Formation of the Andromeda Giant Stream: Asymmetric Structure and Disc Progenitor

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ABSTRACT

We focus on the evidence of a past minor merger discovered in the halo of the Andromeda galaxy (M31). Previous N–body studies have moderately succeeded to reproduce observed giant stellar stream (GSS) and stellar shells in the halo of M31. The observed distribution of red giant branch stars in the halo of M31 shows an asymmetric surface brightness profile across the GSS; however, most of the theoretical studies have not paid much attention to the internal structure of the GSS. We notice that numerical experiments so far have not examined the morphology of the progenitor galaxy in detail. To investigate the physical connection between the characteristic surface brightness in the GSS and the morphology of the progenitor dwarf galaxy, we perform systematic surveys of N–body simulations varying the thickness, rotation velocity, and initial inclination of the disc dwarf galaxy. Our result suggests that the key to the formation of the observed structures is the progenitor’s rotation. Not only we reproduce observed GSS and two shells in detail, but also we predict additional structures for further observations. We predict the detectability of the progenitor’s stellar core in phase–space density distribution, azimuthal metallicity gradient of the western shell-like structure, and an additional extended shell at the north–western direction that will limit the properties of the progenitor galaxy.

Key words: galaxies: individual(M31)-galaxies: interactions-galaxies: kinematics and dynamics.

1 INTRODUCTION

Local group is one of the greatest laboratories to investigate the formation and evolution of galaxies by comparing theoretical approach with observation even for extremely faint structures. Snapshot of the Local group should be packed with a history of the hierarchical structure formation of the universe based on the generally accepted cold dark matter model. In fact, spatial, kinematic, and metallicity distribution of sub-structures such as tidal debris and dwarf satellite galaxies in a host halo are the key probes to investigate the formation history of galaxies, density profile of the host galaxy, and accretion history of massive black holes (MBHs) associated with satellite galaxies.

Recent deep photometric observations of the halo of the Andromeda galaxy (M31) have discovered a wealth of faint structures including the past and on-going galaxy mergers (Ibata et al. 2001; Irwin et al. 2005; McConnachie et al. 2009; Martin et al. 2013). Giant stellar stream (hereafter GSS) and fan–like stellar structures have been discovered in the halo of M31. Its spatial, metallicity, and line-of-sight velocity distribution have been observed in detail (Ibata et al. 2004; Ferguson et al. 2004; Kalirai et al. 2006; Gilbert et al. 2009). Then, the halo region of M31 has been surveyed wider and deeper represented by PAndAS (Pan–Andromeda Archaeological Survey) (McConnachie et al. 2009; Martin et al. 2013) and by SPLASH (Spectroscopic and Photometric Landscape of Andromeda’s Stellar Halo) survey (Kalirai et al. 2010; Tollerud et al. 2012). In particular, the GSS locates in the south–eastern region from the center of M31 and extends more than 120 kpc away along the line-of-sight (McConnachie et al. 2003; Conn et al. 2016). Also, fan–like structures spread north–eastern and western side of M31 and the radius are approximately 30 kpc (Fardal et al. 2007). Various works have explored the formation of these structures using N–body simula-
Figure 1. Stellar mass $M_\ast$ and morphological type of the observed dwarf galaxies surrounding M31 as a function of the projected distance from the center of M31 (data are taken from McConnachie (2012)). Each symbol shows dSphs (open red squares), dIrrs (filled blue circles), dEs (filled magenta triangles), compact elliptical (filled cyan square), and Sb galaxy (inverted filled triangle), respectively.

Figure 1 shows the stellar mass of the observed dwarf galaxies around M31 as a function of the projected distance from the center of M31. Predicted mass range of the progenitor dwarf galaxy of the GSS is virtually dominated by dwarf Ellipticals and dwarf Irregulars. On the contrary, all of such satellite galaxies in M31 has rotating stellar and/or gas component (McConnachie 2012). Even M32 that is classified compact elliptical has a rotating stellar component with the measured velocity of 55 km s$^{-1}$ (Bender, Kormendy & Dehnen 1996). Although previous studies have usually used a spherical, non-rotating model for the progenitor galaxy, these reasonable conditions motivate us to assume a disc-like galaxy as the GSS progenitor.

Using star count maps around M31, McConnachie et al. (2003) analyzed surface brightness profile of the orthogonal direction to the extending direction of the GSS and revealed an asymmetric surface brightness of the GSS. The star counts of the GSS decrease sharply at the north–eastern side seeing from the most luminous direction of the GSS. On the other hand, that of the western side extends wide and smoothly. This asymmetrical structure of the GSS has not been demonstrated by any simulations assumed an infall of a spherical, non-rotating dwarf galaxy (e.g., Fig. 11d). The characteristic surface brightness profile of the GSS would be an excellent tracer of the morphology of the disrupted progenitor galaxy. To verify the disc merger scenario, we need to scrutinize a considerably large parameter space. It is necessary to perform a systematic survey to find out the suitable condition of the progenitor following a complicated evolution. The previous studies pay little attention to examining the asymmetric surface brightness, and recent few disc satellite merger simulations performed by Fardal et al. (2008) and Sadoun, Mohayaee & Colin (2014) did not exhibit the observed asymmetric structure of the GSS. For example, the main motivation in Fardal et al. (2008) was to explore the formation of two arc-like structures on the eastern side of the GSS (stream C and D in Ibata et al. (2007)), and it should be noted that the clearer sharp eastern edge-like structure of the GSS could not be reproduced.

The estimation of the progenitor’s mass suggests that the progenitor galaxy is not likely nearby dSphs that have mass–to–luminosity ratio of $\sim 100$. It is reasonably thought that the progenitor associated a dark matter halo initially, with the dark matter mass corresponding to the mass–to–luminosity ratio $(M/L = 2 - 5)$ similar to those of local satellite dwarf galaxies (see fig. 11 of McConnachie (2012)). On the other hand, dark matter halo component of the progenitor galaxy has not been definitely concerned in most previous works because of a rationalization that the dark matter halo component has been stripped before the first interaction with M31. However, a relatively inner gravitationally well-bound region of the dark matter halo would survive even after the collision to M31. Additionally, it is not obvious that how the stripped dark matter halo component spreads and relaxes in the host halo in the scope of hierarchical structure formation of the universe.

Spatial distribution of the heavy elements in the galaxies provides clues to investigate the formation history of the galaxies. Ibata et al. (2007) showed the metallicity distribution based on color–magnitude diagrams in the southern area of M31 and suggested that the GSS has a clear difference of metallicity between an eastern high-surface-brightness region (metal-rich) and a faint western region (metal-poor) of the GSS. Spectroscopic measurements of the metallicity distribution based on CaII triplet absorption lines have also revealed the similar trend in the GSS (Gilbert et al. 2009). In addition, Fardal et al. (2012) measured the metallicity distribution of the western shell along the minor axis of the M31’s disc. Only recently, Conn et al. (2016) observed radial metallicity distribution along the GSS. On the other hand, observed dwarf galaxies often have radial metallicity gradient (Koleva et al. 2009). Such observed metallicity distributions in the GSS would be originated in the progenitor dwarf galaxy (Fardal et al. 2008; Miki, Mori & Rich submitted).

