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ON THE FORMATION OF AN ECCENTRIC DISK VIA DISRUPTION OF A BULGE CORE NEAR A MASSIVE BLACK HOLE

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ABSTRACT

We consider the possibility that an infalling bulge or stellar cluster could form an eccentric disk following tidal disruption by a massive black hole in the center of a galaxy. As a function of central black hole mass, we constrain the core radii and central densities of cluster progenitors capable of becoming nearly Keplerian disks that can support lopsided slow modes. We find that progenitor stellar clusters with core radii less than a parsec and densities above a few times $10^5\ M_\odot\ \mathrm{pc}^{-3}$ are likely eccentric disk progenitors near a massive black hole of mass 10^7–$10^8\ M_\odot$. Lower density and larger progenitor cores are capable of causing eccentric stellar disks near more massive black holes. Our constraints on the progenitors are consistent with existing *N*-body simulations, which in one case has produced an eccentric disk. For M31 and NGC 4486B, the estimated progenitor clusters are dense and compact compared with Galactic globular clusters; however, the nuclei of nearby galaxies, such as M33, M32, and M31 itself, are in the right regime. If galaxy mergers can create eccentric disks, then they would be a natural consequence of hierarchical galaxy formation.

Key words: galaxies: kinematics and dynamics

1. INTRODUCTION

Ever since the double-peaked nucleus of M31 was clearly resolved by *Hubble Space Telescope* (*HST*) imaging (Lauer et al. 1993), the morphology of this system has been a challenge to explain. The most successful kinematic model is the eccentric stellar disk proposed by Tremaine (1995), where stars in apsidally aligned elliptical orbits about a massive black hole result in an overdensity at their apoapses, thus accounting for the brighter peak P1. The black hole itself resides near the fainter, more centrally located peak denoted P2. Though this model has been successful at matching the observed velocity and luminosity distribution (Kormendy & Bender 1999; Statler et al. 1999; Bacon et al. 2001; Sambhus & Sridhar 2002), eccentric disk formation remains a mystery.

Touma (2002) showed that a small fraction of counter-rotating stars, possibly originating from an disrupted globular cluster on a retrograde orbit, could cause a more massive pre-existing stellar disk to develop a lopsided or $m = 1$ instability. The self-consistent kinematic modeling of Sambhus & Sridhar (2002), which requires a small percentage of counter-rotating stars, supports this scenario. Bacon et al. (2001) proposed that a collision from a passing molecular cloud or globular cluster could knock a pre-existing stellar disk off center, resulting in a long-lived, precessing mode. The *N*-body simulations of Jacobs & Sellwood (1999) and Taga (2002) have illustrated that lopsided stellar disks could be long lived.

The scenarios discussed by Sambhus & Sridhar (2002), Touma (2002), Jacobs & Sellwood (1999), Taga (2002), and Bacon et al. (2001) begin with an initially axisymmetric stellar disk, which then becomes lopsided either because of a violent event (such as a collision with a globular cluster) or the growth of an instability. However, Bekki (2000a) proposed that M31's eccentric disk could have been a result of a single disruption event. He succeeded at producing an eccentric stellar disk by disrupting a globular cluster near a massive black hole in an *N*-body simulation, though an SPH simulation of the disruption of a massive gaseous cloud did not yield an eccentric disk (Bekki 2000b). The massive black hole in M31 is moderate, with a mass 3–$7 \times 10^7\ M_\odot$ (Kormendy & Bender 1999; Bacon et al. 2001). The eccentric disk itself is nearly as massive as the black hole, $\sim 3 \times 10^7\ M_\odot$ (Peng 2002; Sambhus & Sridhar 2002; Bacon et al. 2001), presenting a problem for the globular cluster disruption scenario proposed by Bekki (2000a), which assumed that the globular cluster was typical of Galactic globular clusters and of order a million solar masses.

Here we reconsider Bekki's proposal, that a single disruption event could have produced the eccentric disk in M31. The disruption event is likely to be complex, so we focus on what final disks are capable of supporting lopsided modes, drawing from the recent work of Tremaine (2001), who developed a formalism for the purpose of predicting the precession rates and eccentricities of discrete modes for low-mass, nearly Keplerian disks.

We place limits on the density and core radius of progenitor clusters for eccentric disks near massive black holes. The resulting diagram is useful for predicting what types of galaxies are most likely to harbor eccentric disks, for predicting the probability that eccentric disk formation events occur, and for guiding the initial conditions of *N*-body simulations that may determine if and how they form.

