HYPERVELOCITY INTRACLUSTER STARS EJECTED BY SUPERMASSIVE BLACK HOLE BINARIES
KELLY HOLLEY-BOCKELMANN\textsuperscript{1,2}, STEINN SIGURDSSON\textsuperscript{1,2}, J. CHRISTOPHER MIHOS\textsuperscript{3}, JOHN J. FELDMEIER\textsuperscript{4,5}, ROBIN CIAIDULLO\textsuperscript{6} & CAMERON McBRIDE\textsuperscript{6}

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ABSTRACT

Hypervelocity stars have been recently discovered in the outskirts of galaxies, such as the unbound star in the Milky Way halo, or the three anomalously fast intracluster planetary nebulae (ICPNe) in the Virgo Cluster. These may have been ejected by close 3-body interactions with a binary supermassive black hole (SMBBH), where a star which passes within the semimajor axis of the SMBBH can receive enough energy to eject it from the system. Stars ejected by SMBBHs may form a significant sub-population with very different kinematics and mean metallicity than the bulk of the intracluster stars. The number, kinematics, and orientation of the ejected stars may constrain the mass ratio, semimajor axis, and even the orbital plane of the SMBBH. We investigate the evolution of the ejected debris from a SMBBH within a clumpy and time-dependent cluster potential using a high resolution, self-consistent cosmological N-body simulation of a galaxy cluster. We show that the predicted number and kinematic signature of the fast Virgo ICPNe is consistent with 3-body scattering by a SMBBH with a mass ratio $10:1$ at the center of M87.

\textit{Subject headings:} clusters, supermassive black holes, galaxies, n-body simulations

1. INTRODUCTION

A significant fraction of the stellar component of a galaxy cluster is not confined to any galaxy. This intracluster light (ICL) has been identified via planetary nebulae (PNe) (Feldmeier et al. 2004; Aguerri et al. 2005), Red Giant Branch (RGB) stars (Durrell et al. 2002), and ultra-deep surface photometry (e.g., Feldmeier et al. 2002, 2004; Mihos et al. 2005). It is commonly thought that intracluster stars are stripped from galaxies as the cluster assembles (Merritt 1984), via high speed galaxy encounters (Moore et al. 1996), interactions with the cluster potential (Byrd & Valtonen 1990), or by tidal stripping in infalling groups (Mihos 2004). These processes will generate a debris field that is highly inhomogeneous, with distinctly non-Gaussian velocities, reflecting an unrelaxed intracluster population (Napolitano et al. 2003).

The continued search for intracluster PNe (ICPNe) reveals several in the Virgo Cluster with radial velocities that are extremely rapid compared both to its nearest galaxy and to the background cluster. In one point ~65 kpc from M87, Arnaboldi et al. (2004) found that of 15 ICPNe radial velocities, only 12 were consistent with M87’s stellar velocity dispersion profile (Romanowsky & Kochanek 2001) and systemic velocity. Of the three remaining ICPNe, two had velocities which were offset $\sim -900$ km/sec from the systemic velocity of M87 and one had a $\sim +1500$ km/sec difference.

While these ICPNe could be associated with an unrelaxed tidally-stripped intracluster stellar population, there is an alternative explanation. In this paper, we explore the possibility that the high velocity ICPNe were ejected after interacting with a supermassive binary black hole (SMBBH) at the center of M87. Supermassive black holes (SMBH) are a standard component of elliptical galaxies and spiral bulges (e.g., Richstone et al. 1998). When galaxies evolve through hierarchical merging, each SMBH participates and at some point forms a hard binary. This implies that many galaxies host SMBBHs. Perhaps the best evidence for this is the double X-ray bright nuclei in NGC 6240 (Komossa et al. 2003).

During the hard binary phase, stars that pass between the two SMBHs siphon energy from the binary’s orbit via 3-body scattering, and most are ejected with hypervelocities (Hills 1988; Yu & Tremaine 2003). These SMBBH-driven ejecta may constitute a different ICL population than stars stripped by dynamical interactions between galaxies; they are more likely to be metal rich, and, as we will show, have distinct kinematics and spatial structure. This makes the two populations easy to separate.