In this paper, we perform systematic surveys using N-body simulation of a galaxy collision between M31 and a dwarf satellite galaxy composed of a stellar disc, a stellar bulge, and a dark matter halo component to reproduce the asymmetric surface brightness of the GSS. In §2, we describe the observational data and the treatment of them, including our simple analysis of the asymmetric surface brightness...
profile of the GSS. In §3, we introduce our modeling of the potential of M31, N-body satellite progenitor, and the numerical model for systematic surveys. The results of numerical simulations and quantitative comparison with observed data are displayed in §4. Several discussions such as metallicity distribution, distribution of disrupted dark matter halo component of the progenitor, the position of an MBH initially located at the center of the progenitor galaxy, and extended stellar shell at the north–western area of M31 are described in §5, and we summarize our findings in §6.

2 OBSERVED STRUCTURES

2.1 Spatial faint structures around M31

Merger remnants are the key to understanding not only the property of the host galaxy but also that of the disrupted progenitor galaxy like its mass and morphological type. Some of the faint stellar structures in the halo of M31 have been well reproduced using an ongoing merger of a satellite galaxy (Fardal et al. 2007; Mori & Rich 2008; Fardal et al. 2008; 2013; Miki et al. 2014; Sadoun, Mohayaee & Colin 2014; Kirihara, Miki & Mori 2014; Miki, Mori & Rich submitted). Irwin et al. (2005) surveyed the M31 halo intensively using the Isaac Newton Telescope Wide-Field Camera (INT/WFC). Their map covers an elliptical region of the semi-major axis of 4° with the aspect ratio of 5:3 and an additional ∼10 deg² extension toward the south of M31. We analyze their data set of red giant branch (RGB) stars to compare with our results of numerical simulations.

The star count maps include non-GSS components such as halo stars of M31, foreground halo stars of MW, and other substructures around M31. We simply subtract a constant background to obtain the clearer structure of the GSS as follows. At first, we take away the area of the M31’s disc, the eastern and the western shell, the GSS, and several stellar substructures from the star count map to calculate the background on the GSS. Next, we evaluate the averaged star counts in each cell except for the area as mentioned above. The averaged count of background is 1.18 RGB star per cell. Then, star counts in each cell are subtracted from this count. Owing to the treatment, a clearer structure of the GSS can be obtained.

2.2 Asymmetric structure of the GSS

An asymmetric surface brightness across the GSS was found by McConnachie et al. (2003) through an analysis of star count maps. They discovered that the star counts increase sharply from the eastern side of the GSS comparing with that at the western side. In order to compare the simulated GSS with the observed GSS, we reanalyze the observed data and obtain azimuthal surface brightness profile of the GSS.

It is hard to obtain the pure GSS component inside the radius $R = 2.5$[degrees] (∼30 kpc) due to the superposition of the M31’s disc and the clumpy stellar structures. The data do not have sufficient star counts at the outside of $R = 3.5$[degrees]. Therefore, as shown by the enclosed area with solid lines in Fig. 2a, we adopt the analyzed region in $2.5$[degrees] $< R < 3.5$[degrees] for the distance from the center of M31 and $30° < \theta_a < 100°$ for the azimuthal angle $\theta_a$ from the eastern direction to southern direction. The distance is divided into two areas (i.e., inner and outer areas) at the distance $R = 3.0$[degrees] for $\chi^2$ analysis.

Fig. 2b shows the azimuthal star counts distribution of the GSS. The brightest azimuthal angle is $\theta_a \sim 65°$ and we define the GSS axis in this direction hereafter. At the western side (bigger $\theta_a$) from the GSS axis, the surface brightness decreases gradually. On the other hand, that of the eastern side decreases sharply. We fit this asymmetric star count profile by an asymmetrical exponential function for each side in proportion to $\exp(-|d_{\theta_a}|/\delta_{\theta_a})$. Here, $\delta_{\theta_a}$ and $\delta_{\theta_a}^{\text{obs}}$ are the observed width of the eastern edge and that of the broad western structure, respectively. The fitted values

Figure 2. (a) Background subtracted RGB stellar count map of the halo of M31 (Irwin et al. 2005). Circles describe the observed edges of the eastern and the western shells, and squares are along the previously observed area of the GSS (Font et al. 2006; Fardal et al. 2007). The white ellipse is the shape of the M31’s disc. The azimuthal angle $\theta_a$ is taken from the eastern direction on the M31 center coordinate. (b) Azimuthal star counts distribution of the GSS. The analyzed area is like a portion of an annulus ($30° < \theta_a < 100°$) that is shown in panel (a). The dotted and dashed lines are the profiles of the inner and outer region of the annulus, respectively.
are summarized in Table 1. The asymmetric spatial distribution is apparent in the significant difference in the width of the eastern side and the western side.

### 3 NUMERICAL MODELS

#### 3.1 M31 potential model

In this work, we assume a fixed gravitational potential model for M31 with a Hernquist bulge (Hernquist 1990), an exponential disc, and a dark matter halo with NFW profile (Navarro, Frenk & White 1996). The scale radius and the total mass of the bulge component are 0.61 kpc and $3.24 \times 10^{10} M_{\odot}$, respectively. The disc of M31 is set to have the scale height of 0.6 kpc, radial scale length of 5.4 kpc, and the total mass of $3.66 \times 10^{10} M_{\odot}$. The inclination angle and position angle of the disc of M31 are $77^\circ$ and $37^\circ$, respectively (Geehan et al. 2006). The scale radius of the NFW halo is 7.63 kpc, and the scale density is $6.17 \times 10^7 M_{\odot} \text{kpc}^{-3}$. These conditions of the M31 model nicely reproduces the observed surface brightness of the bulge and disc components, the velocity dispersion of the bulge, and the rotation curve of the disc (Geehan et al. 2006; Fardal et al. 2007).

Note that Mori & Rich (2008) examined the dynamic response of the interaction of the progenitor using full N-body simulation and the collision of the less massive progenitor ($<5 \times 10^9 M_{\odot}$) gives rise to little change in the gravitational potential of the M31. Therefore, it is valid to treat M31 as a fixed gravitational potential, and above mentioned parameters for M31 are the same conditions as the previous studies using the same initial orbital variables of the progenitor (Fardal et al. 2007; Mori & Rich 2008; Fardal et al. 2008; Miki, Mori & Rich submitted).

#### 3.2 N-body satellite models

In order to elucidate the origin of the asymmetric surface brightness of the GSS, we consider a galaxy collision of M31 with a disc dwarf satellite galaxy in contrast with previous works using spherical non-rotating dwarf galaxies. We model a dwarf satellite galaxy as a self-consistent N-body realization of stellar and dark matter system. The initial position vector and velocity vector of the progenitor galaxy are taken from Fardal et al. (2007).

