fe/H] < -2) globular clusters (GCs) along the polar-axis of the Galaxy and suggested that the GC distribution is consistent with accretion of a satellite
galaxy which lost their GCs by tidal stripping of the Galaxy. The GCs along the polar-axis have ring-like or disky spatial distribution and rotational kinematics, which appear to be similar to dynamical properties of the stripped LMC stellar halo stars in SPS of the present study. These results imply that some of original GCs in the LMC halo were tidally stripped during the accretion of the LMC more than \( \sim 4 \) Gyr ago to become the halo GCs with a disky spatial distribution along the polar axis of the Galaxy. This picture would be consistent with the observed similarities in physical properties of GCs (e.g., locations on \([\text{Fe}/\text{H}]-P_{\text{ab}}\) relation, where \( P_{\text{ab}} \) is the mean period of type ab RR Lyraes) between the seven GCs and the LMC GCs.

5 CONCLUSIONS

We have investigated dynamical evolution of the stellar halo of the LMC orbiting the Galaxy using fully self-consistent N-body simulations in which the LMC, the SMC, and the Galaxy are represented by collisionless N-body particles. We also have investigated orbital evolution of the LMC for different initial velocities of the LMC at its first passage of the virial radius of the Galaxy. This is for the purpose of discussing whether orbital properties of the LMC in the previous successful formation models for MS and LAs are consistent with those predicted from recent cosmological simulations based on a ΛCDM model. The main results are summarized as follows.

(1) The tidal interaction between the LMC and the Galaxy can strip stars initially in the extended stellar halo of the LMC and the stripping processes depend strongly on the past orbit of the LMC. For example, if the epoch of the first LMC accretion onto the Galaxy from outside its virial radius is more than \( \sim 4 \) Gyr ago (i.e., at least two pericenter passages), the stars stripped from the stellar halo of the LMC can form an irregular polar ring or a thick disk with a size of \( \sim 100 \) kpc and rotational kinematics. On the other hand, if the LMC was first accreted onto the Galaxy quite recently (\( \sim 2 \) Gyr ago), the stripped stars form shorter leading and trailing stellar stream at \( R = 50 - 120 \) kpc. The distributions of the stripped stars in phase space between the two cases can be significantly different.

(2) Differences in dynamical properties of the stripped LMC halo stars between FPS and SPS do not depend on model parameters such as \( M_{\text{dim,now}}, R_{\text{h,L}}, \) and \( f_v. \) Also the SMC is found to be unable to significantly change the final distribution of the stripped LMC stellar halo around the Galaxy. Therefore the derived differences between FPS and SPS suggest that if we compare the observed three-dimensional (3D) distribution and kinematics of the outer Galactic stellar halo along the polar-axis, then we can give strong constraints on the past orbit of the LMC. Future observational surveys such as the Southern Sky Survey by the SkyMapper telescope would be ideal for the detection of the dark matter ring formed from the LMC-Galaxy interaction, which is possible in early accretion of the LMC, can repetitively enhance star formation in the SMC for the last few Gyr (YN03), which is indeed observed (e.g., Harris & Zaritsky 2004). Thus, the observed star formation histories of the LMC and the SMC, bifurcated MS, and elongated LAs strongly suggest that the LMC first passed the Galactic virial radius more than 4 Gyr ago.

(3) The LMC can lose its mass, energy, and orbital angular momentum during its orbital decay caused by dynamical friction against the dark matter halo of the Galaxy. The significant mass loss of the LMC during its orbital evolution can make the timescale of dynamical friction significantly longer. A result of this, the LMC can not merge with the Galaxy within \( \sim 6 \) Gyr after its first passage of the Galactic virial radius, even if the initial total mass of the LMC is about 10% of that of the Galaxy. The LMC with \( f_v \sim 1 \) (\( f_v,y = 0.5 \) and \( f_v,x = 0.9 \)) that is predicted to be typical in recent ΛCDM cosmological simulations can not merge within \( \sim 10 \) Gyr for \( M_{\text{t,L}} = 9.6 \times 10^{10} M_\odot \) and \( M_{\text{dim,now}} = 10^{12} M_\odot \). These results allow the previous successful MS formation models which assume that the LMC and the Galaxy have been dynamically interacting with each other without merging at least a few Gyr.

(4) The LMC in the models with \( f_y \sim 1 \) can finally have \( R_y (\sim 50 \) kpc) and \( V_p (300 - 380 \) km s\(^{-1}\)) that are observed in the present LMC. This result implies that the orbit of the LMC needs not be unusual one in the ΛCDM model. This also suggests that it is promising for future formation models of MS and LAs based on cosmological simulations to reproduce both the present location/velocity of the LMC and the physical properties of MS and LAs in a self-consistent manner.

(5) The previous successful formation models of MS and LAs predict at least two pericenter passages of the LMC about the Galaxy (i.e., the first passage of the Galactic virial radius) more than 4 Gyr ago. The models also predict \( \epsilon \sim 0.4, \gamma \sim 0.3, \) and strongly bound orbit for the LMC. Orbital properties of early-accreted LMC analogs (\( t_\text{f} > 4 \) Gyr) predicted from recent cosmological simulations are therefore consistent with those in the successful formation models of MS and LAs. This consistency strongly suggests that the LMC was accreted onto the Galaxy more than 4 Gyr ago so that the bifurcated MS and elongated LAs could be formed as a result of tidal interaction between the LMC, the SMC, and the Galaxy.