We investigate the structure and kinematics of the debris ejected via 3-body scattering within a high resolution N-body simulation of a cluster potential. We model the SMBBH ejection velocities and study how well the ejected population remains kinematically distinct within a clumpy and still evolving cluster potential. We compare the expected mass fractions of the ICL generated by 3-body interactions with more traditional tidal interactions. According to our models, it is plausible that the fast ICPNe were ejected after interacting with a SMBBH in M87. We discuss how this theory can be tested with spectroscopic observations.

2. GENERATING HYPERVELOCITY STARS

Galaxy mergers provide an impetus for SMBHs to meet and form a bound system. During a galaxy merger, each SMBH sinks to the center of the new galaxy potential due to dynamical friction, and eventually becomes bound as a SMBBH. Dynamical friction then continues to shrink the orbit until the binary is hard (i.e., the separation be-
between each SMBH, $a_{\text{BBH}}$, is such that the system tends to lose energy during stellar encounters). Thereafter, further decay is mediated by 3-body scattering with the ambient stellar background until the SMBBH becomes so close that the orbit can lose energy via gravitational radiation. It will thereafter presumably coalesce. The final stages of SMBBH coalescence emit so much gravitational radiation that they are extremely likely to be detected by the Laser Interferometer Space Antenna (LISA), a planned NASA mission to detect gravitational waves, set to launch in the next decade.

When black holes form a hard binary, any star that passes nearby takes energy from the system and changes the star’s velocity (see Yü 2002):

$$\delta v \sim \sqrt{\frac{3.2GM_1M_2}{(M_1 + M_2)a_{\text{BBH}}}},$$

(1)

where $M_1$ and $M_2$ are the black hole masses, and $a_{\text{BBH}} = GM_2/4\sigma_0^2$, where $\sigma_0$ is the central velocity dispersion. Since 3-body scattering preserves the z-component of the angular momentum, the ejected debris is confined to a torus with a major axis aligned with the instantaneous SMBBH orbital plane (Zier & Biermann 2001). The kinetic energy exchange takes place over a timescale:

$$\delta t \sim \sqrt{\frac{G(M_1 + M_2)}{a_{\text{BBH}}^3}},$$

(2)

To model this process in M87, we need to choose appropriate parameters for a SMBBH at the galaxy center. This is currently ill-constrained. If the jet in M87 were a long-lived structure, we could estimate the masses and separation of the binary by shape of jet, since a large secondary mass could induce periodic structure. However, the jet’s length, along with a reasonable choice for the bulk gas velocity, implies that M87’s jet may only be 2-3 Myr old. Thus, it provides no real constraint on the component masses. We therefore set the total mass of the SMBBH to $3.3 \times 10^6 M_\odot$ (Harms et al. 1994; Macchetto et al. 1997). Semi-analytic models of the assembly and growth of SMBHs using an extended Press-Schechter formalism indicate that the most probable mass ratio for coalescing SMBBHs at low redshift is $M_1/M_2 = 10$ (e.g., Sesana et al. 2004). Hence, we set the ratio of the two SMBHs to be $M_1/M_2 = 10$. If we assume the binary is hard, then the separation is $a_{\text{BBH}} = 2.1$ pc, and $\delta v \sim 1350$ km/sec. A full loss cone then implies a SMBBH coalescence timescale of $O(10^5)$ years, in which case the SMBBHs may already have merged (and may even be associated with the jet). However, less optimistic assumptions about the loss cone reservoir yield a much longer coalescence timescale, suggesting that the SMBBH may be observable.

