MERGING BETWEEN A CENTRAL MASSIVE BLACK HOLE AND A COMPACT STELLAR SYSTEM: A CLUE TO THE ORIGIN OF M31’s NUCLEUS

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ABSTRACT

The central bulge of M31 is observed to have two distinct brightness peaks with the separation of ~2 pc. S. Tremaine recently proposed the new idea that M31’s nucleus is actually a single thick eccentric disk surrounding the central supermassive black hole. In order to explore the origin of the proposed eccentric disk, we numerically investigate the dynamical evolution of a merger between a central massive black hole with a mass of \( \sim 10^7 M_\odot \) and a compact stellar system with a mass of \( \sim 10^6 M_\odot \) and size of a few parsecs in the central 10 pc of a galactic bulge. We find that the stellar system is destroyed by the strong tidal field of the massive black hole and consequently forms a rotating nuclear thick stellar disk. The orbit of each stellar component in the developed disk is rather eccentric with a mean eccentricity of \( \sim 0.5 \). These results imply that M31’s nuclear eccentric disk proposed by Tremaine can be formed by merging between a central massive black hole and a compact stellar system. We furthermore discuss when and how a compact stellar system is transferred into the nuclear region around a massive black hole.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: individual (M31) — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

Since high-resolution photographs by the Stratoscope II balloon-borne telescope first resolved the nucleus of M31 (Light, Danielson, & Schwarzchild 1974), the origin of the peculiar nature of M31’s nucleus has been extensively investigated both observationally and theoretically. In particular, the asymmetry of the central brightness peak of M31 was observationally investigated in various bands, and the origin of the asymmetry was extensively discussed (e.g., Light et al. 1974; Nieto et al. 1986; Mould et al. 1989; Bacon et al. 1994). Recent observational studies by the Hubble Space Telescope (HST) have revealed that M31’s central bulge has two distinct brightness peaks with a separation of about 1.7 pc (Lauer et al. 1993; King, Stanford, & Crane 1995). The component with the lower surface brightness (represented by P2) coincides with the bulge photocenter, whereas the higher surface brightness (and off-center nuclear) component (P1) coincides with the nuclear core revealed by the Stratoscope (Lauer et al. 1993; King et al. 1995). Furthermore, a growing number of spectroscopic studies have accumulated that can reveal the detailed kinematics of M31’s nuclear region (e.g., Dressler & Richstone 1988; Kormendy 1988; Bacon et al. 1994; van der Marel et al. 1994). One of the most remarkable results of these is that, although the nuclear rotation curve is symmetric with the peak nearly coincident with P2, the profile of the velocity dispersion is not symmetric (e.g., Bacon et al. 1994).

Although a few ideas (e.g., partial dust obscuration and a separated P1 stellar system) are suggested by Lauer et al. (1993) and Bacon et al. (1994) as plausible explanations of the asymmetries observed in M31’s nucleus, these are suggested to be implausible from simple dynamical arguments (Tremaine 1995). Recently, Tremaine (1995) proposed that the nucleus of M31 is actually a thick eccentric disk composed of stars traveling on nearly Keplerian orbits around a massive black hole (MBH) (or dark compact object). Tremaine (1995) furthermore suggested that this eccentric disk model can clearly explain the rotation curve and asymmetric dispersion profile revealed by recent ground-based spectroscopic observations. Kormendy & Bender (1999) confirmed that Tremaine’s model is very consistent with M31’s structural and kinematical properties revealed by HST photometric studies and ground-based spectroscopic ones. Although several ideas as to why M31’s nuclear disk should be eccentric are discussed (Tremaine 1995), it remains highly uncertain how such a stellar disk can be formed in the nuclear region of M31’s bulge.

The purpose of this Letter is to investigate numerically merging between a central massive black hole with a mass of \( \sim 10^7 M_\odot \) and a compact stellar system with a mass of \( \sim 10^6 M_\odot \) and size of a few parsecs. We demonstrate that tidal disruption of the stellar system by the massive black hole in the nuclear region of M31 is important for the formation of M31’s nuclear eccentric disk proposed by Tremaine (1995). We also show eccentricity distribution of stars in the developed disk and structural and kinematical properties of the disk. Not all of the fundamental structural and kinematical properties of M31’s nuclei can be clearly explained by the present model owing to some limitations of the model. However, we consider that the present study provides a new clue to the origin of the proposed nuclear eccentric disk, because there are only a few extensive numerical studies (e.g., Charlton & Laguna 1995; Emsellem & Combes 1997) addressing the origin of the suggested nuclear thick disk of M31.

