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A CAPTURED RUNAWAY BLACK HOLE IN NGC 1277?

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ABSTRACT

Recent results indicate that the compact lenticular galaxy NGC 1277 in the Perseus Cluster contains a black hole of mass $\sim 10^{10}\ M_\odot$. This far exceeds the expected mass of the central black hole in a galaxy of the modest dimensions of NGC 1277. We suggest that this giant black hole was ejected from the nearby giant galaxy NGC 1275 and subsequently captured by NGC 1277. The ejection was the result of gravitational radiation recoil when two large black holes merged following the merger of two giant ellipticals that helped to form NGC 1275. The black hole wandered in the cluster core until it was captured in a close encounter with NGC 1277. The migration of black holes in clusters may be a common occurrence.

Key words: black hole physics – galaxies: active – quasars: general

1. INTRODUCTION

Recent imaging and spectroscopic analysis of the compact lenticular galaxy NGC 1277, located in the Perseus Cluster, indicates a central ultra-massive black hole (UMBH) with a mass of $M_{\rm BH} \approx 1.7 \times 10^{10}\ M_\odot$ (van den Bosch et al. 2012, hereafter VB12). The mass exceeds by two orders of magnitude the value expected on the basis of the galaxy's luminosity. In fact, it is one of the largest black hole (BH) masses reported to date on the basis of stellar dynamics. The origin of this BH is therefore of great interest. Such a massive BH might be expected to form in the center of a giant elliptical galaxy of the kind found in the centers of rich clusters of galaxies (McConnell et al. 2012). Here we propose that the giant BH in NGC 1277 did indeed originate in another, much larger galaxy in the cluster. Its formative event was the merger of two giant elliptical galaxies, each having a massive BH similar to the $\sim 10^{9.8}\ M_\odot$ BH in M87 (Gebhardt et al. 2011). The inspiral and merger of these holes resulted in ejection of the product BH from the merged host galaxy by means of gravitational radiation recoil. We identify the progenitor galaxy with the giant cD galaxy NGC 1275 that dominates the cluster. The ejected BH wandered in the core of the cluster until a chance encounter with NGC 1277 led to its capture and orbital decay into the nucleus. Meanwhile, NGC 1275 reformed its present, relatively small BH through subsequent mergers and accretion of gas.

2. THE ESCAPE

On the basis of dynamical models of the stellar light profile and kinematics of NGC 1277, VB12 derived a BH mass of $(17 \pm 3) \times 10^9\ M_\odot$. This large mass is out of proportion to the host galaxy, for which VB12 give a total stellar mass of $(1.2 \pm 0.4) \times 10^{11}\ M_\odot$. These authors fit the light profile with a disky component plus a central pseudo-bulge containing 24% of the light. Therefore, $M_{\rm BH}$ is 14% of the total stellar mass and $\sim$59% of the bulge mass. In contrast, BHs in galactic nuclei typically have a mass $\sim 10^{-2.9}$ of the bulge mass (Kormendy & Gebhardt 2001). Although NGC 1277 has an unusually large stellar velocity dispersion for its luminosity, $\sigma_* \approx 333$ km s^{-1}, its BH mass still exceeds by nearly an order of magnitude the value expected by the normal $M_{\rm BH}$–σ relationship (VB12). NGC 1277 is such an extreme outlier in the $M_{\rm BH}$–σ plane as to raise the question of a qualitatively different evolutionary history.

BHs with enormous masses similar to that in NGC 1277 have been discovered in recent years. They are mostly found in large elliptical galaxies, often brightest cluster galaxies (BCGs). McConnell et al. (2012) present measurements for four BCGs and summarize earlier work. Notable cases include $M_{\rm BH} = (21 \pm 16) \times 10^9\ M_\odot$ for NGC 4889 in the Coma cluster, $(9.7 \pm 2.5) \times 10^9\ M_\odot$ for NGC 3842 in Abell 1367, $(3.6 \pm 1.1) \times 10^9\ M_\odot$ for NGC 6086 in Abell 2162, and $(6.6 \pm 0.4) \times 10^9\ M_\odot$ for M87 in the Virgo Cluster (McConnell et al. 2012; Gebhardt et al. 2011). Consistent with these measurements, cosmological simulations by Yoo et al. (2007) show that BHs with mass up to $\sim 1.5 \times 10^{10}\ M_\odot$ can form by mergers in massive clusters.

