Origin of rotational kinematics in the globular cluster system of M31: a new clue to the bulge formation

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ABSTRACT
We propose that the rotational kinematics of the globular cluster system (GCS) in M31 can result from a past major merger event that could have formed its bulge component. We numerically investigate kinematical properties of globular clusters (GCs) in remnants of galaxy mergers between two discs with GCs in both their disc and halo components. We find that the GCS formed during major merging can show strongly rotational kinematics with the maximum rotational velocities of $\sim 140-170$ km s$^{-1}$ for a certain range of orbital parameters of merging. We also find that a rotating stellar bar, which can be morphologically identified as a boxy bulge if seen edge-on, can be formed in models for which the GCSs show strongly rotational kinematics. We thus suggest that the observed rotational kinematics of GCs with different metallicities in M31 can be closely associated with the ancient major merger event. We discuss whether the formation of the rotating bulge/bar in M31 can be due to the ancient merger.

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

1 INTRODUCTION
The structural and kinematical properties of globular cluster systems (GCSs) are considered to provide valuable information on the formation and evolution of their host galaxies (e.g. Searle & Zinn 1978; Romanowsky et al. 2009). Recent observational studies on kinematical properties of GCSs in galaxies and their comparison with theoretical and numerical works have advanced our understanding on mass distributions of galaxies (e.g. Pierce et al. 2006; Romanowsky et al. 2009), formation of elliptical galaxies (e.g. Bekki et al. 2005), and formation and evolution of dwarf galaxies (e.g. Beasley et al. 2009). A growing number of observational data sets on kinematical properties of GCSs have been now accumulated not only for galaxies in the Local Group, but also for nearby galaxies (Brodie & Strader 2006 for a recent review) so that we can discuss formation processes of their host galaxies and their dependences on galactic global properties (e.g. Hubble types) in more detail based on the observations.

One of the intriguing properties of GCSs in galaxies is the observed rotational kinematics of the GCS in M31 (e.g. Huchra, Stauffer & van Speybroeck 1982; Perrett et al. 2002). Recent wide-field surveys of the GCS in M31 (Lee et al. 2008) have confirmed that the GCS composed both of metal-poor ([Fe/H] $< -0.9$ in their criterion) and metal-rich ([Fe/H] $> -0.9$) objects has a rotational amplitude of $\sim 190$ km s$^{-1}$. Such kinematics are in a striking contrast with the low rotation of the Galaxy’s GCS (e.g. Armandroff 1989) with an origin that remains unclear.

The purpose of this Letter is to discuss (i) why the GCS of M31 shows such a large amount of rotation and (ii) what implications it has for the formation and evolution of M31. Previous numerical works showed that rotational kinematics of GCSs in elliptical galaxies can be due to past major merger events that formed the galaxies (e.g. Hernquist & Bolte 1993; Bekki et al. 2005). We thus consider that the rotational kinematics of the GCS is closely associated with a major merger event in M31 long ago, and thereby investigate whether galaxy merging can reproduce well the observed kinematics of the GCS. We also discuss whether the observed rotating bulge/bar in the M31 (e.g. Beaton et al. 2007) can be due to the major merger event responsible for the formation of the GCS with rotational kinematics.

2 THE MODEL
Since the numerical methods and techniques we employ for modelling dynamical evolution of mergers between two discs with GCs have already been detailed elsewhere (Bekki et al. 2005; Bekki & Forbes 2006), we give only a brief review here. The progenitor disc galaxies that take part in a merger are given a dark halo, a thin exponential disc, and GCs initially in discs (referred to as ‘DGCs’ from now on) and in haloes (‘HGCs’). The total mass and size of an exponential disc with no bulge are $M_d$ and $R_d$, respectively.
We consider that the total stellar mass of a merger remnant should be similar to the total mass \((M_s)\) of the present bulge of M31 \((M_s = 3 - 4 \times 10^{10} \, M_\odot\); e.g. Geehan et al. 2006; Seigar, Barth & Bullock 2008). We thus adopt \(M_d = 2 \times 10^{10} \, M_\odot\) as a reasonable value in the present study. We adopt the density distribution of the NFW halo (Navarro, Frenk & White 1996) and a concentration parameter determined by \(M_{dm}\) according to the formula derived by recent cold dark matter simulations (e.g. Neto et al. 2007). The stellar disc has the scale length \((R_d)\) of 0.2\(R_d\).