2. TIDAL DISRUPTION OF A CLUSTER

The observed correlation between mass of a black hole and the bulge dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2001) allows us to relate the black hole to the bulge of its host galaxy:

$$\log(M_{\rm bh}/M_\odot) = (8.13 \pm 0.06) + (4.02 \pm 0.32) \log\left(\frac{\sigma_*}{200\ \mathrm{km\ s^{-1}}}\right), \quad (1)$$

where σ_* is the stellar bulge dispersion and we adopt constants in the relation given by Tremaine et al. (2002). For a discussion on the systematics of measuring the velocity dispersion within r_e, the effective or half-light radius, see Tremaine et al. (2002).

The transition radius (sometimes called the sphere of influence), where the gravity from the black hole takes over from the bulge is

$$r_t = \frac{GM_{\rm bh}}{2\sigma_*^2} = 0.5\left(\frac{M_{bh}}{10^7\ M_\odot}\right)\left(\frac{200\ {\rm km\ s^{-1}}}{\sigma_*}\right)^2\ {\rm pc}\ . \quad (2)$$

Using the above relation between the bulge and the black hole mass,

$$r_t \approx 1.8\left(\frac{M_{\rm bh}}{10^7\ M_\odot}\right)^{0.5}\ {\rm pc}\ . \quad (3)$$

We now consider disruption of a stellar cluster or molecular cloud by a massive black hole. Assuming that the bulge is a singular isothermal sphere, the tidal force from the black hole and bulge is

$$F_{\rm tidal} = \left(\frac{2GM_{\rm bh}}{r^3} + \frac{2\ \sigma_*^2}{r^2}\right)s \quad (4)$$

at distance r from the galaxy nucleus and distance s from the cluster nucleus. We set this equal to the gravitational force from the cluster on itself to determine how the cluster disrupts.

We describe the nucleus of a cluster with two parameters, the core radius r_0, and the density within this radius ρ_0. The cores of isothermal spheres and King models are characterized with these two parameters (e.g., Binney & Tremaine 1987). Within the core radius of the cluster, we assume that the cluster has nearly constant density, so its gravitational force is proportional to s. We set the tidal force from the galaxy equal to that from the cluster and determine the distance r_d (the disruption radius) when the two are equal. The distance from the galaxy nucleus where the entire core of the cluster disrupts is then set only by the cluster core density, ρ_0;

$$\frac{GM_{\rm bh}}{r^3} + \frac{\sigma_*^2}{r^2} \sim 2G\rho_0\ . \quad (5)$$

Inside the transition radius the disruption radius

$$r_d \sim \left(\frac{M_{\rm bh}}{2\rho_0}\right)^{1/3} \sim 3.7\left(\frac{M_{\rm bh}}{10^7\ M_\odot}\right)^{1/3}\left(\frac{10^5\ M_\odot\ {\rm pc^{-3}}}{\rho_0}\right)^{1/3}\ {\rm pc}\ . \quad (6)$$

Outside the transition radius

$$r_d \sim \left(\frac{\sigma_*^2}{2G\rho_0}\right)^{1/2} \sim 3.3\left(\frac{\sigma_*}{100\ {\rm km\ s^{-1}}}\right)\left(\frac{10^5\ M_\odot\ {\rm pc^{-3}}}{\rho_0}\right)^{1/2}\ {\rm pc}\ . \quad (7)$$

We expect that it is difficult to make a slowly precessing eccentric disk in a region where the black hole does not dominate the gravitational field. Outside the sphere of influence, the potential is strongly non-Keplerian. The requirement that the cluster be disrupted (survive to) within the transition radius is $r_d < r_t$. Using the previous equation, the definition for r_t, and the relationship between the bulge stellar dispersion and the black hole mass, this inequality gives the requirement

$$\rho_0 \gtrsim 4.6 \times 10^5\left(\frac{M_{\rm bh}}{10^7\ M_\odot}\right)^{-0.5} M_\odot\ {\rm pc^{-3}}\ . \quad (8)$$

From this we see that, the less massive the black hole, the more dense a cluster would be required to form an eccentric disk. This condition is our first constraint on progenitor clusters for eccentric disks.

At radii larger than the disruption radius, the outer parts of the stellar cluster or galaxy bulge would be stripped. We expect that the radial distribution of the resulting disk will depend upon the concentration of the cluster or radial profile of the infalling galaxy bulge. Since the densest part of the cluster is disrupted at r_d, we expect that this part is most likely to be involved in any large eccentricity amplitude variation. So we can estimate the mass of the eccentric disk formed at disruption using the core radius of the cluster r_0, resulting in an eccentric disk of mass equal to the mass within the core of the cluster, $M_c \sim \rho_0 r_0^3$. The width of this eccentric disk would be of the order of the core radius of the cluster. The outer parts of the cluster, which are disrupted before the core, may form an outer stellar disk, which may not be eccentric. We refer to the inner, eccentric part of the resulting disk as M_c (formed from the core of the cluster); however, M_c is less than the total mass of the progenitor cluster, and the entire mass of a stellar disk formed following disruption may also be larger than M_c.