NGC 1277 is located in the core of the Perseus Cluster of galaxies ($z = 0.018$), one of the largest nearby clusters (richness class 2). The dominant galaxy of this cluster is NGC 1275, a large cD galaxy with a radio source (Per A), X-ray emission (Fabian et al. 2011 and references therein), and optical active galactic nucleus activity with a narrow-line (Sy 2) spectrum (Seyfert 1943). The nucleus of NGC 1275 is the most natural place to form a UMBH (followed by NGC 1272, the next brightest galaxy in the cluster). For the largest galaxies, the bulge luminosity is a better predictor of $M_{\rm BH}$ than σ_* (e.g., Lauer et al. 2007a). The luminosity of NGC 1275 is half a magnitude fainter (in $M_{\rm V}$) than NGC 4889, and similar to that of NGC 3842, according to the Hyperleda database (Paturel et al. 2003).[3] Thus, it is reasonable to consider the possibility that a UMBH of the mass of the one in NGC 1277 may have originally formed in NGC 1275.

How might a UMBH have been ejected from the nucleus of NGC 1275? One possibility is gravitational radiation recoil when two BHs merge (Merritt et al. 2004). The escape velocity from the nucleus may be estimated as $v_{\rm esc} \approx 5\sigma_*$ (Merritt et al. 2009), giving $v_{\rm esc} \approx 1250$ km s^{-1} based on $\sigma_* \approx 250$ km s^{-1} for NGC 1275 (Heckman et al. 1985). Gravitational radiation recoil during the final merger of spinning BHs is capable of launching the product BH with kick velocities upward of several thousand km s^{-1} (Campanelli et al. 2007a; González et al.

[3] http://leda.univ-lyon1.fr

2007). The magnitude and probability of the recoil velocity is dependent on the spin alignment of the BHs. Initially, kicks of up to 4000 km s^{-1} were predicted for anti-aligned spins in the orbital plane (Campanelli et al. 2007b). This may be an astrophysically disfavored scenario in the case of gas-rich mergers, as accretion may align the BH spins with the binary orbital axis, limiting recoil velocities to several hundred km s^{-1} (Bogdanović et al. 2007; Dotti et al. 2010). In recent years, further exploration of non-linear spin couplings has indicated that even larger kicks can result from BH spins partially aligned with the orbital angular momentum (Lousto & Zlochower 2011, 2013; Lousto et al. 2012). The probability of a large recoil velocity increases in the light of these results. For both BHs maximally spinning, Lousto & Zlochower (2013) give a maximum kick of 4900 km s^{-1} for equal mass holes, dropping only to 4500 km s^{-1} for $q \equiv M_2/M_1 = 0.5$. The probability is 9% for kicks greater than 1000 km s^{-1} in the "hot accretion" cosmology-based simulations by Lousto & Zlochower (2013). However, this reflects the effect of accretion of gas in aligning the BH spins and suppressing large kicks. The merger leading to the formation of a UMBH in NGC 1275 may well have been "dry," in which case the simulations with random spin orientations by Lousto et al. (2010) may be more appropriate. Figure 26 of Lousto et al. (2010) indicates a fraction ∼25% of mergers with nearly equal masses will give $v_{\rm kick} > 1250$ km s^{-1}. Even this value may be pessimistic, because it assumes a uniform distribution of spin magnitudes, whereas astrophysical BHs are likely to be rapidly spinning because of past accretion and mergers. Furthermore, this value does not reflect the increase in $v_{\rm kick}$ caused by the new "cross kick" and "hangup kick" effects discussed by Lousto & Zlochower (2013) and references therein. Since large kicks can occur for substantially unequal BH masses, there may be more than one opportunity for a merger and BH ejection as a BCG grows. Accordingly, the production of runaway BHs may be a common occurrence in clusters and groups of galaxies.

The escaping BH will carry with it a compact cluster of bound stars (Merritt et al. 2009). Essentially, this will involve the stars that were within the radius such that they are bound to the hole after the kick, $r_{\rm k} = GM_{\rm BH}/v_{\rm kick}^2$. If we follow Merritt et al. in assuming a power-law stellar density profile inside $r_{\rm infl}$ such that $\rho \propto r^{-\gamma}$, then the mass of bound stars as a fraction of the BH mass is $f_{\rm b} \equiv M_{\rm b}/M_{\rm BH} \approx 10^{-2}$ or less for γ in the range 1–2. This is consistent with the more detailed treatment by Merritt et al. Thus, the bound cluster, while an interesting potential diagnostic of the kick velocity in other contexts, will be small in comparison to the observed stellar mass of NGC 1277. The runaway BH must have merged with one or more galaxies to form the system that we observe as NGC 1277 today.

