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Possible evidence for the ejection of a supermassive black hole from an ongoing merger of galaxies

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ABSTRACT

Attempts of Magain et al. to detect the host galaxy of the bright quasi-stellar object (QSO) HE0450–2958 have not been successful. We suggest that the supermassive black hole (SMBH) powering the QSO was ejected from the observed ultraluminous infrared galaxy (ULIRG) at the same redshift and at 1.5 arcsec distance. Ejection could have been caused either by recoil due to gravitational wave emission from a coalescing binary of SMBHs or the gravitational slingshot of three or more SMBHs in the ongoing merger of galaxies which triggered the starburst activity in the ULIRG. We discuss implications for the possible hierarchical build-up of SMBHs from intermediate and/or stellar mass black holes, and for the detection of coalescing supermassive binary black holes by *LISA*.

Key words: black hole physics – stellar dynamics – celestial mechanics – binaries: general– galaxies: nuclei.

1 INTRODUCTION

In their recent paper, Magain et al. (2005) describe observations of the bright quasar HE0450–2958 which suggest that its host galaxy is at least six times fainter than expected for the typical relation of black hole mass to bulge luminosity. Such efficient black hole formation, with a large black hole mass surrounded by a relatively small mass of stars, would be somewhat surprising. In this Letter we suggest an alternative explanation for their observation: namely that the supermassive black hole (SMBH) powering the quasar has been ejected from the centre of an ongoing merger of galaxies during the violent dynamical interaction of two or more black holes. A plausible location for such an event is the ultraluminous infrared galaxy (ULIRG) also described by Magain et al., which lies at a distance of ∼1.5 arcsec.

ULIRGs are known to be powered by bursts in star formation activity that are often triggered by the merger of two (or more) gas-rich galaxies. Each of the merging galaxies is expected to have contained at least one SMBH with a mass that scales roughly with the mass of the bulge of the merging galaxies (e.g. Kormendy & Richstone 1995). The black holes in the merging galaxies will sink quickly to the centre of the merger product and will form a hard binary (Begelman, Blandford & Rees 1980; Milosavljevic & Merritt 2001). The further evolution is somewhat uncertain. Hardening by gravitational interaction with stars passing close to the binary will be much slower than the typical duration of the star formation bursts in ULIRGs. However, if the binary were submerged in a gaseous disc which formed from gas funnelled to the centre during the ongoing merger the separation of the binary could shrink fast to the point where gravitational radiation leads to rapid coalescence (Begelman et al. 1980). Of course the dynamical interaction could be more complex if one or both of the two merging galaxies contained binary or multiple SMBHs. There are two basic gravitational processes that can eject one or more of the black holes from the merging galaxies, the gravitational radiation recoil due to asymmetric emission of gravitational radiation and the gravitational slingshot during the violent dynamical interaction of three or more black holes.

This Letter is arranged as follows. We will briefly assess the required ejection velocity in Section 2. We will then discuss the two ejection mechanisms and their possible implications for the build-up of SMBHs from intermediate mass and/or stellar mass black holes in Sections 3 and 4. We discuss in Section 5 how the ejected black hole is likely to be supplied with material. In Section 6 we summarize and discuss our results.

2 THE REQUIRED KICK VELOCITY

HE0450–2958 is at redshift $z = 0.285$. Assuming standard cosmological parameters, 1 arcsec is equivalent to ∼4.3 kpc at that redshift. In projection, the quasar is observed to be around 1.5 arcsec away from the centre of the companion galaxy. In order to see whether the black hole merger and ejection picture works, let us assume that the distance is in fact 10 kpc. Assuming an average velocity of 300 km s^{-1}, the black hole would take about 30 Myr to travel the required distance, which is consistent with the picture that a starburst was triggered by a merger involving the companion galaxy some 100 Myr ago (Canalizo & Stockton 2001). This velocity is