Tremaine (2001) and Lee & Goodman (1999) assume that the mass of the disk is less than that of the black hole. If we consider the active (or eccentric) part of the disk, this is even true in M31 (the center of mass is closest the black hole). It is difficult to imagine a stable situation when the lopsided part of the disk is as massive as the black hole, so we arrive at another constraint on our progenitor cluster,

$$M_c < M_{\rm bh}\ . \quad (9)$$

It is unlikely that a thin disk will result following disruption unless the disk Mach number $\mathscr{M}(r) > 1$ (Tremaine 2001),

$$\mathscr{M}(r_d) \equiv \Omega(r_d) r_d/\sigma_c > 1\ , \quad (10)$$

where $\Omega(r_d)$ is the angular rotation rate at the disruption radius r_d, and σ_c is the central cluster dispersion.

Following disruption of the cluster, the energy spread of the particles is set by the cluster core radius r_0, so we expect that the resulting width of the disk $\sim r_0$. The angular momentum spread at disruption is also set by the size of the cluster core, $\frac{\Delta J}{J_0} \sim \frac{r_0}{r_d}$, where J_0 is the angular momentum of the bulk motion of the cluster at disruption. Consequently, following disruption we expect a disk radial velocity dispersion of at least

$$\sigma_c \sim \sqrt{\frac{GM_{\rm bh}}{r_d}}\frac{r_0}{r_d}\ . \quad (11)$$

This scaling is similar to that outlined by Johnston et al. (2001) for the disruption of dwarf galaxies. Alternately, we can use the relation between central dispersion, core density, and radius for a King model ($\sigma_c^2 = 4\pi G\rho_0 r_0^2/9$). Using either estimate for σ_c and inserting into equation (10), and assuming that we are within the transition radius so that $\Omega = (GM_{\rm bh}/r^3)^{1/2}$, we estimate

$$\mathscr{M}(r_d) \sim \frac{M_{\rm bh}^{2/3}}{\rho_0^{2/3} r_0^2} \gtrsim 1 \ , \qquad (12)$$

which is equivalent to requiring $M_{\rm bh} > M_d$.

In summary, we can constrain properties of an incoming cluster that subsequently forms an eccentric disk:

1. $r_d < r_t$. The disruption radius should be less than the transition radius.
2. $r_0 < r_t$. The cluster core radius should be less than the transition radius.
3. $M_c < M_{\rm bh}$. The cluster core mass should be less than the black hole mass. This constraint is equivalent to requiring $r_0 < r_d$ or $\mathscr{M} > 1$.

We plot these three constraints as lines in Figure 1 for three different black hole masses and as a function of cluster core radius r_0 and density ρ_0. The allowed region of parameter space for a disrupted cluster to form an eccentric disk is the upper left-hand corner, corresponding to core radii above about a parsec and core densities above about 10^5 $M_\odot$ pc^{-3}.

Also shown in Figure 1 are measured core radii and central densities (assuming a mass to light ratio of $M/L_V = 5$ in solar units) for the Milky Way globular clusters based on the quantities compiled by Harris (1996).[1]

We also include on Figure 1 the massive globular cluster G1 (based on core properties estimated by Meylan et al. 2001) and the cores of M31, M32, and M33, based on density profiles (or limits in the case of M32) estimated by Lauer et al. (1998). Limits on the density and core radius are placed on Figure 1 for the two densest galaxies (other than M31, M32, and M33) studied by Faber et al. (1997). Higher angular resolution (better than 0\".1) observations would be needed to find out if more distant galaxies have nuclei with stellar densities comparable to those of M31, M32, and M33.

We see from Figure 1 that Galactic globular clusters are capable of forming eccentric disks if they are extremely dense and have compact cores, and they are more likely to do so in galaxy nuclei containing larger black holes. However, to provide a plausible progenitor for an eccentric disk, a cluster must not only have a dense and compact core but be massive enough to account for the mass of the entire disk. Galactic globular clusters are not massive enough to account for the disk in M31.