2. MODEL

We consider a purely dissipationless merger between a central MBH with mass \( M_{\text{BH}} \) and a compact stellar system (simply, a cluster) with mass \( M_{\text{cl}} \) in the central region of a galactic bulge. Both the MBH and the cluster are assumed to feel the fixed external gravitational field of the bulge component. The MBH is assumed to be initially located at the center of the bulge, and the initial separation between the MBH and the cluster is set to be \( r_{\text{ini}} \). From now on, all the mass and length are measured in units of \( M_{\text{BH}} \) and \( R_{\text{BH}} \), respectively, unless specified. Velocity and time are measured in units of \( v = (GM_{\text{BH}}/R_{\text{BH}})^{1/2} \) and \( t_{\text{dyn}} = (R_{\text{BH}}/GM_{\text{BH}})^{1/2} \), respectively, where \( G \) is the gravitational constant and assumed to be 1.0 in the present study. If we adopt \( M_{\text{BH}} = 10^7 \) (\( 10^8 \)) \( M_\odot \) and \( r_{\text{ini}} = 10 \) pc as a fiducial value, then...
The characteristic radius of the bulge, we adopt the universal profile proposed by Navarro, Frenk, & White (1996). We assume that the scale length (or the characteristic radius \( r_\text{c} \)) is equal to 10\( R_\text{in} \) and determine the central density so that the total mass of the bulge within 200\( R_\text{in} \) (\( \sim 2 \) kpc) is 200\( M_\text{BH} \). The adopted ratio of bulge mass to MBH mass is well within a reasonable value derived by Faber et al. (1997). The total mass of the bulge within \( R_\text{in} \) is hereafter represented by \( M_\text{gal} \). We use the so-called Plummer model with the scale length of 0.04\( R_\text{in} \) for the initial density profile of the cluster. For the fiducial model, the mass ratio \( M_\text{t}/M_\text{BH} \) and \( M_\text{gal}/M_\text{BH} \) are set to be 0.1 and 0.3, respectively. The mean mass density of the cluster is rather high (\( \sim 10^2 M_\odot \text{ pc}^{-3} \)) and similar to that of a possibly young compact stellar cluster (e.g., object 1) found in the central region of Arp 220 (Shaya et al. 1994).

The initial orbital plane of the merger is assumed to be exactly the same as the \((x, y)\)-plane. Initial \( x \) and \( y \) positions \((x, y)\) are set to be \((0, 0)\) for the MBH and \((1, 0)\) for the cluster in all models. Initial \( x \) and \( y \) velocity \((V_x, V_y)\) is set to be \((0, 0)\) for the MBH and \((-0.5V_{\text{cir}}, 0.75V_{\text{cir}})\) for the cluster in the fiducial model, where \( V_{\text{cir}} \) is the circular velocity (1.14 in our units) at the radius of \( R_{\text{in}} \). The number of particles for the cluster is 10,000, and the parameter of gravitational softening is set to be fixed at \( 4.7 \times 10^{-3} \) in our units for all the simulations. All the calculations related to the above dynamical evolution have been carried out on the GRAPE board (Sugimoto et al. 1990) at the Astronomical Institute of Tohoku University. Using the above model, we mainly describe structural and kinematical properties of the merger remnant in the fiducial model. We furthermore investigate the distribution of orbital eccentricity \((e)\) of the merger remnant in order to confirm whether the remnant is an eccentric disk. Here \( e \) for each stellar particle is defined as

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e = \frac{r_{\text{apo}} - r_{\text{peri}}}{r_{\text{apo}} + r_{\text{peri}}},
\]

where \( r_{\text{apo}} \) and \( r_{\text{peri}} \) are apogalactic and perigalactic distances from the center of the bulge, respectively. The eccentricity distribution of the merger remnant (i.e., a stellar disk around the MBH) derived in the present study does not change so significantly for the timescale of \( 10^5-10^7 \) yr. Moreover, we summarize briefly the dependence of mass distribution of the merger remnant on the initial merger parameters such as \( M_\text{BH}, V_x \), and \( V_y \). More details on the parameter dependences will be described in our future papers.

3. RESULT

Figure 1 shows the time evolution of mass distribution of a stellar cluster in the present merger model. As the cluster comes close to the MBH, some fraction of stars is tidally stripped away from the cluster and consequently forms inner, very low density eccentric ringlike structures \((T = 2.0)\). When the cluster passes by the pericenter of the merger orbit, it suffers severely from the strong tidal gravitational field of the MBH and is consequently distorted greatly \((T = 3.2)\). As a result of this, the cluster spherical shape is transformed into a thick flattened disk with the morphology looking like a crescent \((T = 3.2)\). During this morphological transformation, the initial orbital angular momentum of the merging cluster is efficiently changed into the intrinsic angular momentum of the forming disk around the MBH. Finally, a rotating thick stellar disk with a small central hole (i.e., a central very low-density region) is formed around the MBH \((T = 4.0)\). The vertical scale height of the developed thick disk depends on the initial half-mass radius of the cluster.
As is shown in the upper left panel of Figure 2, the orbits of stars are more likely to be rather elongated, and the mean orbital eccentricity is estimated to be about 0.55. Most stars located at \( R < R_{\text{int}} (= 1.0) \), where \( R \) is the distance from the center of the bulge, show \( e > 0.5 \) and accordingly form the peak around 0.8 in the distribution. Stars at \( R > R_{\text{int}} \) on the other hand, show moderately small eccentricity (\( e < 0.3 \)). These results clearly demonstrate that the inner thick disk formed by merging is composed mainly of stars with eccentric orbits. As is shown in Figure 2 for \( T = 4.0 \), the developed disk shows strong asymmetry in structural and kinematical properties. The radial density profile shows double peaks owing to the hole formed during tidal interaction between the MBH and the cluster. The rational velocity rapidly increases along the \( x \)-axis for \( 0 < R < 0.2 \), rapidly decreases for \( 0.2 < R < 0.6 \), and again increases gradually for \( 0.6 < R \). The peak of the velocity dispersion does not coincide with the center of the bulge [i.e., \( (x, y) = (0, 0) \); the peak is close to the location of the MBH [i.e., \( (x, y) = (0.9, 0.14) \)] rather than to the bulge center at \( T = 4.0 \). The derived structural and kinematical properties of the nuclear disk are qualitatively similar to those observed by Kormendy & Bender (1999) for M31.