3. SIMULATING EJECTA KINEMATICS

To compare the kinematics of the SMBBH-ejected stars to the stellar kinematics within a complex cluster potential, we use a high-resolution N-body galaxy cluster simulation as a testbed for our analytic 3-body ejection scheme (Mihos et al. in prep). To create this simulation, a $50^3$ Mpc$^3$ $\Lambda=0.7$, $\Omega_M=0.3$ cosmological dark matter simulation was run from $z=50$ to $z=0$, at which point a collapsed cluster with mass $\sim 10^{14} M_\odot$ was chosen to re-simulate at higher resolution. At $z=2$, individual halos destined to end up within the $z=0$ cluster were identified; halos more massive than 10% Milky Way mass were excised from the simulation and high resolution collisionless galaxy models inserted in their place. To do this, we used the “halo occupancy distribution” formalism (Berlind & Weinberg 2002) wherein massive halos are more likely to have multiple galaxies inserted. Both spiral and elliptical galaxy models were used. Spirals consisted of an exponential disk plus a Hernquist (1990) bulge (with bulge:disk ratio of 1:5), while ellipticals were a pure Hernquist (1990) model. Both galaxy types were embedded in high resolution isothermal dark halos which blended smoothly into the background dark matter distribution. The galaxy models were scaled in mass to match the halo mass they replaced, scaled in size by $M^{1/2}$, and scaled in velocity by $M^{1/4}$. In total, 121 high resolution galaxy models were inserted into 80 dark halos; the simulation consisted of approximately 10 million particles, 5.4 million of which represented stars with a gravitational smoothing length of 0.28 kpc. Initialized at $z=2$, the simulation was evolved to $z=0$ using the N-body code GADGET (Springel et al. 2001). Figure 1a shows the simulation at $z=0$ assuming a stellar mass-to-light ratio of 5.

To compare the characteristics of tidally-released stars with stars ejected via 3-body interactions, we must first identify the tidal ICL. Definitions of ICL abound, based on binding energy, morphology, or surface brightness. For our illustrative purposes, we simply identify particles as ICL if their local density falls below a threshold, set so that when the cluster is initialized at $z=2$, the ICL fraction is essentially zero, and at $z=0$ the ICL particles no longer trace the galaxy morphologies. As a consistency check, using this criterion we arrive at an ICL fraction of 13%, similar to that inferred for Virgo from observations of ICPNe (Feldmeier et al. 2004).

Even with such a high resolution N-body simulation, no particle would pass within $a_{\text{BBH}}$ of our M87-analogue nucleus. We therefore developed a Monte Carlo approach to mimic the interaction between stars and a SMBBH. We pinned a spherical region with radius $a_{\text{BBH}}$ to the center of the most massive cluster galaxy (with a mass comparable to M87), and embedded the cluster with 8000 particles. We then gave these particles a small isotropic velocity dispersion so that they were destined to pass within $a_{\text{BBH}}$ rather quickly. Each particle received the velocity kick of equation 1 whenever it passed within $a_{\text{BBH}}$ of the galaxy center. The direction of this kick was planar, to ensure the debris would form a torus. Otherwise, all particles moved within the substructure-rich potential. This simulation was followed for 100 Myr.

Figure 1b and 1c depict the inner 300 kpc of the most massive galaxy. Here the torus of ejected PNe is plainly visible and the radial velocities are typically much faster than the ambient ICL.

4. TOTAL MASS EJECTED BY SMBBHs

We can estimate the total fraction of ICL ejected from M87 by a SMBBH during the hard binary phase:

$$M_{ej} = J(M_1 + M_2)\ln\left(\frac{a_{gw}}{a_{\text{BBH}}^2}\right),$$

(3)
where $J$ is a dimensionless mass ejection rate. For equal-mass circular binaries, $J \sim 0.5$ (Milosavljević & Merritt 2001). Quinlan (1996) argues that $J$ drops as $M_1/M_2$ increases, and varies with the orbital speed of the SMBBH. We ignore the variation of $J$ during the binary’s evolution, setting $J = 0.3$. The separation where gravitational radiation dominates, $a_{gw}$ is:

$$a_{gw} = \left( \frac{256 G^2 (M_1 + M_2)^2 \sigma_0}{c^5 \rho H} \right)^{1/5},$$  