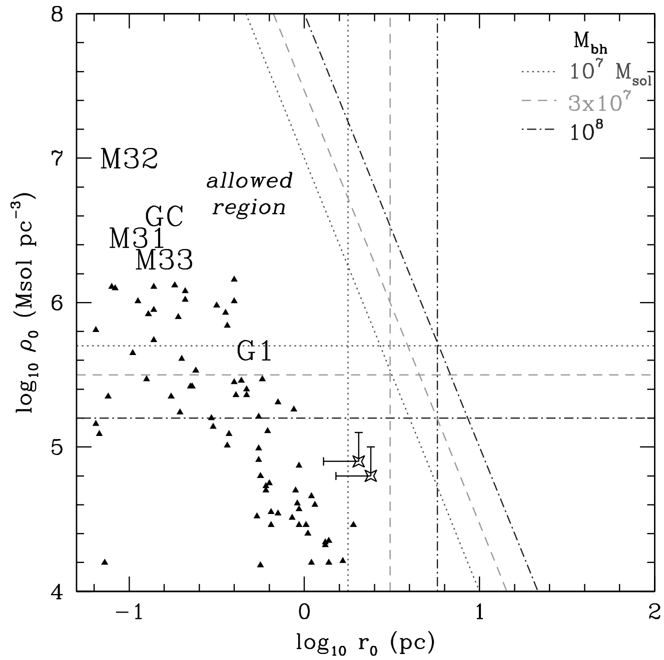

FIG. 1.—Outline of the range of progenitor core radii and central densities that would allow the creation of an eccentric disk near a massive black hole. Dotted lines are for a black hole mass of $M_{\rm bh} = 10^7$ $M_\odot$. The dashed lines are for $M_{\rm bh} = 3 \times 10^7$ $M_\odot$ and the dot dashed lines for $M_{\rm bh} = 10^8$ $M_\odot$. Horizontal lines are set from the constraint $r_d < r_t$ (see eq. [8]), where we require that the disruption radius be within the region where the black hole dominates the gravitational potential (the sphere of influence). The allowed region for the progenitor core is that above the horizontal lines. Vertical lines are set from the constraint $r_0 < r_t$, requiring that the core radius of the cluster is smaller than the region in which the black hole dominates the gravitational potential. The allowed region is that to the left of the vertical lines. The diagonal set of lines are set from the constraint $M_d < M_{\rm bh}$, where we require that the mass of the active (or eccentric) part of the disk $M_d \sim \rho_0 r_0^3$ be less than the black hole mass. Parameter space for progenitor clusters that could result in the formation of an eccentric is limited to the upper leftmost area on the plot. Galactic globular clusters (Harris 1996) (assuming $M/L_V = 5$, solar units) are shown as triangles. The densities and core radii are based on fits to photometric measurements (Harris 1996). The G1 cluster in M31 (labeled as "G1") is placed using parameters by Meylan et al. (2001). M31, M32, and M33 are placed on this plot with values derived by Lauer et al. (1998). In the case of M32 the core radius is only an upper limit. The Galactic center (denoted "GC") is placed on this plot based on values summarized by Alexander (1999). Limits on the cores of two additional power-law galaxies, NGC 3377 and NGC 3115, are shown as diamonds with bars extending outward to show that these points are limits. The values for these two galaxies are based on values derived by Faber et al. (1997).

2.1. *Bekki's Simulations*

We examine the properties of the simulated disruptions done by Bekki (2000a, 2000b) to see if they are consistent with our proposed progenitor cluster limits. In an *N*-body simulation Bekki (2000a) succeeded in producing a stellar eccentric disk by disrupting a globular cluster of mass 0.1 times the black hole mass, for $M_{\rm bh} = 10^7$ $M_\odot$. The bulge he adopted was described by an Navarro-Frenk-White profile with a scale radius of 100 pc. For this adopted bulge profile we calculate that the mass enclosed within 10 pc was less than a million solar masses, so that the entire disruption took place within what we have called the transition radius, where the gravity from the black hole takes over from the bulge (eq. [2]). His simulated cluster disrupted at a radius of $r_d \sim 3$ pc from the black hole, and since the cluster core was much smaller than this, $r_0 \sim 0.4$ pc, the stellar system was capable of forming an eccentric disk. We conclude that the success of his simulation in producing the eccentric disk is consistent with the crude limits we have placed on progenitor cluster properties.

The SPH simulation by Bekki (2000b), however, produced a circular disk, not an eccentric one. The gas cloud in this simulation was of similar mass to that of the stellar cluster, (Bekki 2000a) but had a significantly larger scale length of 10 pc. The cluster disrupted at $r_d \sim 10$ pc, which is

[1] We used the updated catalog, available at http://physun.physics.mcmaster.ca/~harris/mwgc.dat.

approximately the same as the core radius of the gas cloud. We suspect that a gas cloud with a smaller core radius would have been capable of producing an eccentric disk. Again, we find that the failure of this simulation in producing the eccentric disk is consistent with the crude limits we have placed on progenitor cluster properties.