3. THE CAPTURE

For $v_{\rm esc} = 1250$ km s^{-1} from the nucleus of NGC 1275, the runaway UMBH will leave the galaxy with a terminal velocity of 800 km s^{-1} for $v_{\rm kick} = 1500$ km s^{-1} or 1300 km s^{-1} for $v_{\rm kick} = 1800$ km s^{-1}. For comparison, the velocity dispersion of the Perseus Cluster is $\sigma_{\rm cl} \approx 1300$ km s^{-1} (Struble & Rood 1991). However, NGC 1277 is close to NGC 1275 both in position on the sky (80 kpc) and in line-of-sight velocity, with $\Delta v \equiv v_{1277} - v_{1275} = -280$ km s^{-1} (Brunzendorf & Meusinger 1999). It appears to be part of an inner core or subcluster of galaxies encompassing NGC 1275 and NGC 1272. We focus here on the hypothesis that the runaway BH orbited in the vicinity of this subcluster until captured by NGC 1277. Based on inspection of images of the cluster, we approximate the subcluster with an area extending $\pm 0\overset{\prime}{.}1$ (±120 kpc) in R.A. and in declination from a center at $\alpha = 49.9125$, $\delta = +41.5278$. The catalog of Brunzendorf & Meusinger (1999) gives 10 (14) galaxies in this region that are no fainter than 1 mag (2 mag) fainter than NGC 1277. The velocity dispersion of the 10 galaxies is $\sigma \approx 1100$ km s^{-1}. Of these 10 galaxies, 3 including NGC 1277 have radial velocities differing by less than 300 km s^{-1} from NGC 1275. In addition, PGC 12443, only 1.1 mag fainter than NGC 1277, has $\Delta v = 222$ km s^{-1}.

A galaxy can capture the BH in a close encounter if dynamical friction on the galaxy's stellar and dark matter background density ρ robs the hole of enough orbital energy to leave it bound to the galaxy. For supersonic velocities ($v \gg \sigma_*$), the Chandrasekhar dynamical friction formula can be expressed $a_{\rm df} = -4\pi G^2 M\rho \ln\Lambda\, v^{-2}$, where $a_{\rm df}$ is the deceleration, v is the relative velocity, and $\ln\Lambda \approx 6$ (Binney & Tremaine 2008). VB12 find a relatively flat rotation curve with circular velocity $v_{\rm c} \approx 250$ km s^{-1}. For a rough estimate of the dynamical friction efficiency, we therefore take $\rho = v_{\rm c}^2/(4\pi G r^2)$ with $v_{\rm c} \approx$ const, by analogy to a singular isothermal sphere (Binney & Tremaine). Then we have $a_{\rm df} \approx (10^{-9.28}\ {\rm cm\ s^{-2}}) M_{10} v_{\rm c,250}^2 r_{10}^{-2} v_3^{-2}$, where $M_{10} \equiv M_{\rm BH}/(10^{10}\ M_\odot)$, $v_{\rm c,250} \equiv v_{\rm c}/(250\ {\rm km\ s^{-1}})$, $r_{10} \equiv r/(10\ {\rm kpc})$, and $v_3 = v/(10^3\ {\rm km\ s^{-1}})$ is the encounter velocity. We may roughly estimate the energy per unit mass lost to dynamical friction during the encounter as $\Delta E \approx -\pi a_{\rm df}(r_{\rm p}) r_{\rm p}$, where $r_{\rm p}$ is the distance of closest approach, and the factor π is motivated by a straight line encounter at constant velocity. A more detailed calculation would take account of gravitational focusing giving $r_{\rm p} < b$, where b is the impact parameter. This can give $r_{\rm p}$ several times smaller than b for parameters of interest. However, the greater background density near $r_{\rm p}$ is offset by the smaller radius and the higher velocity of the BH. Therefore, for purposes of a rough estimate, we simply consider a straight line encounter and use b for $r_{\rm p}$. Then we find for the energy loss in the encounter relative to the initial energy a ratio $\Delta E/E \approx -10^{-2.01} M_{10} v_{\rm c,250}^2 b_{10}^{-1} v_3^{-4}$. With $M_{10} = 1.7$ and $v_{\rm c,250} = 1$ for NGC 1277, this gives $\Delta E/E \approx -10^{-1.78} b_{10}^{-1} v_3^{-4}$. A higher velocity requires a smaller impact parameter for capture ($\Delta E/E < -1$), because there is more energy to be dissipated and the higher velocity inhibits dynamical friction. The best chance for capture involves an encounter with a relatively low velocity in comparison to the cluster velocity dispersion. For example, capture with $b = 10$ kpc requires $v < 360$ km s^{-1} while $b = 30$ kpc requires $v < 270$ km s^{-1}.