We thus conclude that the LMC was accreted onto the Galaxy more than 4 Gyr ago (i.e., the first pericenter passage more than \( 2 - 3 \) Gyr ago). This early accretion suggests that the global star formation of the LMC could have been enhanced by its dynamical interaction (Bekki & Chiba 2005) and hydrodynamical one (Mastropietro et al. 2009) with the Galaxy since more than 2 \( \sim 3 \) Gyr ago (i.e., after the first pericenter passage). This LMC-Galaxy interaction which can trigger star formation can provide physical explanations both for the observed enhancement of star formation in the LMC about a few Gyr ago (e.g., Gallagher et al. 1996) and for the unusually blue colors of the LMC as a massive satellite in Galaxy-scale halos (Tollerud et al. 2011). Furthermore, the long-term LMC-SMC-Galaxy interaction, which is possible in early accretion of the LMC, can repetitively enhance star formation in the SMC for the last few Gyr (YN03), which is indeed observed (e.g., Harris & Zaritsky 2004). Thus, the observed star formation histories of the LMC and the SMC, bifurcated MS, and elongated LAs strongly suggest that the LMC first passed the Galactic virial radius more than 4 Gyr ago.
6 ACKNOWLEDGMENT

I am grateful to the anonymous referee for constructive and useful comments that improved this paper. KB acknowledge the financial support of the Australian Research Council throughout the course of this work. The work was supported by iVEC through the use of advanced computing resources located at the University of Western Australia.

REFERENCES

Bekki, K., 2008, ApJ, 684, L87
Bekki, K., 2011, ApJ, 730, L2
Bekki, K., Chiba, M., 2005, MNRAS, 356, 680
Bekki, K., Chiba, M., 2009, PASA, 26, 48
Benson, A. J., 2005, MNRAS, 358, 551
Benes, G., Kallivayalil, N., Hernquist, L., van der Marel, R. P., Cox, T. J., Keres, D., 2010, ApJ, 721, L97
Boylan-Kolchin, M., Besla, G., Hernquist, L., 2011, MNRAS, in press
Brück, M. T., Hawkins, M. R. S., 1983, A&A, 124, 216
Brüns, C., et al., 2005, A&A, 432, 45
Chiba, M., Beers, T. C., 2000, AJ, 119, 2843
Connors, T. W., Kawata, D., & Gibson, B. K., 2006, MNRAS, 371, 108
Costa, E., et al., 2009, AJ, 137, 4339
Diaz, J., Bekki, K., 2011, MNRAS, 413, 2015 (DB11)
Freeman, K., Bland-Hawthorn, J., 2002, ARA&A, 40, 487
Harris, J., Zaritsky, D., 2004, AJ, 127, 1531
Gallagher et al., 1996, ApJ, 466, 732
Gardiner, L. T. & Noguchi, M., 1996, MNRAS, 278, 191 (GN96)
Guhathakurta, P., Reitzel, D. B., 1998, Galactic Halos, Edited by Dennis Zaritsky, ASP Conference Series 136, p. 22.
Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J., Geha, M., 2006, ApJ, 638, 772
Keller, S. C., et al., 2007, PASA, 24, 1
Li, Y., Helmi, A., 2008, MNRAS, 385, 1365
Lux, H., Read, J. I., Lake, G., 2010, MNRAS, 406, 2312
Majewski, S. R., Nidever, D. L., Muñoz, R. R., Patterson, R. J., Kunkel, W. E., Carlin, J. L., 2009, The Magellanic System: Stars, Gas, and Galaxies, Proceedings of the International Astronomical Union, IAU Symposium, Volume 256, p. 51-56
Mastropietro, C., Burkert, A., Moore, B., 2009, MNRAS, 399, 2004
Metz, M., Kroupa, P., Theis, C., Hensler, G., Jerjen, H., 2009, ApJ, 697, 269
Minniti, D., Borissova, J., Rejkuba, M., Alves, D. R., Cook, K. H., & Freeman, K. C., 2003, Science, 301, 1508
Muñoz R. R., et al. 2006, ApJ, 649, 201
Murai, T., Fujimoto, M., 1980, PASJ, 32, 581
Navarro, J. F., Frenk, C. S., White, S. D. M., 1996, ApJ, 462, 563 (NFW)
Noël, N. E. D., Gallart, C., 2007, ApJ, 665, L23
Piatek, S., Pryor, C., Olszewski, E. W., 2008, AJ, 135, 1024
Saha, A., et al., 2010, AJ, 140, 1719
Subramaniam, A., Subramaniam, S., 2009, A&A, 503, L9
Sugimoto, D., Chikada, Y., Makino, J., Ito, T., Ebisuzaki, T., Umemura, M., 1990, Nat, 345, 33
Tollerud, E. J., Boylan-Kolchin, M., Barton, E. J., Bullock, J. S., Trinh, C. Q., 2011, in press (arXiv1103.1875)
Vieira, K., et al. 2010, AJ, 140, 1934
Wetzel, A. R., 2011, MNRAS, 412, 49
Yoon, S.-J., Lee, Y.-W., 2002, Science, 297, 578
Yoshizawa, A., Noguchi, M., 2003, MNRAS, 339, 1135 (YN03)
Zibetti, S., White, S. D. M., Brinkmann, J., 2004, MNRAS, 347, 556