The present bulge-less disc model would be reasonable for less massive disc galaxies with no/little bulges like the Large Magellanic Cloud and Magellanic-type galaxies with total masses of \(\sim 10^{10} \, M_\odot\), but it would not be so realistic for luminous disc galaxies like the merger progenitor discs of M31. We however conjecture since the bulge masses are quite small in comparison with total masses of galaxies (inclusive of dark matter haloes), final kinematics of GCs in merger remnants would not depend strongly on whether or not we include bulges in initial discs. Thus, as long as we mainly discuss global kinematical properties of GCs in merger remnants, the present model can be regarded as an appropriate one.

Previous observations revealed that less luminous disc galaxies, which are considered to form the bulge component of M31 with rotational kinematics of the GCS in the present study, have discy distributions with rotational kinematics in their GCs (e.g. Freeman, Illingworth & Oemler 1983; Olsen et al. 2004). We thus consider the presence of DGCs in merger progenitor discs in the present study: DGCs were not considered in our previous works (e.g. Bekki et al. 2003a, 2005) and such DGCs with strongly rotational kinematics are not observed in the metal-rich GCs of the Galaxy. The DGCs have the same exponential distribution and rotational kinematics as field stars in the stellar disc of their host galaxy. The initial rotational amplitude of DGCs is \(\sim 170 \, \text{km s}^{-1}\) for \(M_d = 2 \times 10^{10} \, M_\odot\) and \(M_{dm}/M_d = 9\).

The Galactic HGCs and the stellar halo have similar radial density profiles of \(\rho \propto r^{-3.5}\) (van den Bergh 2000). We therefore assume that the HGCs in our galaxies have a power-law profile with an exponent of \(-3.5\) and a half-number radius of 1.4\(R_d\) (which is \(\sim 5 \, \text{kpc}\) for the Galaxy and thus consistent with observations). The HGCs are assumed to have isotropic velocity dispersions determined by the mass distribution of the galaxy. Total numbers of DGCs and HGCs in a galaxy are set to be 100 and 100, respectively.

The mass ratio of the two discs \(m_2\) in a merger is assumed to be a free parameter. In all of the simulations of pair mergers, the orbit of the two discs is set to be initially in the \(x\)\(\,y\) plane and the distance between the centre of mass of the two discs is assumed to be 12\(R_d\). The pericentre distance \((r_p)\) and the eccentricity \(e_p\) in a pair merger are assumed to be free parameters that control orbital energy and angular momentum of the merger. The spin of each galaxy in a merger is specified by two angles \(\theta_i\) and \(\phi_i\), where suffix \(i\) is used to identify each galaxy, \(\theta_i\) is the angle between the \(z\) axis and the vector of the angular momentum of a disc. \(\phi_i\) is the azimuthal angle measured from the \(x\) axis to the projection of the angular momentum vector of a disc on to the \(xy\) plane.

We mainly show the results of ‘the standard model’ with \(M_d = 2 \times 10^{10} \, M_\odot\), \(M_{dm}/M_d = 9\), \(r_p = 2R_d\), \(e_p = 0.72\), \(\theta_1 = 30^\circ\), \(\theta_2 = 45^\circ\), \(\phi_1 = 45^\circ\) and \(\phi_2 = 120^\circ\). We describe the results of this standard model with an orbital configuration similar to ‘prograde–prograde’ merging (in which the orbital spin axis of the merger is parallel to intrinsic spin axes of the two discs), mainly because the final GCS can clearly show strongly rotational kinematics as observed in M31. We also show the results of the model with a ‘prograde–retrograde’ orbital configuration in which \(\theta_2 = 225^\circ\) and other parameters are exactly the same as those in the standard model.