Let us assume that the nine galaxies discussed above (after excluding NGC 1275) are contained in a cubical volume of $(0.24\ {\rm Mpc})^3$, giving a volume density of $n_{\rm gal} \approx 610$ galaxies per cubic Mpc. The mean free path is then $\lambda \approx (f_v n_{\rm gal} \pi b^2)^{-1} \approx 5 f_v^{-1} b_{10}^{-2}$ Mpc, where f_v is the fraction of the encounters with velocity less than v. The typical collision time is then $t_{\rm coll} \approx \lambda/v \approx (10^{9.7}\ {\rm yr}) f_v^{-1} b_{10}^{-2} v_3^{-1}$. If the ejected BH spends much of its time near the apocenter of its orbit and has a relatively low velocity, then we may estimate f_v from the velocity distribution of the galaxies. Of the nine bright galaxies in the subcluster other than NGC 1275, two have velocities within 200 km s^{-1} of NGC 1275 ($\Delta v = +87$ and -78 km s^{-1}). If this fraction applies in all three dimensions, then roughly $f_v \approx (2/9)^3 = 10^{-2.1}$ for $v = 360$ km s^{-1}, since $360/\sqrt{3} = 208$. (A Maxwellian distribution with $\sigma = 1000$ km s^{-1} gives $f_v = 10^{-2.4}$ for $v = 300$ km s^{-1}.) Then with $b_{10} = 1$, we find a capture probability of about $10^{-1.6}$ in a Hubble time. Likewise, for

$b_{10} = 3$ and $v = 270$ km s^{-1}, we find a capture probability of about $10^{-1.1}$ in a Hubble time, where we have scaled f_v as v^3. This assumes that the halo of NGC 1277 persists beyond 30 kpc.

The implication of this very rough estimate is simply that capture of the runaway hole by a galaxy of the size of NGC 1277 is possible. Several authors have discussed evidence for low-velocity subclusters surrounding some BCGs (e.g., Gebhardt & Beers 1991 and references therein). If such a subcluster was in existence at the time that NGC 1275 ejected its BH, the probability of capture may be enhanced. More generally, the ejection event may have occurred substantially earlier in the evolution of the cluster, so that estimates of the probability of capture are necessarily uncertain. Once in orbit, dynamical friction leads to the inspiral of the BH to the center of the galaxy in a time $\sim 10^8$ yr. Thus, if the capture occurred more than a billion years ago, there has been ample time for the galaxy to settle down to its current, symmetrical appearance.

4. DISCUSSION

The scenario outlined here is speculative, but it involves known processes. Any explanation of the UMBH in NGC 1277 is likely to involve exceptional events.

Is the present-day appearance of NGC 1275 consistent with the idea that it long ago formed and ejected a UMBH? One indicator might be the presence of an unexpectedly small BH in the nucleus today. Scaling linearly in L_V from NGC 4889 or NGC 3842, one might expect $M_{BH} \approx 10^{9.5}$ $M_\odot$ in NGC 1275. In contrast, Wilman et al. (2005) derive $M_{BH} \approx 10^{8.5}$ $M_\odot$ from a study of the molecular gas in the nucleus. A larger value $M_{BH} \approx 10^{8.9}$ $M_\odot$ is derived by Scharwächter et al. (2013), although these authors regard their measurement as an upper limit because of the abundance of gas in the nucleus. These values equal or exceed the value predicted by the M_{BH}–σ_* relationship (Wilman et al. 2005). However, Lauer et al. (2007a) argue that for the largest galaxies, M_{BH} is better predicted by stellar luminosity than by velocity dispersion, in which case the BH in NGC 1275 is indeed undersized. The observed BH may have been regenerated by means of mergers or accretion of gas following the ejection event. Merger tree simulations by Volonteri (2007) indicate that a dark matter halo of mass $\sim 10^{12}$ $M_\odot$ will likely have undergone one or two major mergers more recently than $z = 0.5$, likely introducing a substantial BH that would spiral to the nucleus of the merged galaxy. Alternatively, Inoue et al. (1996) find 3×10^{10} $M_\odot$ of molecular gas inside a radius of 10 kpc in NGC 1275, with 6×10^9 $M_\odot$ contained in a ring of radius 1.2 kpc around the nucleus, so that ample gas is available to form a massive BH. The physics regulating the M_{BH}–σ_* relationship is not well established, and some feedback process might lead to regrowth of a BH to a limiting value similar to the one given by the normal M_{BH}–σ_* relationship (e.g., Di Matteo et al. 2007).