2.2. *M31's Eccentric Disk and Possible Progenitor Cluster or Galaxy Nuclear Properties*

The two peaks observed in the nucleus of M31 are separated by 1.87 pc (Lauer et al. 1993) and the black hole mass is approximately $3 \times 10^7\ M_\odot$ (Kormendy & Bender 1999), so we expect a transition radius of $r_t \sim 3.1$ pc, which is, as we expect, outside the location of the eccentric part of the disk. Note that Bacon et al. (2001) estimate a larger black hole mass of $\sim 7 \times 10^7\ M_\odot$. The width of the eccentric part of the disk is about 0.″2 or 0.7 pc. If the disk formed from a disrupted cluster, the progenitor's core radius would have been smaller than 0.7 pc. The total mass in the most eccentric part of the disk is about $10^6\ M_\odot$ (Bacon et al. 2001), so we would require a progenitor cluster of $r_0 \sim 0.7$ pc and ρ_0 of about a few times $10^6\ M_\odot\ \mathrm{pc}^{-3}$. For $\rho_0 \sim 4 \times 10^6\ M_\odot\ \mathrm{pc}^{-3}$ the disruption radius r_d (estimated by eq. [6]) is consistent with the location of the eccentric disk itself.

To provide a plausible progenitor, a cluster must not only have a dense and compact core but be massive enough to account for the mass of the entire disk. The extended, nearly circular part of the M31 stellar disk dominates its mass and has been estimated to be $3 \times 10^7\ M_\odot$ (Peng 2002; Sambhus & Sridhar 2002; Bacon et al. 2001). This is massive compared with Galactic globular clusters, presenting a problem for the globular cluster disruption scenario proposed by Bekki (2000a). However, extremely massive extragalactic clusters have been identified. For comparison, we show in Figure 1 the location of the massive globular cluster (or perhaps nucleus of a dwarf galaxy), which is 40 kpc from the center of M31. This cluster has a mass of 7–17 $\times 10^6\ M_\odot$ (Meylan et al. 2001), a core radius $r_0 \approx 0.''14 = 0.52$ pc and a core density $\rho_0 \approx 4.7 \times 10^5\ M_\odot\ \mathrm{pc}^{-3}$ (Meylan et al. 2001). G1 is massive enough that it could have accounted for the mass in the extended (and almost circular) part of M31's eccentric disk, though its tidal radius is large, $\sim$200 pc, which implies that much of the cluster would have disrupted well outside the location of the eccentric disk in M31.

The estimated progenitor properties required to form the M31 eccentric disk are surprising if we compare them with Milky Way globular clusters and nearly matched by the exotic and extremely massive extragalactic cluster G1. However, they are similar to what has been measured in nearby galaxy centers, such as M33, M32, and M31 itself, which we have also placed on Figure 1. We see from this figure that galaxy nuclei can have the high densities and compactness to be eccentric disk progenitor candidates. Moreover, they are usually more massive than globular clusters and so can more easily account for the mass in M31's eccentric disk.

2.3. *NGC 4486's Eccentric Disk and Its Progenitor*

The other well-known example with a double nucleus is NGC 4486B, with a separation of 0.″15, or 12 pc, between the two isophotal peaks Lauer et al. (1996) and a black hole mass of $M_{\mathrm{bh}} \sim 10^9\ M_\odot$ (Magorrian et al. 1998). The transition radius in this galaxy would be $r_t \sim 17$ pc; so again we find that the eccentric stellar disk lies within r_t. From equation (6), and using 12 pc for the disruption radius, we estimate that the progenitor core density would be $\rho_0 \sim 6 \times 10^5\ M_\odot\ \mathrm{pc}^{-3}$. The width of the peaks comprising the disk (and hence the progenitor core radius) is estimated to be 2–4 pc. However, NGC 4486A is much more distant than M31, and consequently the eccentric disk mass is probably much higher than that of M31, probably exceeding $10^8\ M_\odot$, and this is too massive for a globular cluster. However, as in the case of M31's estimated progenitor, the central densities, core radius, and total mass are reasonable for a galaxy nucleus.

2.4. *Comparison with the Properties of Galaxy Nuclei*

In equation (2) we have assumed a singular isothermal profile for the stellar density profile of the background galaxy. However, as shown by multiple studies (e.g., Faber et al. 1997; Lauer et al. 1998), galaxy nuclei at small radii are seldom fitted with a surface brightness profile proportional to R^{-1} (where R is the observed angular radius from the nucleus on the sky) corresponding to an isothermal density profile $\propto r^{-2}$. Images from the *HST* have been part of a major effort to classify the nuclear stellar profiles in early-type galaxies, resulting in the classification of light profiles into two categories: galaxies with shallow inner cusps, denoted "core-type" profiles, and galaxies with "power-law" light profiles (Lauer et al. 1995; Faber et al. 1997). Power-law–type galaxy nuclei tend to have the steepest nuclear surface brightness profiles $\mu(R) \propto R^{-\gamma}$, with γ nearly equal to 1 in only the most extreme cases. Most of the galaxies studied by Faber et al. (1997) had shallower profiles. This implies that equation (3) somewhat underestimates the transition radius in most galaxies, particularly in the galaxies classified as core type in which γ is close to zero. We can regard our estimated radius (eq. [3]) as a lower limit on the transition radius for all but the galaxies with the steepest nuclear profiles.