In order to discuss the origin of the central bar/bulge of M31, we investigate in which models the merger remnants show rotating stellar bars. Although we investigate 34 models, we show the results of five representative models which either show clearly rotating bars or have no such rotating components in merger remnants: comparison between these models enables us to understand better the role of an ancient merger event in the formation of the bulge component in M31.

The model parameters and some brief results are given in Table 1. The total particle number for a major merger in a simulation is \(10^9\) and the simulation is carried out on the latest version of GRAPE (GRAVITY PipE, GRAPE-7) which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990). In estimating the GCS kinematics, the merger remnant is viewed near to edge-on, and binned major-axis profiles are constructed. In order to have enough objects in each bin, GCs at all minor axis distances are included, which also approximately replicates the comparison observations. Formation of metal-rich GCs through dissipative gas dynamics of galaxy merging (e.g. Bekki et al. 2002) and adiabatic contraction of the GCS in M31 due to later massive growth of the disc component could increase appreciably the rotational amplitude \(V\) of the GCS. The quantitative estimation of this effect is not done here and will be done in our future studies. It should be stressed that this Letter is meant to be schematic rather than reproducing the observed galaxy in a fully self-consistent manner.

| Model | \(M_{dm}/M_d\) | \(m_2\) | \(r_p(\times R_d)\) | \(e_p\) | Orbital | \(V_{\text{max, DGC}}\) (km s\(^{-1}\)) | \(V_{\text{max, HGC}}\) (km s\(^{-1}\)) | Comments |
|-------|----------------|--------|-----------------|--------|---------|-----------------------|-----------------------|----------|
| 1     | 9              | 1.0    | 2.0             | 0.72   | PP      | 136                   | 123                   | The standard model |
| 2     | 9              | 1.0    | 2.0             | 0.72   | PR      | 114                   | 133                   |                      |
| 3     | 9              | 1.0    | 1.0             | 0.85   | PP      | 95                    | 92                    |                      |
| 4     | 9              | 0.5    | 2.0             | 0.72   | PP      | 107                   | 38                    | Unequal-mass merger |
| 5     | 19             | 1.0    | 2.0             | 0.72   | PP      | 174                   | 91                    |                      |

*\(a\)The mass ratio of dark matter halo to stellar disc in a galaxy.

*\(b\)The mass ratio of two discs in a galaxy merger.

*\(c\)The pericentre distance of a merger in units of the disc size \(R_d\).

*\(d\)The orbital eccentricity of a merger.

*\(e\)‘PP’ and ‘PR’ represent prograde–prograde and prograde–retrograde merging, respectively.

*\(f\)The maximum rotational velocity of DGCs (GCs initially in discs) in a merger remnant.

*\(g\)The maximum rotational velocity of HGCs (GCs initially in haloes) in a merger remnant.
3 RESULTS

Fig. 1 shows that both DGCs and HGCs can be spatially mixed to form a new GCS during violent dynamical relation that results in transformation from two discs into one spheroidal galaxy. Owing to angular momentum redistribution during major merging, not only HGCs but also DGCs can be transferred to the outer halo region and thus seen there in the merger remnant. The half-number radii for the DGCs and the HGCs are both $\sim 5.0$ kpc in the merger remnant, which is consistent with the observations by Battistini et al. (1993). As the stellar remnant shows a rotating bar (discussed later in Section 4), DGCs and HGCs also show barred structures, appreciably flattened shapes (qualitatively consistent with observations), and figure rotation.