where $\rho$ is the central stellar density, $c$ is the speed of light and $H$ is the hardening rate, set by restricted 3-body experiments and direct N-body simulations. We adopt $H = 16$ in the estimate that follows (Quinlan 1996), and use Faber et al. (1997) to set M87’s $\rho$ and $\sigma_0$. Given these constraints, we find that $\sim 6 \times 10^9 M_\odot$ should be ejected by a 10:1 SMBBH in M87 during the hard phase. Although this is a significant amount of mass, it is only about 1.5% of M87’s total mass within 10 kpc (Nulsen & Böhringer 1995). Assuming $M/L = 5$, and that M87’s V-band luminosity is $7.7 \times 10^{10} L_\odot$, nearly 2% of M87’s light could be ejected during one 10:1 SMBBH merger.

Scaling this result from M87 to the cluster as a whole requires a model for the SMBBH merger history of each Virgo galaxy, along with SMBH masses and mass ratios as the cluster assembles. To obtain a rough estimate, however, we can assume that each Virgo cluster galaxy hosted one 10:1 SMBBH merger in its lifetime, and ejected debris during the merger with an efficiency that depends on the black hole mass, $M_\bullet$. In reality, only a fraction of Virgo cluster galaxies would host SMBBHs mergers, yet each of these would likely have undergone several mergers by $z = 0$. Our simple model averages over the galaxy ensemble and avoids the problem of identifying mergers over a Hubble time. This reduces the problem to simply counting the appropriate galaxies and assigning a SMBBH mass to each one.

Using the observed Virgo luminosity function (Sandage, Binggeli, & Tammann 1985), we take a census of the number of galaxies per absolute blue magnitude, between $-22 < M_B < -12$, as well as the variation of morphological type in each magnitude bin. Since SMBHs are thought to exist in every elliptical and spiral galaxy bulge, we include only spirals and ellipticals in our analysis. We model all spirals after the Milky Way, with the same mass, $\sigma_0$, and bulge to disk ratio of 1:3; our elliptical galaxies are modeled using Fundamental Plane parameters (Dressler et al. 1987). Naturally, spiral galaxies are more varied than the Milky Way, but as we will see, the choice of our spiral model matters very little for this exercise.

Now that we have the number of SMBBH-embedded galaxies, as well as $\sigma_0$ for each, we determine the SMBBH mass in each galaxy using the $M_\bullet - \sigma$ relation (Gebhardt et al. 2000; Ferrarese & Merritt 2000). Unfortunately, there is some disagreement on the precise slope of the relation, so we adopt $M_\bullet \propto \sigma_0^4$ (e.g., Tremaine et al. 2004). Since we have the SMBBH mass and $\sigma_0$, we also have $a_{BBH}$ and $a_{gw}$, and hence $M_{ej}$ for each galaxy.

Folding in these various relationships and summing over the luminosity function, we obtain a total SMBBH-ejecta luminosity $\sim 2\%$ of the total Virgo Cluster luminosity. SMBBHs in low luminosity ellipticals contribute slightly more per galaxy to the ICL (3%) than the brightest ellipticals, but most SMBBH ejections occur in the brightest magnitude bins, which are occupied by large ellipticals like M87. The contribution from spirals is negligible (0.01%). Of course, the fraction of light from galaxy interactions is more substantial; N-body simulations suggest 10 – 50% of the luminosity of the Virgo Cluster could come from intrachannel stars stripped during galaxy interactions (Napolitano et al. 2003). However, this study indicates that as much as 20% of the ICL could come from the more exotic SMBBH origin. We caution that since this estimate clearly hinges on $M_\bullet$, varying the $M_\bullet - \sigma$ relation can change $M_{ej}$ (and hence, the fraction of SMBBH-generated ICL) significantly.

5. IMPLICATIONS

Intracluster stars may be released via two very distinct mechanisms: tidal stripping of the outskirts of galaxies, and 3-body interactions with a SMBBH deep within a galaxy potential well. Stars ejected by a SMBBH are
kinematically separable from the ambient cluster kinematics and also preserve an easily discernible shape, even in a complex and evolving cluster potential.