Figure 3 briefly summarizes the parameter dependences of final mass distribution of mergers. Models described in Figure 3 all fail to form a nuclear thick disk after merging and tidal interaction and thus show the following four physical conditions required for the formation of the disk around the MBH. First, \( M_{\text{BH}} \) should be much (~10 times) larger than \( M_\odot \) so that the MBH can tidally disrupt a cluster during merging. Second, the initial orbit of a cluster should be rather elongated (i.e., small pericenter distance) so that a cluster can be well within the tidal radius of the MBH during tidal interaction. Third, merging rather than simple tidal interaction between an MBH and a cluster is necessary (we here note that even for the tidal interaction, an eccentric ringlike object can be formed). Fourth, the initial impact parameter (or pericenter distance) should not be so small that the cluster cannot be completely destroyed and randomly dispersed. These required conditions imply that even if merging or tidal interaction between an MBH and a cluster frequently occurs in the central region of a bulge, the bulge does not necessarily contain a nuclear thick stellar disk.

4. DISCUSSION

Although the present study shows one possible mechanism for the formation of a thick stellar disk around the MBH of M31, there is one important remaining question: What is the progenitor of a compact stellar system that can finally evolve into M31’s nuclear disk? We here suggest the following three promising candidates. The first is an old and relatively metal-poor globular cluster system. Tremaine, Ostriker, & Spitzer (1975) demonstrated that globular clusters passing near the center of M31 spiral into the center of M31 owing to dynamical friction and consequently are tidally disrupted there to form a distinct high-density nucleus. This demonstration leads us to propose that a globular cluster spiraling into the surrounding MBH is a likely candidate for the progenitor stellar system. The second candidate is a massive clump that is composed of gas and stars and is developed in M31’s disk. Shlosman & Noguchi (1993) found that if the gas mass fraction of a globally unstable disk is larger than 0.1, massive gas clumps (with masses of \( \sim 10^7 M_\odot \)) formed from local gravitational instability can be transferred into the central inner kiloparsec owing to dynamical friction. Noguchi (1998) furthermore demonstrated...
that these massive clumps are more likely to be formed in the early disk formation phase when disk galaxies have a larger amount of gas. These numerical studies imply that if star formation very efficiently proceeds in the gas clumps, the compact stellar system can reach the surrounding of M31’s MBH.

The third candidate is a young massive star cluster that is similar to those observed in infrared luminous major mergers such as Arp 220. Shaya et al. (1994) revealed a number of bright and possibly young star clusters in the core of Arp 220 and suggested that these clusters can be very quickly transferred to the inner 10 pc within an order of 10^6 yr owing to dynamical friction. Based on the metallicity distribution and global structure of M31’s stellar halo, Freeman (1999) suggested that M31’s bulge was formed by the past merging events. Accordingly, it is not unreasonable to say that young massive clusters newly created in the epoch of M31’s bulge formation by major merging (at relatively high redshift) can be transferred to the inner parsec region around the MBH. Since the nature of the stellar population can be greatly different between the above three candidates (very old and metal-poor for the first, young and metal-rich for the second, and relatively old and metal-rich for the third), the most plausible and realistic candidate of the progenitor can be determined if the age and metallicity distribution of the stellar components in M31’s nuclear disk is investigated in detail. Kormendy & Bender (1999) found that the stellar population of the P1 nucleus is more similar to that of P2 than it is to the bulge or to a globular cluster. This result strongly suggests that it is unlikely that M31’s eccentric disk consists of accreted old stars. Lauer et al. (1998) furthermore revealed that the P2 nucleus shows the spectral energy distribution consistent with late B–early A stars and thus can have relatively young stellar populations. Although these observational results seem to imply that the above second candidate is the most promising for the progenitor object of M31’s nuclear disk, observational results have not accumulated so as to reveal clearly the nature of the stellar population of M31’s nucleus. Thus, more detailed spectroscopic studies that can clarify the age and metallicity distribution will provide valuable information on the origin of M31’s nucleus.

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