Fig. 2 clearly shows global rotation both in DGCs and HGCs, though the radial profiles of $V$ and $\sigma$ do not smoothly change owing to the small numbers of GCs at each bin. The maximum $V(V_{\text{max}})$ and $\sigma(\sigma_{\text{max}})$ for DGCs (HGCs) within the central 16 kpc are $136 \pm 20$ km s$^{-1}$ ($123 \pm 13$ km s$^{-1}$) and $102 \pm 15$ km s$^{-1}$ ($106 \pm 16$ km s$^{-1}$), respectively. Therefore, $V_{\text{max}}/\sigma_{\text{max}}$ for DGCs and HGCs is 1.3 and 1.2, respectively, which means that the final GCS has strongly rotational kinematics. The velocity profile becomes flat ($V \sim 100$ km s$^{-1}$) at $R \sim 4$ kpc. The simulated two-dimensional line-of-sight velocity map of the GCS shows clearly global rotation.

We here compare the simulated rotational kinematics with the observed one in M31 (e.g. $V = 138 \pm 13$ km s$^{-1}$ in Perrett et al. 2002). Observational error bars in $V$ are not so small, and $V$ ranges from 98 to 188 km s$^{-1}$ for $0 \leq |Y| \leq 5$ kpc (Lee et al. 2008), where $|Y|$ is the projected vertical distance from the M31 disc plane. The simulated rational amplitude of the GCS is slightly smaller than the observed one by Perrett et al. (2002): it should be noted that the observational results depend on the details of how the data are binned and fitted.

We consider that the best model needs to reproduce the above $V$ of $\sim 140$ km s$^{-1}$. Fig. 3 shows that even the dark matter halo of the merger remnant can have a small amount of rotation ($V \sim 34$ km s$^{-1}$) owing to the redistribution of angular momentum (i.e. conversion of orbital angular momentum of merging two galaxies into internal one of the merger remnant). This result suggests that if the two galaxies have hot gaseous haloes, then the remnant is highly likely to have a slowly rotating gaseous halo. Fig. 3 also shows that the stellar component of the merger remnant has a significant amount of rotation ($V_{\text{max}} \sim 100$ km s$^{-1}$), which means that the spheroid is rapidly rotating (i.e. rotating bulge is formed from major merging).

The reason for the smaller $V$ of the dark matter halo in comparison with the GCS is due largely to the difference in the initial spatial distribution between the halo and the GCS, demonstrating that GC rotation would not be used to infer dark matter halo rotation. The inner part of the merger can more strongly spin-up during and after major merging owing to (i) the prograde–prograde orbital
configuration of the merging and (ii) the development of the rotating bar. The distribution of the GCS in the merger progenitor disc is by a factor of 4 more compact than that of the halo so that the GCS can more strongly spin-up: most of the individual GCs can obtain a larger amount of intrinsic spin angular momentum with respect to the centre of the merger remnant.

Fig. 4 shows that strongly rotational kinematics of GCs can be seen only in DGCs in the model with \( m_2 = 0.5 \) (model 4): \( V_{\text{max}} \) is 107 km s\(^{-1}\) for DGCs, and 38 km s\(^{-1}\) for HGCs. The higher and lower \( V_{\text{max}} \) in DGCs and HGCs, respectively, are confirmed in other unequal-mass merger models (e.g. \( m_2 = 0.3 \)). It should be noted here that the model 1 shows only slightly higher \( V_{\text{max}} \) in DGCs, which is due to different kinematics between DGCs and HGCs (i.e. initial global rotation only in DGCs). These results therefore mean that if metal-poor and metal-rich GCs originate from HGCs and DGCs, respectively, then kinematical properties of GCs in the remnants of galaxy merging with smaller \( m_2 \) (or unequal-mass merging) can be significantly different between metal-poor and metal-rich ones. These results furthermore imply that the observed rotational kinematics both for metal-poor and metal-rich GCs in M31 can give some constraints on the mass ratio (\( m_2 \)) of two discs in galaxy merging that could have occurred in M31.