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consistent with the observed radial velocity difference between the quasar and the companion galaxy which is about 130 km s^{-1} (Magain et al. 2005). Assuming a lifetime of a the starburst phase in a ULIRG of 10^7 to 10^8 yr, an average velocity of 100–1000 km s^{-1} is required to travel the observed distance. Note, however that the black hole is likely to sit deep in the potential well of the dark matter halo hosting the ULIRG and therefore may have been decelerated. We can only speculate about the properties of the dark matter halo hosting the ongoing merger of galaxies. The rather large mass of the black hole powering HE0450–2958 suggests however that its mass and virial radius are large. Ferrarese (2004) has established an empirical relation between the circular velocity of the dark matter (DM) haloes which host galactic bulges and the mass of the central SMBH. If the black hole radiates at 50 per cent of its Eddington luminosity, as assumed by Magain et al., the mass of the central black hole is $\sim 8 \times 10^8$ $M_{\odot}$. This would correspond to a mass of the dark matter halo of $\sim 10^{13}$ $M_{\odot}$ and a virial radius of $\sim$300 kpc. These values are somewhat larger than for typical ULIRGs (Tacconi et al. 2002). The escape velocity from such a dark matter halo will be about $\sim$1000 km s^{-1}. It thus appears indeed likely that the black hole is being decelerated and will not be able to escape the DM halo, unless the average velocity of the SMBH in HE0450–2958 is at the upper limit of our estimate or we have overestimated the escape velocity of the DM halo. Obviously if the black hole is decelerated then the current velocity will be lower than the average velocity since ejection. Note further that unless the ejection velocity exceeds 50 per cent of the escape velocity the black hole would be expected to fall back to the centre of the potential well in 10^8 yr or less (Merritt et al. 2004).

3 EJECTION BY GRAVITATIONAL RADIATION RECOIL

When two black holes of unequal mass merge, the merger product will receive a kick due to the asymmetric emission of gravitational radiation (Fitchett & Detweiler 1984; Redmount & Rees 1989). Full numerical simulations of this process are not yet possible. Analytical calculations rely on perturbation theory and are somewhat uncertain for mass ratios of the merging black holes which are not small. The most recent calculations of this kind by Favata, Hughes & Holz (2004) and Blanchet, Qusailah & Will (2005) obtain values of 50–300 km s^{-1}. The exact value of the kick velocity is a function of the black holes masses and spins. The major question is posed by the required very short merging time-scale for the black holes. The interaction with a gaseous disc could in principle lead to a fast merging of the black holes (Begelman et al. 1980; Armitage & Natarajan 2002; Escala et al. 2004). If this is indeed what has happened in HE0450–2958, this is good news for the planned space-based gravitational wave interferometer LISA[1], which aims to detect the merging of SMBH binaries albeit of somewhat smaller mass.

The ejection of a SMBH also has very interesting implications for models of the joint hierarchical build-up of SMBHs and galaxies (e.g. Kauffmann & Haehnelt 2000). If HE0450–2958 was indeed ejected by recoil due to gravitational radiation, the recoil velocities would have to lie towards the upper end of the range suggested by Favata et al. (2004) and Blanchet et al. (2005) Binary mergers would then easily eject black holes from dwarf galaxies and could lead to the displacement of SMBHs to the outer parts of even the most massive galaxies (Merritt et al. 2004). The hierarchical build-up of SMBHs would then need to be highly fine-tuned if it were to extend to stellar mass black holes. Volonteri, Haardt & Madau (2002) have discussed such a model where the stellar mass black hole seeds are not much more numerous than the number of SMBHs in bright galaxies, and binary mergers in small galaxies are relatively rare. Note further that Haehnelt & Kauffmann (2002, see also Volonteri, Haardt & Madau 2003) have argued that the merging of SMBHs has to occur on time-scales of less than a Hubble time to avoid excessive scatter in the $M_{\bullet} - \sigma_*$ relation between black hole mass and the stellar velocity dispersion of galactic bulges (Gebhardt et al. 2000; Ferrarese & Merritt 2000). Otherwise there should be the occasional bright elliptical galaxy with no (or a significantly underweight) central black hole, which appears not to be the case (see Merritt & Milosavljevic 2005 for a review on supermassive binary black holes and evidence for their coalescence).