Many large elliptical galaxies have cores in which the density profile increases toward the center more gently than in galaxies with a central cusp. One explanation of these cores is scouring by a binary SMBH during its inspiral to the nucleus (Milosavljević & Merritt 2001). Lauer et al. (2007a, 2007b) find that cores are prevalent in brighter ellipticals, with $M_V < -21$. The mass deficit involved in these cores is of order the central BH mass. If NGC 1275 formed and ejected a UMBH, then a substantial core might be expected, with a radius $\sim$1 kpc and a mass deficit out of proportion to the mass of the current BH. (Postman et al. (2012) find a large core in A2261-BCG and suggest that it may have ejected a UMBH.) Optical and ultraviolet surface brightness profiles for NGC 1275 by Marcum et al. (2001) show no break down to a radius $\sim$0.3 kpc. However, Lauer et al. (2007a) find considerable scatter in core mass and radius relative to M_{BH}. Furthermore, Postman et al. (2012) note that cores that have lost their central BH may quickly be filled in by inspiralling nuclei from captured galaxies.

Is the present-day appearance of NGC 1277 consistent with this scenario? One possible difficulty is the lack of a classical bulge. VB12 report only a psuedo-bulge in NGC 1277 having 24% of the light, the rest being in a flattened disk. Simulations of the capture are needed to determine whether a merger with a BH having 14% of the stellar mass of the galaxy can avoid forming a bulge and disrupting the disk. The merger could add a substantial amount of angular momentum to the galaxy. VB12 find a rotational velocity $v_{rot} \approx 250$ km s^{-1} for NGC 1277, and an effective radius for the starlight of $R_e = 1.6$ kpc. If the BH approaches with an impact parameter b and a relative velocity v_{rel} , then its angular momentum as a fraction of the current rotational angular momentum of the galaxy is

$$J_{BH}/J_{gal} \approx 10^{0.2} b_{10} M_{10} v_{rel,3}, \quad (1)$$

where $b_{10} = b/10$ kpc, $M_{10} = M_{BH}/10^{10}$ $M_\odot$, and $v_{rel,3} = v_{rel}/10^3$ km s^{-1}. The merger could have contributed substantially to the current rotation of the galaxy.

BH migration in galaxy groups and clusters may occur with some frequency. Volonteri (2007) discusses the ejection of BHs following galaxy mergers in cosmological simulations and illustrates how this can contribute downward scatter in the M_{BH}–bulge relationships. As noted by Blecha et al. (2011), runaway BHs may stand a good chance to be reincorporated into adoptive galaxies. This can contribute upward scatter to the BH–bulge relationship when large BHs fall into relatively small galaxies. NGC 1277 may be an extreme example.

If the UMBH in NGC 1277 grew by accretion, then the average growth rate over the Hubble time is $\dot{M} \approx 1$ $M_\odot$ yr^{-1}. Luminous accretion at this rate produces a luminosity $L \approx 10^{46}$ erg s^{-1}. The relative proximity of NGC 1277 to the Milky Way together with the observed space density of luminous quasars places constraints on the growth of the UMBH by accretion of gas (Fabian et al. 2013). These requirements are eased if the UMBH reached its final size by means of mergers.

Our scenario requires a combination of seemingly unlikely events. NGC 1275 must have produced an exceptionally massive BH though a merger of two fairly equal mass BHs, themselves already comparable to the largest BHs in nearby BCGs. The merger must have had a favorable spin–orbit configuration leading to a large recoil velocity. The runaway BH must have been captured by NGC 1277, an unusual galaxy in terms of its velocity dispersion and compactness. However, rare events do occur, and it is important to consider all possibilities. Confirmation of the BH migration scenario would have significant implications for the evolution of galaxies and for our understanding of general relativity in the strong field limit.

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