An equilibrium model for disc dwarf galaxy is constructed by the public code GalactICS (Kuijken & Dubinski 1995), which generates a self-consistent bulge-disc-halo N-body system. For the disc progenitor model as model THIN, we assume a one hundredth mass-reduction model of the M31 Model A represented in Widrow, Perrett & Suyu (2003). In this model, the density profile of the dark matter halo is a lowerd Evans profile (Kuijken & Dubinski 1994) that is based upon an isothermal distribution function. The disc component follows exponential density profile radially and isothermal profile vertically. The bulge component is constituted by a King sphere.

Here, we summarize the input parameter set of the disc dwarf progenitor models. When using GalactICS, the unit of length, velocity, and mass are 1 kpc, 100 km s$^{-1}$, and $2.325 \times 10^6 M_{\odot}$, respectively (Kuijken & Dubinski 1995 and Widrow, Perrett & Suyu 2003)). As the input parameters for the halo of the model THIN are the central potential $\Phi(0) = -1.483$, the central velocity dispersion $v_0 = 0.952$, and a characteristic radius $r_0 = 0.981$. The total mass of the disc component $M_d = 0.318$, the scale length $R_d = 1.11$, and the scale height $Z_d = 0.13$. The outermost cutoff radius of the disc $R_{\text{outer}}$ is 8.0, and truncation length around the cutoff radius is 0.2. The central density of the bulge component $\rho_0$ is 6.68, the velocity dispersion $\sigma_0$ is 0.508, and its cutoff potential $\Phi_{\text{cut}} = -0.835$ to control the extent of the bulge.

It is well-known that the disc thickness of nearby dwarf galaxies is relatively large (Spolaor et al. 2010; Toloba et al. 2011). Accordingly, we construct two additional models THICK and HOT that have a simply larger scale height $Z_d = 0.52$ (4 times the scale height of the disc of THIN) and $Z_d = 1.11$ (the same length as the scale length), respectively. The value of input parameters are listed in Table 2. In our models for parameter surveys, we use 203,418 particles composed of 153,752 dark matter particles, 36,756 disc particles, and 12,910 bulge particles. For convergence test, we use 1,017,090 particles that are five times larger than the number of particles in the survey. It should be noted that the total mass of our models is slightly changed even in the case of simply varying the different value of the thickness of the disc due to the Poisson solver employed in the GalactICS code. Table 3 shows the mass of the bulge, disc, and dark matter halo in each disc model.

In addition to the three disc models, we expand the parameter space of the model THICK (with keeping $Z_d$) to have different rotation curve since it would affect the shape of the GSS. In order to vary different rotation velocity of the disc, we simply change the central gravitational potential of the dark matter halo (THICK2-THICK9; see Table 2).

For the N-body study, we use original parallel tree code with a tolerance parameter of 0.5 for calculating gravity and the softening length of $\sim 8$ pc for all parameters. The orbit integration is performed with a second–order leapfrog integrator. Numerical calculations for the present work have been carried out on T2K–Tsukuba System, HA–PACS System, and COMA System in Center for Computational Sciences, University of Tsukuba.

#### 3.3 Rotation of satellite progenitor

In contrast to the spherical progenitor model, it is obvious that an initial inclination of the disc progenitor is important to reproduce the observed shape of the GSS and shells. Therefore, it is indispensable to examine the initial inclination of the disc systematically and perform a galaxy merger simulation between M31 and the progenitor galaxy. As Fig. 3 shows, we set two dimensional plane ($\phi, \theta'$) (later we use $\phi(\equiv 180^\circ - \phi')$, $\theta(\equiv 180^\circ - \theta')$) in the polar coordinate system for the systematic survey. Initially, the pole of the satellite system points the direction of the angular momentum vector of the disc of M31. In other words, the disc plane and
Morphology of the GSS progenitor

4 NUMERICAL RESULTS

4.1 Representative models

We perform galaxy collision simulations between M31 and a disc dwarf satellite galaxy. At first, we show a successful model that well reproduces the GSS axis, width of the sharp eastern edge, and width of the broad western structure of the GSS. Fig. 4 shows the whole spatial distribution of the remnant of the satellite galaxy and the normalized stellar number count as a function of the azimuthal angle for one of the successful parameters (model THICK7 with $(\phi, \theta) = (-15^\circ, 30^\circ)$). The shape and size of the north-eastern shell and the western shell are also well reproduced.

Fig. 5 shows the time evolution of the disrupted dwarf galaxy on the sky coordinate until the current epoch. Here, we use the data of high-resolution runs that are for convergence test of our simulations (see §5.1). The initial position of the progenitor galaxy is set at the north-western area of M31 (Fig. 5i). After the simulation starts, the progenitor experiences almost head-on collision with M31. In our simulation, it takes approximately one dynamical time of the disc of the progenitor from the initial condition to the first pericentric passage of the orbital motion. Then, the progenitor is disrupted, and the component spreads into south-eastern area and the GSS grows (Fig. 5j). At the same time, a part of the debris falls and goes through at just western side of the center of M31, and spreads after the second pericentric passage to a large area like a fan that is called the eastern shell (Fig. 5k). Immediately, some of them also move to the western area and form similar shell that is called the western shell (Fig. 5l). In each run, a current epoch is defined as the snapshot when the simulated edge positions of the eastern and western shells match most closely with the observed positions.

In Fig. 5i, the dense region of the simulated GSS lies along the observed fields which are marked by the open squares (Font et al. 2006). The result of simulation shows that boundaries of the shell structures at the north-eastern and western area reach the observed edges of the shells indicated by the open circles which are analyzed by Fardal et al. (2007). It is clear that most of the bulge component resides in the eastern shell (Fig. 5d), and almost no bulge component is in the GSS area. That is because bulge stars are well bound by the gravitational potential of the progenitor’s bulge, and it was able to endure the tidal disruption of the gravitational field of M31 at the first pericentric passage. In our simulation, the progenitor also has a spherical dark matter halo component, and the bottom panels of Fig. 5

Table 2. Properties of the progenitor models

| Model   | THIN | THICK | THICK2 | THICK3 | THICK4 | THICK5 | THICK6 | THICK7 | THICK8 | THICK9 | HOT |
|---------|------|-------|--------|--------|--------|--------|--------|--------|--------|--------|-----|
| $Z_c$   | 0.13 | 0.52  | 0.52   | 0.52   | 0.52   | 0.52   | 0.52   | 0.52   | 0.52   | 0.52   | 1.11|
| $\Psi_c$| -1.483 | -1.483 | -1.400 | -1.450 | -1.500 | -1.550 | -1.600 | -1.650 | -1.700 | -1.750 | -1.483|
| $V_0$   | 0.952 | 0.952 | 1.000  | 1.100  | 1.200  | 1.300  | 1.400  | 1.500  | 1.600  | 1.650  | 0.952|

Table 3. Mass abundance of the progenitor models

| Model   | THIN | THICK | HOT |
|---------|------|-------|-----|
| $Z_c$ [kpc] | 0.13 | 0.52 | 1.11 |
| Bulge $[M_\odot]$ | $2.9 \times 10^9$ | $3.1 \times 10^9$ | $3.1 \times 10^9$ |
| Disc $[M_\odot]$ | $7.8 \times 10^9$ | $7.3 \times 10^9$ | $6.5 \times 10^9$ |
| DM halo $[M_\odot]$ | $3.2 \times 10^9$ | $3.5 \times 10^9$ | $3.9 \times 10^9$ |