4 EJECTION BY GRAVITATIONAL SLINGSHOT

It is far from certain that the gas driven to the centre of a ULIRG will actually lead to the fast merging of a supermassive binary. Most of the gas may actually be consumed at larger radii by the starburst or may be accreted by the two black holes without efficiently hardening the binary black hole. An alternative scenario for the ejection of a black hole during a galaxy mergers is the gravitational slingshot (Saslaw, Valtonen & Aarseth 1974; Hut & Rees 1992). One or perhaps even both of the galaxies may already have contained a hung-up, hard supermassive binary black hole. When the two galaxies merge the black holes will undergo a violent dynamical interaction. To be more specific, consider the case of a binary plus a single black hole. The most likely outcome is that the lightest of the black holes will be flung out with a velocity comparable to the circular velocity of the hard binary. The two other black holes will stay bound to each other and receive a smaller kick in order to conserve the total momentum. Yu (2002) has used the stellar density profiles of nearby galaxies to estimate the most likely circular velocity of hung-up binaries assuming that they contain supermassive binary black holes hardened by scattering of stars. The results depend on the details of the stellar orbits, assumptions about loss cone refilling and the mass ratio of the binary. The values range from 500–2000 km s^{-1}. This and the rather large mass of the black hole in HE0450–2958 make it then perhaps more likely that a lighter black hole of $\sim 10^7$–10^8 $M_{\odot}$ was flung out at a speed comparable to the circular velocity of a hung-up binary and that the black hole powering HE0450–2958 is the binary that is ejected at somewhat lower speed in the opposite direction. If the lighter black hole is much less massive than the binary, the binary has to be very hard if the binary is to be ejected with adequate speed. The scattering of stars would then be too slow to bring the third black hole close enough for the gravitational slingshot during the lifetime of the ULIRG, but interaction with a gas disc could drive the third black hole in on the required time-scale. Note that Yu (2002) will have underestimated the circular velocity at which supermassive binary black holes in nearby galaxies should have got hung up if the hardening of the binaries has significantly affected the stellar distribution at the centre of these galaxies.

If the SMBH in HE0450–2958 was ejected by a gravitational slingshot, the possible implications for the hierarchical build-up of SMBHs are less clear. Hardening by scattering of stars should be more efficient in small galaxies where loss cone refilling should

[1] http://lisa.jpl.nasa.gov/

occur on shorter time-scales (Yu 2002). The presence of a hung-up hard supermassive binary is thus much less likely in small galaxies. The second ejection scenario would therefore not necessarily be bad news for *LISA* which will be sensitive to black holes of smaller mass.

5 FEEDING HE0450–2958

Magain et al. claim that their deconvolution of the *HST* image of HE0450–2958 has revealed a blob of gas to one side of the point-like quasi-stellar object (QSO) emission opposite to the location of the ULIRG. The blob has a diameter of ∼2 kpc. Its emission shows no sign of a stellar continuum, but is bright in H_α, H_β and $O_{\rm III}$ with line ratios consistent with no dust absorption. Magain et al. interpret this blob as an emission nebula excited by the QSO emission. The obvious question is whether this blob is related to the feeding of the SMBH in HE0450–2958. The presence of such a gas cloud at a distance of 10 kpc from an ULIRG is not implausible, as the merging galaxies powering ULIRGs are gas-rich and are surrounded by substantial amounts of tidal debris. Could this cloud actually feed the SMBH in HE0450–2958? If the black hole accretes at the Bondi–Hoyle accretion rate it would have to accrete from material with a density $n_{\rm gas} \sim 15(\eta/0.1)^{-1}\,(v_{\rm bh}/200\,{\rm km\,s^{-1}})^3\,{\rm cm}^{-3}$ to produce the observed luminosity, where η is the efficiency for turning rest mass energy into radiation and $v_{\rm bh}$ is the relative velocity between black hole and gas cloud. The SMBH in HE0450–2958 must have travelled at an average velocity $\gtrsim 100\,{\rm km\,s^{-1}}$, but as discussed in Section 2 the current velocity could be smaller than the ejection velocity. If the SMBH in HE0450–2958 indeed sits in a potential well corresponding to a 1D velocity dispersion of 300 km s^{-1}, as suggested by the $M_\bullet - \sigma_*$ relation, then the mass contained in a 10-kpc sphere would be $4 \times 10^{11}\,{\rm M}_\odot$. The gas distribution should be inhomogeneous. The probability for hitting material of the density for Bondi–Hoyle accretion at the required rate would be $0.005(v_{\rm bh}/200\,{\rm km\,s^{-1}})^{-3}\,(M_{\rm gas}/10^{10}\,{\rm M}_\odot)$, where $M_{\rm gas}$ is the mass of gas at this density. Even for a rather small fraction of the total mass in gas at the right density this is thus not implausibly low given the number of observed ULIRGs. It would, however, imply that ejection of a supermassive (binary) black hole is a common phenomenon in ULIRGs. The accretion from a blob of such density at a rate close to the Eddington rate should not be much different from the accretion during the typical QSO phase of an accreting black hole at the centre of merging galaxies. Unfortunately, we would therefore not expect a special spectral signature, other than that obscuration is less likely – and indeed on first sight the spectrum of HE0450-2958 appears to show no peculiarities.