We now consider the problem of two merging galaxies, both with more complex stellar density profiles and both with massive black holes. We can approximately describe the primary as having a transition radius given by equation (3) (which is actually a lower limit, as mentioned above). If the secondary has a power-law form for its density profile, then it will not completely disrupt at a particular radius, like the nonsingular isothermal sphere or King models.

One component of the Nuker surface brightness profile (Faber et al. 1997) is the break radius r_b, where the slope of the surface brightness profile changes. For profiles denoted core type, within r_b, the surface brightness (and so density) rises much less steeply with decreasing radius than outside it. Because the surface brightness for core-type galaxies only increases slightly within r_b, we can associate the break radius and density estimated at this radius, with the core radius r_0 and density ρ_0, which we have used in the previous sections. This lets us determine whether the bulge or stellar component of the secondary galaxy will survive tidal truncation to within the transition radius of the primary. A secondary with break radius exceeding its own transition radius $r_b > r_t$ (likely to be true for luminous galaxies) will almost completely disrupt when the tidal truncation radius reaches its break radius. The black hole of the secondary will then spiral in to the nucleus of the primary, leaving the stellar component of the secondary behind.

However, for bulges and fainter ellipticals we expect $r_b < r_t$. For example, M32's profile is steeply rising well within its transition radius $r_t \sim 0.5$ pc and increases in density to its last measured point (Lauer et al. 1998). In this case the bulge would be continuously disrupted, though we expect a change in the surface brightness profile of the resulting disk set by the location at which the tidal truncation radius of the secondary was equal to its own transition radius. The continuous stripping of the secondary in the presence of the secondary's black hole may prevent the formation of a lopsided disk.

2.5. *Tidal Disruption of a Power-Law Galaxy*

The radius of tidal disruption can be estimated by comparing the mean density of the object with that of the object disrupting it (e.g., Sridhar & Tremaine 1992). At a distance r from the nucleus of the primary galaxy, the mean density resulting from the black hole is $\bar{\rho}(r) = M_{\rm bh,1}/(4\pi r^3/3)$, where $M_{\rm bh,1}$ is the mass of the primary's black hole. We have assumed that $r < r_{t,1}$, where $r_{t,1}$ is the transition radius of the primary, so the contribution from the primary's bulge is negligible.

For a secondary galaxy with a power-law density profile (see Binney & Tremaine 1987, § 2.1e)

$$\rho(s) = \rho_a (a/s)^\alpha \ , \tag{13}$$

the mass integrated out to radius s is

$$M(s) = \frac{4\pi\rho_a a^\alpha}{3-\alpha} r^{3-\alpha} \ , \tag{14}$$

so the mean density within this radius,

$$\bar{\rho}(s) = \frac{3\rho_a}{3-\alpha}\left(\frac{a}{s}\right)^\alpha \ , \tag{15}$$

for radii $s > r_{t,2}$ outside the transition radius of the secondary. We set the mean density of the primary within r (due to the primary's massive black hole) equal to the that of secondary (within stripping radius s), $\bar{\rho}(s) = \bar{\rho}(r)$, and find that

$$r^3 \approx \frac{M_{\rm bh}(3-\alpha)}{4\pi\rho_a}\left(\frac{s}{a}\right)^\alpha \ . \tag{16}$$

When the secondary is at a distance r from the nucleus of the primary, it will be stripped out to a distance s from its own nucleus, where s is related to r by the previous equation.

The stripping radius s is the same size as the distance from the primary's nucleus r at a radius

$$r_e = \left[\frac{M_{\rm bh,1}(3-\alpha)}{4\pi\rho_a a^3}\right]^{1/(3-\alpha)} a \ , \tag{17}$$

where $M_{\rm bh,1}$ is the mass of the primary's black hole. When s estimated from equation (16) exceeds r, then the secondary engulfs the nucleus of the primary.