![Figure 3. Initial inclination $(\phi', \theta')$ of the spin axis of the progenitor’s disc on the calculating coordinate. Gray elliptical disc shows the M31’s disc on the coordinate of numerical simulations, and the orange elliptical disc is the inclined disc of the progenitor. The green compass shows the direction of north, east, and the Earth. The position of the Earth is the backside of the M31’s disc. Three-dimensional visualisation was conducted with the S2PLOT programming library (Barnes et al. 2006).](image-url)
Figure 4. (a) Surface mass–density distribution of the disrupted progenitor that the parameter is one of the most successful results (model THICK7 with \((\phi, \theta) = (-15^\circ, 30^\circ)\)). The inclined elliptical line describes the shape of the M31’s disc. Square symbols are the observed fields of the GSS stated in table 1 of Font et al. (2006). Circles are the edge positions of the eastern and western shells analyzed by Fardal et al. (2007). (b) Normalized stellar count distribution in the GSS as a function of azimuthal angle. Blue solid line is the result of the \(N\)-body simulation, and the black dashed line is the observed profile of the GSS.

show the evolution of the dark matter halo component. The spatial distribution spread over quite a broad region around M31 such as the eastern side of the GSS. Interestingly, the position of the sharp edge of the dark matter distribution in the western area of M31 seems to match that of the stellar component.

Fig. 6 displays the 3D distribution of the debris in the case of spherical symmetric and axisymmetric progenitor models. The simulation data of galaxy merger with the spherical galaxy is taken from Kirihara, Miki & Mori (2014). The spherical dwarf satellite galaxy has a Plummer equilibrium distribution with the total mass of \(2.2 \times 10^9 M_\odot\) and the scale radius of 1.03 kpc. Three-dimensional distribution of the simulated GSS is consistent with the most recent observation by Conn et al. (2016) that has higher quality than McConnachie et al. (2003). The simulated GSS is a little shorter than the observed GSS, and it would be due to an artificial radial cutoff in the initial progenitor’s disc for simplicity. In Fig. 6, dynamically cold components (e.g., fine structures at the inner region of eastern and western shells) are seen in the case of disc merger. The most important difference is the width of the GSS, particularly, a dynamically cold component on the western side of the GSS. As compared to the case of spherical progenitor’s merger on the 3D view, the GSS spreads extremely broad to the southern and western direction in the case of disc merger.

Fig. 7 shows the 3D distribution of the bulge and the dark matter halo components at the best fitting epoch. In Fig. 7b and Fig. 7c, the progenitor’s bulge is elongated to the line-of-sight direction due to the tidal force of the M31’s potential. The 3D view of the dark matter halo component of the disrupted progenitor shows several shell-like structures. That is the evidence that a part of dark matter halo component crosses the central region of M31 several times.

Here, we show typical cases with the clockwise and the anti-clockwise rotating disc models on the sky coordinate. Fig. 8a and Fig. 8b show the stellar mass–density distribution of the almost clockwise \((\phi, \theta) = (-90^\circ, 100^\circ)\) and the anti-clockwise \((\phi, \theta) = (90^\circ, 75^\circ)\) rotating disc models, respectively. As shown in the figure, the shape of the debris is considerably different from the galaxy merger with the spherical dwarf galaxy. The progenitor experienced almost head–on collision with M31, and the center of the progenitor passed just eastern side of the M31’s center. The shortest distance from the center of M31 at the first pericentric passage is about 1 kpc. In addition, the size of the progenitor’s disc is larger than 1 kpc (Fig. 8a). Although details depend on the inclination of the disc of the progenitor, therefore, the main component of the progenitor passes through the eastern side of the M31’s center, but a part of the progenitor passed through the western area of the M31’s center.

As we can see, there is no GSS like component in Fig. 8a. Instead, this figure shows a curious structure at the south–eastern area of M31. That is because, the stellar component that passes western area of the M31’s center at the first pericentric passage is a clockwise rotating component, and after that, the component is thrown out to the eastern direction. On the other hand, Fig. 8b shows the slight GSS component on the eastern side, and a broad structure spreads to the western side. The reason is that the component that passes just eastern area of the M31’s center has an anti-clockwise rotating component. However, the direction of the GSS is somewhat westerly comparing with the observed one.

To summarize the arguments above, the direction of the GSS and the shape of the GSS highly relate to the rotation of the progenitor galaxy. In order to evaluate the effect of the initial inclination of the progenitor, we below analyze the reproducibility of the GSS axis, the width of the eastern edge, and the width of the broad western extent.

4.2 GSS axis

The GSS axis is one of the explicit information to discuss the reproducibility of the GSS. As stated in §4.1, the azimuthal angle of the density peak in the GSS highly depends on the initial inclination of the progenitor’s disc. In order to examine the effect of the initial inclination of the disc, we need to simulate a complete sweep of the large parameter space.

For quantitative comparison between the observed GSS axis and the simulated one, we use \(\chi^2\) analysis. As same as the analysis of the observed data, simulated GSS axis is obtained by an asymmetric exponential fitting of the az-
Figure 5. Evolution of the surface mass–density distribution of the disrupted dwarf galaxy on the sky coordinate. Evolution of the bulge component (a–d), disc component (e–h), bulge and disc components (i–l), and dark matter halo component (m–p) (are shown from top to bottom). From left panels to right panels, time advances 0.0 Gyr, 0.3 Gyr, 0.6 Gyr, and 0.9 Gyr (current epoch) after the start of the simulation run. Symbols and line in each panel are the same as in Fig. 4a.

The well-fitting area seems to shift larger $\theta$ when the scale height of the disc increases. We discuss the reason for this in §4.5. Here, $\chi^2$ value is 2.5 in the case of Plummer model, and it is suitable to some extent for the GSS axis.

### 4.3 Eastern edge of the GSS

The star counts decrease sharply from the GSS axis to the eastward direction compared to its western direction. We analyze the eastern edge using a similar method that we apply to the GSS axis.

In order to compare the width of the eastern edge between the observed data and the simulated one, we use $\chi^2$ analysis assuming an observed value $\sigma_{\text{east}}^{\text{obs}} = \delta_{\text{obs}}$ stated at Table 1. As same as the analysis of the observed data, the width of the simulated GSS is obtained by the asymmetric exponential fitting. The middle panels in Fig. 9 show the result for the width of the eastern edge of the GSS at the best-fitting epoch on the $(\phi, \theta)$ plane in each disc model. It should be noted that, in models THIN and THICK, we
Figure 6. 3D distribution of the colliding satellite galaxy for the disc (both disc and bulge stars are plotted) and spherical progenitor models at the best-fitting epoch. Symbols and line in each figure are the same as in Fig. 4a. Observed distances for each region are shown using open red circles with error bars (best parameters in Conn et al. (2016)), filled black triangles (most likely parameter values in Conn et al. (2016)), and cyan crosses (McConnachie et al. 2003). Left panels (a–c): Successful disc model as the progenitor model that are the same data as in Fig. 5l. Right panels (d–f): Results for the spherical symmetric Plummer model. Panels (a) and (d): View on the sky coordinate. Panels (b) and (e): View on the plane of the line-of-sight depth $d_{M31}$ [kpc] and $\eta$ [degrees]. Panels (c) and (f): View on the plane of the line-of-sight depth $d_{M31}$ [kpc] and $\xi$ [degrees]. White arrows show the line-of-sight direction from the Earth.

