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

Martin G. Haehnelt\(^1\)*, Melvyn B. Davies\(^2\) and Martin J. Rees\(^1\)

\(^1\)Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA
\(^2\)Lund Observatory, Box 43, SE–221 00, Lund, Sweden

20 March 2022

ABSTRACT
Attempts of Magain et al (2005) to detect the host galaxy of the bright QSO HE0450–2958 have not been successful. We suggest that the supermassive black hole powering the QSO was ejected from the observed ULIRG at the same redshift and at 1.5 arcsec distance. Ejection could have either be caused by recoil due to gravitational wave emission from a coalescing binary of supermassive black holes or the gravitational slingshot of three or more supermassive black holes in the ongoing merger of galaxies which triggered the starburst activity in the ULIRG. We discuss implications for the possible hierarchical build-up of supermassive black holes 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; Celestial mechanics, stellar dynamics; 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 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 ultra-luminous infra-red galaxy (ULIRG) also described by Magain et al. which lies at a distance of \(\sim 1.5\) arcsec.

ULIRGs are known to be powered by bursts in star formation activity which 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 supermassive black hole 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 supermassive black holes. 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 supermassive black holes 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.

* E-mail: haehnelt@ast.cam.ac.uk (MGH); mbd@astro.lu.se (MBD); mjr@ast.cam.ac.uk (MJR)
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THE REQUIRED KICK VELOCITY

HE0450–2958 is at a redshift, \( z = 0.285 \). Assuming standard 
cosmological parameters, 1 arc second is equivalent to ~4.3 
kpc at that redshift. In projection, the quasar is observed 
to be around 1.5 arc seconds 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, 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 consistent with the observed radial 
velocity difference between the quasar and the companion 
galaxy which is about 130 km/s (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 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 prop-
terties 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 ra-
dius are large. Ferrarese (2004) has established an empirical 
relation between the circular velocity of the DM halos host-
ing galactic bulges and the mass of the central supermassive 
black hole. If the black hole radiates at 50% of its Edding-
ton 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 ~ \( 10^{13} \) M\(_\odot\) and a virial 
radius of ~ 300 kpc. These values are somewhat larger than 
for typical ULIRGs (Tacconi et al. 2002). The escape ve-
locity from such a dark matter halo will be about \( \sim 1000 \) 
km/s. It appears thus indeed likely that the black hole is be-
ing decelerated and will not be able to escape the DM halo 
unless the average velocity of the supermassive black hole 
in HE0450–2958 is at the upper limit of our estimate or we 
have overestimated the escape velocity of the DM halo. Ob-
viously if the black hole is decelerated the current velocity 
will be lower than the average velocity since ejection. Note 
further that unless the ejection velocity exceeds 50% 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).

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EJECTION BY GRAVITATIONAL 
RADIATION RECOIL

When two black holes of unequal mass merge, the merger 
product will receive a kick due to the asymmetric emi-
sion 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 et al 2004 
and Blanchet et al 2005 obtain values of 50 – 300 km/s. The 
exact value of the kick velocity is a function of the black 
holes masses and spins. The major question mark is posed 
by the required very short merging time scale for the black 
holes. The interaction with a gaseous disc could in prin-
ciple 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 at detecting the merging of 
supermassive black hole binaries albeit of somewhat smaller 
mass.

The ejection of supermassive black hole has also very 
interesting implications for models for the joint hierarchi-
cal build-up of supermassive black holes and galaxies (e.g. 
Kauffmann & Haehnelt 2000). If HE0450–2958 was indeed 
ejected by recoil due to gravitational radiation, the recoil ve-
locities would have to lie towards the upper end of the range 
suggested by Favata et al. and Blanchet et al. Binary merg-
ers would then easily eject black holes from dwarf galaxies 
and could lead to the displacement of supermassive black 
holes to the outer parts of even the most massive galaxies 
(Merritt et al. 2004). The hierarchical build-up of super-
massive black holes would then need to be highly fine tuned 
if it were to extend to stellar mass black holes. Volonteri 
et al (2002) have discussed such a model where the stellar 
mass black hole seeds are not much more numerous than the 
number of supermassive black holes in bright galaxies, and 
binary mergers in small galaxies are relatively rare. Note fur-
ther that Haehnelt & Kauffmann (2002, see also Volonteri 
et al. 2003) have argued that the merging of supermassive 
black holes 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 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 under-weight) central 
black hole which appears not to be the case (see Merritt & 
Milosavljevic 2004 for a review on supermassive binary black 
holes and evidence for their coalescence).

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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 su-
permassive binary. Most of the gas may actually be con-
sumed at larger radii by the starburst or may be accreted 
by the two black holes without efficiently hardening the bi-
nary black hole. An alternative scenario for the ejection of 
a black hole during a galaxy merger is the gravitational sling-
shot (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 
vigorous 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

\(^1\) http://lisa.jpl.nasa.gov/
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 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 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. 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 $\sim 10^7 \rightarrow 10^8 M_\odot$ 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. 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 supermassive black hole in HE0450–2958 was ejected by a gravitational slingshot the possible implications for the hierarchical build-up of supermassive black holes are less clear. Hardening by scattering of stars should be more efficient in small galaxies where loss cone refilling should 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 QSO emission opposite to the location of the ULIRG. The blob has a diameter of $\sim 2$ kpc. Its emission shows no sign of a stellar continuum, but is bright in $H_\alpha$, $H_\beta$ and $O_{III}$ 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 10kpc of an ULIRG is not implausible as the gravitational slingshot there is the intriguing but not very likely possibility of the detection of one perhaps even two further QSOs 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 be 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 supermassive black hole 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 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 supermassive black holes from intermediate and/or stellar mass black holes. If ejection occurred by gravitational radiation recoil this would be the first identification of the coalescence of a binary of supermassive black holes. The coincidence of the coalescence of the black hole binary and the starburst activity in the ULIRG then suggests that both are causally connected and that the gas funneled 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 supermassive black holes from rather massive seed black holes: the alternative models, assuming the hierarchical build-up of supermassive black holes 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 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 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 supermassive black holes 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.

ACKNOWLEDGMENTS

MBD is a Royal Swedish Academy Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation. We thank the Swedish Royal Academy of Sciences for an invitation to the Crafoord symposium 2005 in Stockholm where this work was initiated by a presentation by David Elbaz. We further thank Mitch Begelman for helpful comments on the manuscript.

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