For a disrupted secondary galaxy center to produce an eccentric disk, we expect that the radius at which the secondary engulfs the nucleus of the primary r_e should be smaller than the transition radius of the primary ($r_{t,1}$). In this case the core of the secondary will survive intact within the transition of the secondary. A reasonable condition for formation of an eccentric disk via the disruption of a galaxy with a power-law density profile should be

$$r_e < r_{t,1} \ . \tag{18}$$

Using equations (17) and (3) this is equivalent to

$$\rho_a > M_{\rm bh,1}^{(\alpha-1)/2} a^{-\alpha} \kappa^{\alpha-3} \frac{3-\alpha}{4\pi} \ , \tag{19}$$

where $\kappa = 5.7 \times 10^{-4}$ pc $M_\odot^{-1/2}$. For an isothermal profile, the limit on the density at $a = 1$ pc:

$$\rho_{a=1\,{\rm pc}} > 5 \times 10^6 \left(\frac{M_{\rm bh,1}}{10^7\ M_\odot}\right)^{1/2} M_\odot\ {\rm pc}^{-3} \ \text{for}\ \alpha = 2 \ . \tag{20}$$

2.6. *Existing Simulations of Galaxy Mergers*

With the exception of Merritt & Cruz (2002) and Holley-Bockelmann & Richstone (2000), few simulations have been carried out with realistic stellar density profiles and central black holes. Merritt & Cruz (2002) presented N-body simulations of two merging galaxies, the primary with a shallow central density profile and the secondary with a steeper profile at the nucleus. They did simulations with and without massive nuclear black holes to illustrate the difference in remnant profiles following the merger. The density profiles adopted for their simulations were generated from the family introduced by Dehnen (1993).

To explore the role of the black holes on the disruption of the secondary in their simulations, we estimate the transition radii for each galaxy. At small radii, $r < a$, both galaxies were power law in form:

$$\rho(r) = \frac{(3-\alpha)M}{4\pi a^3}\left(\frac{a}{r}\right)^\alpha \ , \tag{21}$$

where M was the mass of the galaxy and a was its scale length. Merritt & Cruz (2002) used $\alpha_1 = 1$ for the primary and $\alpha_2 = 2$ for the secondary (subscripts here refer to the primary and secondary galaxy, respectively). We estimate the transition radius for each galaxy (sphere of influence) by calculating the radius at which the integrated stellar mass within equals that of the central black hole. For the primary galaxy

$$r_{t,1} \approx a_1 (M_{\rm bh,1}/M_1)^{1/2} = 0.035 a_1, \tag{22}$$

where we have integrated equation (21) and used the ratio $M_{\rm bh}/M = 0.0012$ (that adopted by Merritt & Cruz 2002). For the secondary galaxy we estimate

$$r_{t,2} \approx a_2 (M_{\rm bh,1}/M_1) = 0.0012 a_2 \ . \tag{23}$$

Because the transition radius of the secondary was so small, its black hole should not have affected the simulations (they were probably not well resolved on that scale).

Both simulations produced similar remnants at radii larger than 0.1 times the primary's scale length. The change in the surface brightness profiles at this radius was probably due to the break radius (scale length at which the density profile changes slope) of the secondary.

For the simulations containing both massive black holes, a change in radial density profile is seen in the remnant at approximately the primary's transition radius (see their Fig. 2*d*). Using their profiles, we estimate that $r_e \sim 0.01$ times the scale length of the secondary, which is consistent with the survival of a fraction of the secondary's core to well within the transition radius of the primary. The constraints developed in the previous section were not violated ($r_e < r_{t,1}$), so this type of simulation might have been capable of forming an eccentric disk in the remnant. If the simulation did not form one, then simultaneous disruption of the densest part of the cluster might be required to form an eccentric disk. This would occur when the core has a well-defined core radius (and nearly constant density within) and may not occur when the secondary has a steeply increasing density profile all the way to its nucleus.

In the simulations lacking the massive black holes (see their Fig. 2*h*), the secondary did not disrupt within its break or scale radius. This follows because the mean density of the secondary significantly exceeds the mean density of the primary within their scale radii; consequently, the primary could not have disrupted the secondary within the secondary's scale radius.

The merger simulations of Holley-Bockelmann & Richstone (2000) were done with a quite massive primary black hole ($M_{\rm bh} > 10^9\ M_\odot$) and lacked a secondary black hole. From their initial density profiles we estimate that the size of the secondary at its disruption radius in their 10 : 1 simulation was only about one-third the disruption radius itself. This implies that a disk could be formed from the secondary following disruption. Holley-Bockelmann & Richstone (2000) reported that their simulations produced a spinning remnant disk; however, it was thick, consistent with our crude estimate of the secondary's largish size during disruption. Much of the secondary survived to within the transition radius of the primary's black hole (about 30 pc). It is possible that a denser secondary (better satisfying the conditions in eqs. [18]–[20]) could result in a thinner stellar disk, which might then be more likely to be lopsided. Alternatively, a secondary with a shallow core (that would disrupt all at once, as simulated by Bekki 2000a) might be required for eccentric disk formation.