Figure 7. 3D distribution of the bulge (left panels) and dark matter (right panels) components of the disrupted dwarf galaxy at the best-fitting epoch. Symbols and line in each panel are the same as in Fig. 4a. Viewing angle is the same as in Fig. 6. The upper right panel of panel (a) is the enlarged view of the green outlined $1.5^\circ \times 1.5^\circ$ region. White outlined region is a selected area for analyzing phase-space distribution of the bulge component (see §5.4). The red circle shows the position and size of a recently discovered density enhancement on the M31’s disc (Davidge 2012).
obtain a specific parameter range that produces both the observed GSS axis and eastern edge of the GSS.

So far, it is not obvious that how this asymmetric surface brightness profile of the GSS has been produced. Here, we examine the mechanism to form the eastern edge of the GSS on the plane $(\phi, \theta)$. The bluer region well fits the observed eastern edge width of the GSS, and a clear boundary of $\chi^2$ values separates the well-fitting parameters from the $(\phi, \theta)$ parameter space. In the bottom panels, we overlay a color map that shows the direction of the initial inclination of the progenitor’s disc viewing from the Earth over the $\chi^2$ map for the eastern edge width of the GSS. The color bar indicates inner product value of the normalized line-of-sight vector into the M31’s center and the unit vector of the progenitor’s disc spin. This figure helps to understand the successful condition intuitively because it describes the behavior of the rotating disc in the sky. The boundaries in the middle panels of Fig. 9 are quite similar to the curve of the edge–on region on the sky coordinate. Viewing from the Earth, the spin vector of the progenitor’s disc switches positive value or negative value if crossing the curve. In other words, the curve is the switching line of the clockwise and anti-clockwise rotation of the progenitor’s disc in the sky. For the case of Plummer model, the edge cannot be constructed, and the minimum $\chi^2$ value is 9.9. Namely, spherical progenitor models fail to reproduce the sharpness of the eastern edge.

4.4 Broad western structure of the GSS

In contrast to the eastern side of the GSS, the star counts of the GSS decrease gradually from the GSS axis to the western direction. We focus on this internal structure and also evaluate the reproducibility of the broad western structure comparing simulated one with observed data. For comparison, we set the half width of the broad western structure $\delta^{+}_\text{obs}/2$ stated in Table 1 as the deviation $\sigma^{\text{west}}_{\text{obs}}$ for the $\chi^2$ analysis. The reason for setting such a large deviation $\sigma^{\text{west}}_{\text{obs}}$ is that the most western region of the GSS is faint and noisy; therefore, the fitting of the observed distribution could somewhat overestimate the width of the broad western structure. Nevertheless, it should be noted that the width of the western side of the GSS is sufficiently wider than the width of the eastern edge.

Fig. 10 shows the $\chi^2$ map for the western side of the GSS at the best–fitting epoch on the $(\phi, \theta)$ plane. The bluer region well reproduces the observed broad western width of the GSS. As same as the analysis of the observed data, the width of the simulated GSS is obtained by the asymmetric exponential fitting. It appears that this analysis does not limit the parameter space. It is obvious that the thicker the thickness of the disc, the better the reproducibility of the observed western width in general. In the models THICK and HOT, the best-fitting parameter for the GSS axis and the eastern edge of the GSS simultaneously reproduces the broad western structure.

Fig. 11 shows the normalized number count as a function of the azimuthal angle at the parameter of $(\phi, \theta) = (5^\circ, 40^\circ)$ for various disc and spherical progenitor models. The selected parameter is a successful model for the model THICK. In the case of the model THIN, the azimuthal angle of the density peak in the GSS matches the observed one. However, the stream is dynamically too cold and forms a too narrow stellar stream. Here, the model THICK (Fig. 11b) well reproduces observed GSS axis and eastern edge of the GSS. The western side of the simulated GSS is wider than the eastern edge. The result of model HOT at this inclination shows similar profile to the spherical model (Fig. 11d) except for the shifted angle of the GSS axis. The western side of the simulated GSS is almost symmetry from the GSS axis. $\chi^2$ value of the analysis for western width with Plummer model is 3.2.

4.5 Effect of rotation velocity

As stated in §4.3, the width of the eastern edge is well explained by the anti–clockwise rotation of the progenitor’s disc in the sky. As displayed in Fig. 9, the well-fitted parameter for the GSS axis is substantially limited on the $(\phi, \theta)$ plane. The parameter space that well reproduces the width of the edge favors smaller $\theta$ if around $\phi = 0$. The model THIN reproduces the GSS axis at smaller $\theta$ than the greater scale height models. One should consider the possibility that the tendency is due to the difference of the thickness of disc models. As a matter of fact, as described in §3.2, the total mass of our progenitor models is changed even if we simply change the thickness of a disc model. That causes the different rotation velocity for each disc model. Since different rotation velocity of the progenitor’s disc would shift the simulated GSS axis, we expand the parameter space of the model THICK (with keeping $Z_0$) to having different rotation curves.

Fig. 12 shows the result of the additional parameter surveys around $(\phi, \theta) = (5^\circ, 40^\circ)$ that is one of the successful parameters of the model THICK. The larger number in the name of disc model has a disc of faster rotation velocity (Table 2), and smaller $\theta$ comes to favor to reproduce the GSS axis. In addition, the shape of the well-fitted parameter tends to be like that of model THIN (Fig. 9 top-left panel) at the thicker disc model that has a disc of faster rotation velocity.

Additionally, we analyze the successful snapshot using the same way as our previous work (Kirihara, Miki & Mori 2014), as follows. The snapshot is the epoch selected by the condition with a minimum $\chi^2_\nu$ value in its simulation run. $\chi^2_\nu$ value is 1.9 for the analysis of the north–eastern shell and
Figure 9. Top panels: $\chi^2$ analysis of the comparison between the azimuthal angle of the density peak in the observed GSS and that of the simulation runs in each disc model on the plane $(\phi, \theta)$ of the initial inclination of the progenitor’s disc. Middle panels: Results for the comparison of the eastern edge width between the observed data and the simulation data. Colored squares show the value of $\chi^2$ for the simulated parameters. Thick solid, thin solid, and dashed contour describes $1\sigma$, $2\sigma$, and $3\sigma$ confidence intervals of the $\Delta\chi^2$, respectively. Thick red contour describes $1\sigma$ confidence interval of the result of the azimuthal angle of the density peak in the GSS shown in top panels. Bottom panels: The relation between the initial spin axis of the progenitor’s disc on the observed frame and the eastern edge width of the GSS. The color bar shows the inner product value of the normalized line-of-sight vector into the M31’s center and the normalized initial spin vector of the progenitor’s disc. Magenta (green) area means that the disc of the progenitor rotates clockwise (anti–clockwise). At the yellow area, the disc is almost edge-on view from the Earth.