A thin torus is the prompt ejection signal from a single SMBBH as it forms a hard binary. Hence, observing a torus of ICPNe can constrain both the recent existence of a SMBBH and its orbital plane without sub-arcsecond observations. For example, given a full loss cone, it takes \( \sim 10^7 \) years for a 10 : 1 SMBBH to evolve from a hard binary to one that decays via gravitational radiation. During that time, \( a_{\text{BH}} \) shrinks, lowering the stellar interaction cross-section but strongly increasing the few ejected velocities. So, if the hypervelocity ICPNe observed are indeed caused by an interaction with a SMBBH, the last major galaxy merger was complete less than \( 10^7 \) years ago. With a 10 : 1 galaxy merger timescale of \( O(10^8) \) years, there should be some fine structure (Schweizer & Seitzer 1992) within M87 associated with the event (and there may be: see Weil et al. 1997).

The current consensus is that most ellipticals have assembled by merging (e.g., van Dokkum 2005). Therefore, in a cluster environment, debris may originate from several galaxies over many epochs, which makes the ejection signature more complex. To determine the aggregate behavior of SMBBH-driven ICL we plan to investigate the long-term time evolution of the ejecta from SMBBHs as galaxies assemble within a cluster environment.

The ICL fraction generated by SMBBHs (4 − 20%) is consistent with the high velocity ICPNe fraction in Virgo, ~ 7%. Hence, the three ICPNe outliers could all be hypervelocity ejections. As a further reality check, given the predicted \( O(10^5) \) km/sec velocity kick, it takes \( O(10^7) \) years to travel 65 kpc from M87. Since the lifetime of a 2M⊙ star is \( O(10^8) \) years, it is plausible that a main sequence star could plunge from the inner kpc, get ejected by the SMBBH, and evolve into a PNe within the allotted time. The tidal disruption radius of such a star is \( O(10^{-5}) \) pc, so it may pass within \( a_{\text{BH}} \) intact.

There is another way to determine the importance of SMBBH ejections. Since this mechanism works deep within the galaxy potential, the ejected stars should retain the metallicity of the elliptical galaxy center. Observations indicate that bright ellipticals have a mean abundance in the range 0 < [\( Z/H \)] < 0.4 and a metallicity gradient of \( \Delta \log Z/\Delta \log R \sim -0.25 \) (Henry & Worthey 1999). This implies that SMBBH ejection candidates will typically have a much higher metallicity than the tidally generated ICL, which usually originate in the outskirts of a galaxy. It would be ideal if this metallicity diversity were clear-cut, but some scatter in the abundances of both types of ICL is expected. Recall that, by far, most of the SMBBH ejecta originate from the center of the largest ellipticals, and should therefore exhibit high metallicities. This high metallicity sample is contaminated, though, with a few low metallicity SMBBH ejections that originate from faintest ellipticals (Bender et al. 1993). Strong galaxy interactions, too, can occasionally dredge up metal-rich material from the inner regions of galaxies (Hibbard & Mihos 1995; Mihos 2006 in prep), after which the cluster potential can easily strip it into the ICL. Finally, since the scatter in \( [Z/H] \) is large within a galaxy, metal poor stars exist even within a metal rich bulge (e.g., Jacoby & Ciardullo 1999). Despite these complications, since the mean metallicities of each population differ, multi-night spectroscopic observations with an 8-meter telescope (or better yet, short observations with a 30-meter class telescope) can divide the population statistically.

The implications for LISA are profound. If a star passes within 100 Schwarzschild radii of either SMBH, it can generate a burst of gravitational radiation with a signal-to-noise ratio of \( O(10^5) \) in the LISA waveband, high enough to be observed in Virgo at a rate of 10 per year (Rubbo, Holley-Bockelmann, & Finn, in prep.). In the future, we may use LISA observations in concert with hypervelocity PNe to confirm and further constrain the masses, mass ratios, separation, and even the SMBBH orbital plane within galactic nuclei.

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