The model 1 does not explain well the observed total halo mass: later numerous accretion events of dwarfs with GCs and stars are required to increase significantly the total mass after the merging. The models with larger \( M_{\text{DM}}/M_2 \) can show higher \( V_{\text{max}} \) in DGCs owing to the initially higher circular velocities of the stellar discs. For example, the model with \( M_{\text{DM}}/M_2 = 19 \) (model 5) shows \( V_{\text{max}} = 174 \) km s\(^{-1}\) and \( \sigma_{\text{max}} = 134 \) km s\(^{-1}\): it should be stressed here that the total mass of the remnant is \( 8 \times 10^{11} \) M\(_{\odot}\); thus, it can be more consistent with observations than model 1 in terms of the total mass of M31. A possible reason for the lower \( V_{\text{max}} \) (91 km s\(^{-1}\)) for HGCs in the model 5 is that more strongly self-gravitating stellar discs can also play a role in increasing global rotation of HGCs: such a role is weaker in the model 5 in which the disc is much more weakly self-gravitating.

Models with different orbital configurations can show stronger rotational kinematics in DGCs and HGCs, if larger \( r_p \) is adopted. For example, the model with a prograde–retrograde orbital configuration (model 2) shows \( V_{\text{max}} = 114 \) km s\(^{-1}\) and \( \sigma_{\text{max}} = 102 \) km s\(^{-1}\) but does not show a bar. The models with smaller \( r_p \) (e.g. model 3) show smaller \( V_{\text{max}} \) in DGCs, which implies that the observed \( V_{\text{max}} \) can give some constraints on the orbital parameters for galaxy merging that occurred in M31. Thus, only the models with larger \( r_p \) can better reproduce the observed kinematical properties of the M31 GCS.

4 DISCUSSION AND CONCLUSIONS

Fig. 5 shows that the stellar remnant looks like a bar if it is viewed from face-on in the standard model of the present study: the bar is confirmed to have figure rotation. The stellar distribution viewed from edge-on appears to have a flattened spherical body, which can be identified as a bulge. The present study thus implies that M31’s observed bulge/bar (e.g. Beaton et al. 2007) can be formed from an ancient major merger event. It should be noted here that dissipative gas dynamics can which determine the final morphological properties of merger remnants (e.g. boxy or discy shapes) is not included in the present study.

If the inner bar/bulge of M31 was really formed from ancient major merging before its disc formation, then the later development of the stellar and gaseous disc may well be significantly influenced by dynamical action of the already formed bar. Also, later slow gas accretion and the resultant disc formation in M31 could change structural and kinematics properties of the already developed GCS to some extent: it would be possible that adiabatic compression of the GCS by later gradual development of the disc can enhance the rotational amplitude of the GCS. It is our future study to numerically investigate disc formation and evolution of M31 under the presence of the already formed bar.

The present work suggests that the hot diffuse halo gas recently detected by Chandra (Li & Wang 2007) can have a significant amount of rotation resulting from angular momentum redistribution of the possible major merger. Furthermore, the observed extensive HI cloud population of M31 (e.g. Thilker et al. 2004; Westmeier et al. 2007) can also have rotational kinematics if they originate from stripped HI gas from the merger progenitor discs. Given that major merging can form very extended stellar haloes (Bekki, Harris & Harris 2003b; Bekki & Peng 2006), the observed extended stellar halo in M31 (e.g. Ibata et al. 2007) would have fossil information in the possible ancient major merger event.

If M31 was formed from multiple and sequential merging of dwarf satellites from random directions, it seems to be highly unlikely that the final GCS has a large amount of global rotation. Therefore, if the rotational kinematics of the GCS derived from previous observations is further confirmed by ongoing observational studies, it then suggests that a dramatic physical process is responsible for the observed globally organized motion of GCs.
Our simulations imply that an ancient major merger of two discs with GCs with different metallicities could be responsible for the enigmatic kinematics of the GCS in M31, as well as the inner bar or bulge.

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