Figure 10. Same as Fig. 9, but for a comparison between the observed western width of the GSS and simulated width.
the western shell ($\Delta \chi^2 = 1.85$ for 2 $\sigma$ level of $v = 14$). By contrast, $\Delta \chi^2 = 21.9$ for the analysis of the surface density ratio among the two shells and the GSS ($\Delta \chi^2 = 19.3$ for 4 $\sigma$ level of $v = 2$). It is possible to change the surface density ratio if we adopt a different density profile for the dark matter halo of M31 (Kirihara, Miki & Mori 2014). Nevertheless, it needs fine-tuning, and more surveys should be performed in additional dimensions not only the mass density profile of the dark matter halo of M31 but also the orbit, more detailed morphology of the progenitor, and the tidal effect of nearby galaxies.

4.6 Line-of-sight velocity distribution
Not only the photometric survey of the RGB stars but also the spectroscopic measurement of the line-of-sight velocity distribution of the GSS has been carried out. The observed area is almost along with the extending direction of the GSS (Ibata et al. 2004). Fig. 13 shows the line-of-sight velocity distribution of the simulated GSS at the best-fitting epoch. The simulated data is the same as in a high-resolution run described in §5.1 (model THICK; $(\phi, \theta) = (15^\circ, 30^\circ)$), and analyzed area is $30^\circ < \theta < 100^\circ$ that is shown in Fig. 2a. We assume the M31 distance of 780 kpc and M31’s heliocentric systemic line-of-sight velocity of $-300$ km s$^{-1}$ (Font et al. 2006). It shows that the line-of-sight velocity distribution of simulation data is consistent with that of the observed data.

5 DISCUSSIONS

5.1 Validity of the model and assumption
For the purpose of a convergence test, we perform high-resolution run for a parameter that reproduces the observed structures (THICK; $(\phi, \theta) = (15^\circ, 30^\circ)$). The total number of particles of the high-resolution run is 1,017,090 that are five times that of the low-resolution runs. Fig. 14 shows the result of the convergence test. Global structures of the low-resolution run are quite similar to the high-resolution run except for some noisy distribution appeared in Fig. 14a. Fig. 14c shows that the azimuthal angle distribution of the GSS in the low-resolution run is in good agreement with that of the GSS in the high-resolution run. Therefore, we consider that our systematic surveys do not contain a resolution problem.

The adopted orbit in this work is consistent with possible parameter space for the infalling orbit of a spherical progenitor galaxy that Miki et al. (2014) evaluated systematically and confirmed.

Kirihara, Miki & Mori (2014) examined the outer density distribution of the dark matter halo of M31. However, their best-fitting parameter also is not able to reproduce the characteristic asymmetric structure of the GSS under the assumption of a merger of a spherical progenitor. In addition, if the morphology of the progenitor is changed, their result could be modified. For this reason, we firstly assume the well-used conditions as the model of M31. The effect of changing the potential of M31 will be examined in future works.

5.2 Progenitor’s DM v.s. M31’s DM
As described in §3.2, progenitor models in this work have a dark matter halo component. Fig. 15 shows the mass fraction of the progenitor origin dark matter to the smoothed dark matter component of M31. The mass distribution of dark matter halo associated with M31 is assumed as described in §3.1. The fraction is around 0.1 even at the highest region. At the edge of the western shell, the mass enhancement of the progenitor’s dark matter is relatively significant in the smooth dark matter halo of M31. It is interesting that the position of the mass-density enhancement of the dark matter component coincides that of the stellar structure at the western shell. However, the fraction is too small to detect even with TMT (Thirty-meter-telescope) with weak lensing method using background halo stars in our rough estimation.

5.3 Metallicity distribution
The metallicity of the GSS is not uniform across the directions that the GSS extends (Ibata et al. 2007; Gilbert et al. 2009). The observed mean metallicity at the “core” region (high-brightness region; outlined with green dashed line in Fig. 16) and “cocoon” region (western envelope; outlined with magenta dashed line in Fig. 16) are $\langle [\text{Fe}/\text{H}] \rangle = -0.54$ and $\langle [\text{Fe}/\text{H}] \rangle = -0.71$, respectively. On the other hand, radial metallicity gradient has been observed in nearby dwarf galaxies with the gradient of $-0.6 < \Delta [\text{Fe}/\text{H}] < 0.2$ (Koleva et al. 2009); defined by the equation following equation:

$$\Delta [\text{Fe}/\text{H}] \equiv \frac{d[\text{Fe}/\text{H}](r)}{d\log[R/R_d]},$$

where $R_d$ is the scale length of the progenitor’s disc. The spatial metallicity distribution of the merger remnants could reveal the initial metallicity gradient of the progenitor galaxy. Actually, Fardal et al. (2008) showed that disc infalling models produce the difference of metallicity in the GSS although the initial radial gradient of the progenitor is quite high $\Delta [\text{Fe}/\text{H}] \sim -1.0$ (read from figure 2b in Fardal et al. (2008) by eyes). In addition, even the case of spherical symmetric progenitor galaxy can make a difference of metallicity in the GSS (Miki, Mori & Rich submitted). However, it
Figure 12. $\chi^2$ analysis for the azimuthal angle of the density peak in the GS S for thick disc models. The detail of the symbols is same as Fig. 9.

Figure 13. Mass density of the line-of-sight velocity distribution of the simulated GSS. Cyan symbols show the analyzed observed data in each field (Ferguson et al. 2004; Kalirai et al. 2006; Gilbert et al. 2009). Each bar on the symbols means the line-of-sight velocity distribution of the stars at the distance.

is also hard for their model to reproduce the observed large difference of the mean metallicity.

To estimate metallicity distribution at the faint regions such as the broad western structure of the GSS, reducing the Poisson noise in the $N$-body simulation is essential. For this purpose, we use 8,136,720 particles that are eight times yet larger than the number of particles in the high-resolution simulation for the convergence test. Other data for the progenitor model are fixed with the convergence test. We perform the numerical simulation using a gravitational octree code optimized for Graphics Processing Units (GPU), GOTHIC (Miki & Umemura in prep.). The code adopts the hierarchical time step with a second-order Runge-Kutta integrator and the multipole acceptance criterion proposed by (Warren & Salmon 1993; Salmon & Warren 1994). The accuracy control parameter $\Delta_{\text{acc}}$ is set to be $2^{-8}$ in the highest resolution run.

As showed in top panels of Fig. 5, most of the disrupted bulge component places on the disc of M31. Therefore, we set a metallicity gradient only to the disc component of the progenitor galaxy. At first, we assume the metallicity gradient of $\Delta [\text{Fe}/\text{H}] = -0.5$ that is consistent with the observed value in dwarf ellipticals (Koleva et al. 2009). Mean metallicity is also set to $\langle [\text{Fe}/\text{H}] \rangle = -0.57$ that is consistent with
the mass-metallicity relation of the nearby dwarf galaxies (Dekel & Woo 2003).