An alternative option is that the ejected black hole is fed by accretion of material that remained bound to the black hole when it was ejected from the host galaxy. An ejected binary should carry with it a substantial amount of gas that is gravitationally bound to it. Considering a sphere of material of total mass $10^9\,{\rm M}_\odot$, one notes that the surface escape speed exceeds 300 km s^{-1} for radii less than ∼100 pc. Any gas within this radius would have been retained by the (merging) black hole(s) when they received a kick of 300 km s^{-1}. Interestingly, 100 pc is the upper limit Magain et al. (2005) quote for the half-light radius for the emission directly surrounding the QSO. We therefore conclude that the black hole should have been able to retain enough fuel to power the quasar during the previous 30 Myr. The location of HE0450–2958 at the edge of the observed gas blob would then be most plausibly explained as being due to the driving of a wind by the QSO activity. In the case of ejection by a gravitational slingshot, there is the intriguing, but not very likely, possibility of the detection of one (perhaps even two) further QSO(s) on the other side of the ULIRG. The distance could be as large as an arcmin or more. These would almost certainly be significantly fainter and would have to have been ejected with sufficient fuel, as feeding a fast-moving black hole at a large distance from the ULIRG would be very difficult otherwise.

6 SUMMARY AND DISCUSSION

We have discussed here the possibility that the SMBH powering the bright quasar HE0450–2958 has been ejected during the ongoing merger of galaxies responsible for the nearby ULIRG. The projected distance between the ULIRG and HE0450–2958 is consistent with an average speed of 300 km s^{-1} since ejection 30 Myr ago. Feeding could be either by accretion from the gas blob located next to HE0450–2958 on the opposite side from the ULIRG or by accretion of material which was flung out from the centre of the merger together with the black hole. It is likely that the ejection velocity is not sufficient to escape the surrounding dark matter halo and that the black hole has been decelerated. The two plausible ejection scenarios have interesting implications for the possible hierarchical build-up of SMBHs from intermediate and/or stellar mass black holes. If ejection occured by gravitational radiation recoil this would be the first identification of the coalescence of a binary of SMBHs. The coincidence of the coalescence of the black hole binary and the starburst activity in the ULIRG then suggests that both are causallly connected and that the gas funnelled to the centre during the merger of the galaxies has led to the rapid hardening of a supermassive binary that either existed in the merging galaxies before the merger or was formed during the merger. Rapid merging of supermassive binary black holes may then be widespread in merging galaxies. This would be excellent news for the planned space-based gravitational wave interferometer *LISA*. It may also argue for the formation of SMBHs from rather massive seed black holes: the alternative models, assuming the hierarchical build-up of SMBHs from intermediate and/or stellar mass black holes, would need considerable fine-tuning to avoid ejection from shallow potential wells at high redshift.

Different conclusions are to be drawn if the ejection was caused by a gravitational slingshot during the violent dynamical interaction of three or more black holes. The occurrence of such a slingshot would suggest that one or both of the galaxies contained a hung-up, hard binary and that the accretion of gas may not be efficient in hardening supermassive binary black holes to the point of rapid coalescence due to gravitational wave emission. There may then also be the small chance of the discovery of one or two fainter QSOs on the other side of the ULIRG. In the case of ejection by a gravitational slingshot, *LISA* and models for the hierarchical build-up of SMBHs from intermediate and/or stellar mass black holes would have to rely on efficient hardening by scattering of stars into the loss cone of supermassive binary black holes in shallow potential wells.

We end with the caveat that further scrutiny of HE0450-2958 may still reveal a very underluminous and compact host galaxy, which would be interesting in its own right.

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