3. DISCUSSION AND SUMMARY

In this paper we have considered the possibility that a single disruption event could result in the formation of an eccentric stellar disk, such as are found in M31 and possibly NGC 4486B. We explore the scenario of a galaxy core that is stripped as it spirals in toward a nuclear massive black hole until it reaches a critical radius, denoted here as r_d, the disruption radius. In the simplest model of an isothermal sphere the disruption radius is set by the cluster core or King radius and central density. We suggest that an eccentric disk cannot form unless the core of the galaxy or stellar cluster is disrupted within the sphere of influence of the massive black hole, referred to here as the transition radius r_t, and the core radius is smaller than the radius at which it disrupts. To succeed in making an eccentric disk, we find that the progenitor cluster core must be denser and more compact for less massive black holes.

For the eccentric disk in M31, the progenitor cluster core density must be greater than $10^5\ M_\odot\ {\rm pc}^{-3}$ and core radius smaller than a parsec. From the radius, width, and mass of the most eccentric region of the disk we estimate that the density of the core was a few times $10^6\ M_\odot\ {\rm pc}^{-3}$, and the core radius was of order a half parsec.

Massive extragalactic globular clusters such as G1 might be dense, compact, and massive enough to be an eccentric disk progenitor; however, they are probably too diffuse to account for the large disk mass in M31 within a few parsecs of its black hole.

Dense bulges such as found in M31 itself and in lower luminosity ellipticals galaxies, such as M32, are dense and compact enough that they could be similar to progenitors for M31's and NGC 4486B's eccentric disks. Nuclear star clusters, such as those found in M33, may also be dense and compact enough to be progenitors. Though the mass of M33's cluster (a few million solar masses) is too small to be a progenitor for M31's nuclear disk (assuming a total mass of a few times $10^7\ M_\odot$), the nuclear stellar clusters observed by Böker et al. (2002) in late-type galaxies have half-light radii of order 5 pc, range in their estimated masses from 10^6–$10^8\ M_\odot$, and so could be progenitors for eccentric disks following disruption by a massive black hole. Because of the large mass of bulges and nuclear star clusters at small radii, it would be easier to account for the high masses of the two known eccentric disks with such progenitors than that possible with a globular cluster progenitor. While the massive black hole in M32 might prevent a progenitor similar to M32 from forming an eccentric disk, nuclear clusters such as found in M33 can lack massive black holes and so might provide better progenitor candidates. To date the high angular resolution of *HST* has resolved extremely high stellar densities of order $10^6\ M_\odot\ {\rm pc}^{-3}$ in only the nearest galaxy bulges. Until higher angular resolution (better than 0$''$.1) observations are available, we will not know whether such high density galaxy centers are common.

The two galaxies with double nuclei, M31 and NGC 4486B, exhibit only moderate color variations in their nuclei (Lauer et al. 1996, 1998), a situation that could be a natural consequence of a scenario that involves the merging of galaxy bulges (proposed here) and is more difficult to explain with a scenario that forms a younger disk in situ (an ingredient of the formation scenarios discussed by Bacon et al. 2001; Touma 2002; Taga 2002; Jacobs & Sellwood 1999).

The scenario proposed here is based on a simple tidal disruption argument and can be most quickly tested with *N*-body simulations such as have been carried out by Merritt & Cruz (2002), Bekki (2000a), and Holley-Bockelmann & Richstone (2000). The simulations of Bekki (2000a) established that the disruption of a cluster could result in the formation of an eccentric disk, and Merritt & Cruz (2002) and Holley-Bockelmann & Richstone (2000) have carried out simulations based on realistic galaxy profiles and with massive black holes. Holley-Bockelmann & Richstone (2000) established that a spinning nuclear stellar disk can be a remnant. It remains to be seen whether the merger of two galaxy cores can result in the creation of an eccentric stellar disk.

We suspect that the merger of a primary galaxy containing a very massive black hole, with a secondary with a "core-type" or shallow central surface brightness profile and significantly lower mass black hole, would be most likely to form an eccentric disk with *N*-body simulations. For the core-type galaxies, the break radius and density at this radius provide an equivalent for the King or core radius and central density used in Figure 1, and so can be used to estimate the likelihood that the core can disrupt to form an eccentric disk.

If the merger of galaxy bulges can result in the formation of an eccentric disk, then their formation would be a natural consequence of hierarchical galaxy formation and can also be used to probe the properties of the parents of galaxies which contain them.

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