Fig. 16b shows the metallicity distribution of the disrupted disc of the progenitor galaxy. In order to remove extremely faint structures for drawing this figure, we set a simple detection limit and draw Fig. 16c. We assume the total absolute magnitude for the GSS of \( M_V = -14 \) (Ibata et al. 2001) and the limit of apparent magnitude in V-band is 24.5 (detection limit of INT/WFC). It is obvious that the initial radial metallicity gradient produces a clear difference of metallicity distribution to the azimuthal direction of the GSS. Fig. 16c suggests that from the east of the GSS toward the west, the stellar population originates from the center to the outside of the disc of the initial satellite progenitor. Interestingly, such azimuthal difference of metallicity is also revealed at the western shell (see Fig. 16c).

The cocoon region, where the mean metallicity is observed by Ibata et al. (2007) and Gilbert et al. (2009), is too far from the “core” of the GSS and the simulated stellar distribution cover only a small fraction of the observed region. Therefore, a direct comparison between the simulation and the observation would not be appropriate. We, therefore, analyze azimuthal metallicity distribution at the similar radius of the observed data (the distance of 3.5 [degrees] < \( R < 4.5 \) [degrees] from the M31’s center). Fig. 17 shows the azimuthal mean metallicity distribution of the GSS in the case that the mean metallicity of the whole progenitor’s disc is \(-0.5\). The difference of each line is the assumption for the initial metallicity gradient of the satellite galaxy from \(-0.5\) to \(-0.2\). The GSS axis is \( \theta_e \sim 65^\circ \) (see Table 1), and the mean metallicity around this axis is relatively higher and almost the mean metallicity of the whole progenitor’s disc. On the other hand, the mean metallicity at the envelope of the GSS (\( \theta_e \geq 80^\circ \)) is relatively lower. We success to obtain strong difference of metallicity from core region to envelope region of the GSS assuming the metallicity gradient of the progenitor’s disc of around \( \Delta [\text{Fe}/\text{H}] = -0.4 \).

Fardal et al. (2012) observed the mean metallicity in the western shell along the minor axis of the M31 disc, and the value is \( \langle [\text{Fe}/\text{H}] \rangle = -0.7 \). Here, we attempt to fit roughly the simulated mean metallicity to the observed value varying a \( \langle [\text{Fe}/\text{H}] \rangle \) under the condition of smaller \( \Delta [\text{Fe}/\text{H}] = -0.3 \) and larger \( \Delta [\text{Fe}/\text{H}] = -0.5 \) metallicity gradient. The well-fitted values are \( \langle [\text{Fe}/\text{H}] \rangle = -0.62 \) and \( \langle [\text{Fe}/\text{H}] \rangle = -0.57 \) for the case of smaller and larger metallicity gradient, respectively.

We also analyze the azimuthal metallicity distribution at the similar radius of the observed data. Fig. 18 shows the azimuthal and radial metallicity distribution of the GSS and the western shell in the case of \( \langle [\text{Fe}/\text{H}] \rangle \sim -0.5, -0.57 \) and the case of \( \langle [\Delta [\text{Fe}/\text{H}] \rangle \sim -0.3, -0.62 \). In Fig. 16a, we show the analyzed area of azimuthal (red solid outlined regions) and radial (blue dashed outlined regions) mean metallicity distribution for the GSS and those for the western shell. Fig. 18a shows the azimuthal mean metallicity distribution of the GSS. The clearest difference of metallicity is obtained at the radii of 3.5 [degrees] < \( R < 4.5 \) [degrees], The difference of metallicity between core region (\( \theta_e = 65^\circ \)) and envelope region (\( \theta_e = 85^\circ \)) is about 0.25 dex in the case of the higher metallicity gradient model. As Fig. 18b shows, on the other hand, the radial difference of metallicity of the GSS is small in a narrow azimuthal range. Only recently, Conn et al. (2016) observed radial metallicity differences of the GSS. Although their data are averaged in azimuth, our result is qualitatively consistent with the difference of metallicity that in the region near the root of the GSS has a higher value than in the tail region of the GSS. In Fig. 18c, we show azimuthal difference of metallicity of the inside and the outside of the western shell. Inside of the western shell, the difference of metallicity is about 0.2 from south to north. On the other hand, the difference of metallicity is very weak on the out-
Figure 16. (a) Selected region of various analysis. The background is grey scale mass density distribution of the disrupted progenitor galaxy. (b) Metallicity distribution assuming the metallicity gradient of $\Delta[\text{Fe/H}] = -0.5$ and the mean metallicity of $\langle[\text{Fe/H}]\rangle = -0.57$. (c) Metallicity distribution filtered by the detection limit of INT/WFC. Green and magenta dashed lines are "core" and "cocoon" region selected in (Ibata et al. 2007), respectively. Other symbols and line in panels are the same as in Fig. 4a.

Figure 17. Azimuthal mean metallicity distribution of the GSS. The mean metallicity of the progenitor’s disc $\langle[\text{Fe/H}]\rangle$ is set to $-0.5$. The difference of each line is the initial metallicity gradient of $-0.2$ (red line with circles), $-0.3$ (blue line with triangles), $-0.4$ (magenta line with squares), and $-0.5$ (black line with diamonds), respectively.

The universe, MBHs that locate at the center of dwarf galaxies should be wandering in the halo of its host galaxy. The progenitor galaxy of the GSS has the stellar mass of about $10^{9–9.5}M_{\odot}$ in its assumed spherical component. Such galaxies generally have an MBH in their center. In observational scope, the mass of MBHs correlates with the mass or the velocity dispersion of the spherical component such as bulges (Magorrian et al. 1998; Gültekin et al. 2009). The bulge component of the modeled disc progenitors is somewhat less massive than that the spherical model assumed in Miki et al. (2014). The velocity dispersion of the bulge $\sigma_{\text{bulge}}$ is $\sim 50$ km s$^{-1}$, and the mass of MBH is simply estimated to $4 \times 10^5M_{\odot}$ assuming M–$\sigma$ relation (Gültekin et al. 2009). Although it is not our attention in this simulation, it is important to notice that the mass of the bulge component can change by a factor of several when using various bulge–disc ratio and mass-to-luminosity ratio.

In our simulations, it is possible to investigate the current position of the MBH if the progenitor has an MBH in its center initially. Actually, Miki et al. (2014) predicted the current position of the MBH of the progenitor in the halo of M31 including the effect of changing the orbit of the progenitor galaxy of the GSS. The radiation spectrum from the gas surrounding the MBH is estimated based on a reasonable model that is the advection–dominated accretion flow (ADAF) model (Kawaguchi et al. 2014). Their results suggest that the MBH could be observed with radio band telescopes such as currently–operating JVLA and ALMA. In their approach, they assumed a spherical progenitor as the progenitor galaxy of the GSS. It should be noted that the mass of the bulge component can change by a factor of several when using various bulge–disc ratio and mass-to-luminosity ratio.

5.4 Progenitor’s Bulge and Central MBH

Here, we discuss the current position of an MBH that initially located at the center of the progenitor galaxy of the GSS. In the context of hierarchical structure formation of the universe, MBHs that locate at the center of dwarf galaxies should be wandering in the halo of its host galaxy. The progenitor galaxy of the GSS has the stellar mass of about $10^{9–9.5}M_{\odot}$ in its assumed spherical component. Such galaxies generally have an MBH in their center. In observational scope, the mass of MBHs correlates with the mass or the velocity dispersion of the spherical component such as bulges (Magorrian et al. 1998; Gültekin et al. 2009). The bulge component of the modeled disc progenitors is somewhat less massive than that the spherical model assumed in Miki et al. (2014). The velocity dispersion of the bulge $\sigma_{\text{bulge}}$ is $\sim 50$ km s$^{-1}$, and the mass of MBH is simply estimated to $4 \times 10^5M_{\odot}$ assuming M–$\sigma$ relation (Gültekin et al. 2009). Although it is not our attention in this simulation, it is important to notice that the mass of the bulge component can change by a factor of several when using various bulge–disc ratio and mass-to-luminosity ratio.

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its orbital motion with a slow drift velocity. Therefore, the progenitor’s bulge has stayed at around the current position relatively longer. Also, the best-fitting epoch of the simulation runs defined by the edges of the eastern and western shells is not changed so much in the case of the disc progenitor compared to the case of the spherical progenitor. Therefore, our results are consistent with the current position of the MBH predicted by Miki et al. (2014).

One should consider the possibility that the progenitor’s bulge would be a tracer of the MBH and be discovered in surface brightness and/or phase-space mass density distribution. One possibility is a north-eastern clump on the M31’s disc that has been reported by Davidge (2012). The position of the clump is at $(\xi, \eta) = (0.24, 0.20)$ with an effective radius of $\sim 600$ pc. In Fig. 7a, the position and the size of the clump are shown with the red circle. The stellar mass of the clump is estimated to be $3 \times 10^8 M_\odot$ in Davidge (2012), and the mass is consistent with the progenitor’s bulge in our models ($\sim 3 \times 10^8 M_\odot$).

We analyze phase-space distribution around the progenitor’s bulge including M31 bulge and disc. M31 model using $N$-body particles is constructed by MAny-component Galactic Initial-conditions generator (MAGI) (Miki & Umemura in prep.), and the physical quantities are the same with the fixed potential model adopted in this study. Fig. 19 shows phase-space mass-density distribution of the disrupted progenitor galaxy and M31 stars. The analyzed region is inner the white outlined area in Fig. 7a. The clumpy region at $R \sim 15$ kpc is mainly constructed by the bulge component of the progenitor galaxy. Of course, there are several uncertainties such as the total mass of the bulge and orbit of the progenitor, but such a bulge remnant should be detected by integral field spectroscopic and/or photometric observations around the predicted position. In addition, if a high velocity dispersion, due probably to the MBH, at the central region is found, the bulge component would be easily recognized (see, e.g., Seth et al. (2014)).

5.5 Extended stellar shell

Owing to our unprecedented high-resolution simulation for the minor merger, we can predict a faint but huge stellar structure at the outside region of the western shell (see Fig. 16). The origin of this structure is the outermost region of the initial progenitor galaxy. As Fig. 16b and Fig. 18c show, the metallicity in the region is lower than that of the...
GSS and the two shells. On the other hand, the origin of the most western side of the GSS is the more outermost region of the initial progenitor galaxy, and the structure has been observed as a broad western structure of the GSS. The metallicity in the extended shell will also limit the initial metallicity distribution of the satellite progenitor. Estimating the surface brightness of the extended stellar shell is important for further observations.

Here, we summarize the extended stellar shell. The shell has almost flat surface brightness, and it needs about 3–4 magnitude deeper detection limit in V-band compared to the apparent magnitude at the western shell on the minor-axis of the M31’s disc. The stars at the extended stellar shell have relatively poorer metallicity and smaller difference in the azimuthal direction although the simulated western shell has large difference of metallicity in the azimuthal direction. If the metallicity of the extended stellar shell (beyond the currently observed region) is measured by further observations, the model of satellite progenitor will be limited in detail.

5.6 Gas distribution

Observed structures of the GSS favor a rotating disc galaxy as the progenitor. Disc galaxies often have gaseous component. Therefore, there would be gaseous components originated in the progenitor disc galaxy in the halo of M31. H\textsc{i} observations around the disc of M31 have pointed out \textsc{h}i high-velocity clumps that align with the GSS offset by ~ 15 kpc has a similar line-of-sight velocity as the GSS (Westmeier, Braun & Thilker 2005; Westmeier, Brüns & Kerp 2008; Lewis et al. 2013). Only recently, another gaseous component is detected on the GSS using an absorption spectra of a background Active Galactic Nuclei source (Koch et al. 2015). In addition, a star-formation ring and spirals of the M31’s disc could also be formed due to a recent gaseous interaction (Gordon et al. 2006). These conditions put us in mind of past gaseous interaction of a gas-rich progenitor. It needs hydrodynamical simulation of the interaction to investigate the origin of the mysterious high-velocity clouds.

6 SUMMARY

Owing to the detailed simulations of the merger and comparison with observed data, physical quantities of M31 and the infalling progenitor such as M31’s potential, orbit of the progenitor, and mass of the progenitor have been well limited. However, the morphology (and the dynamics) of the progenitor of the GSS has been left so far. A simple analysis of stellar count maps of the GSS in the halo of M31 provides a characteristic asymmetric surface brightness profile across the GSS. The structure would be a probe of the morphology of the GSS progenitor, and we perform the first large systematic survey of a minor merger with a disc satellite progenitor galaxy.

We obtain a parameter space that well reproduces the asymmetric surface brightness of the GSS on the plane (\(\phi, \theta\)), which is the degree of the initial disc inclined. The thick disc model (\(R_d = 1.1\) kpc, \(Z_d = 0.52\) kpc) favors to reproduce the structure. It is difficult that dynamically hot disc model reproduces the eastern edge of the GSS because the velocity dispersion of the disc makes it broader. On the other hand, it is hard for the thinner disc model to reproduce the broad western structure due to the too dynamically cold component.

Here, for further observations, we summarize our four predictions owing to the high-resolution simulations. Firstly, the current position of the progenitor’s bulge is in the eastern shell and foreground of the disc of M31, and it is possible to distinguish the progenitor’s bulge from the M31’s disc using phase-space mass density distribution. Secondly, clear metallicity differences of the merger remnants are expected. The GSS has a clear difference of metallicity in the azimuthal direction at around 3.5 [degrees] < \(R < 4.5\) [degrees]. In addition, the western shell also has a clear difference of metallicity in the azimuthal direction. Thirdly, we predict an extended stellar shell on the outside of the western shell. In our model, it is possible to detect this extended shell if we attain photometric observation with about 3–4 magnitude deeper detection limit in V-band compared to the apparent magnitude at the western shell on the minor-axis of the M31’s disc. Finally, the stellar population of the extended shell is clearly different from that of the western shell, and it will limit the progenitor’s model in detail if the metallicity is observed.

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