

## Review Article

# Recoiling Black Holes: Electromagnetic Signatures, Candidates, and Astrophysical Implications

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Supermassive black holes (SMBHs) may not always reside right at the centers of their host galaxies. This is a prediction of numerical relativity simulations, which imply that the newly formed single SMBH, after binary coalescence in a galaxy merger, can receive kick velocities up to several 1000 km/s due to anisotropic emission of gravitational waves. Long-lived oscillations of the SMBHs in galaxy cores, and in rare cases even SMBH ejections from their host galaxies, are the consequence. Observationally, accreting recoiling SMBHs would appear as quasars spatially and/or kinematically offset from their host galaxies. The presence of the “kicks” has a wide range of astrophysical implications which only now are beginning to be explored, including consequences for black hole and galaxy assembly at the epoch of structure formation, black hole feeding, and unified models of active galactic nuclei (AGN). Here, we review the observational signatures of recoiling SMBHs and the properties of the first candidates which have emerged, including follow-up studies of the candidate recoiling SMBH of SDSSJ092712.65+294344.0.

## 1. Introduction

Interaction and merging of galaxies occurs frequently throughout the history of the universe. If both galaxies do harbor SMBHs, binaries will inevitably form [1]. Galaxy mergers are believed to be the sites of major black hole growth, and an active search for SMBH pairs and binaries of wide and small separations is currently ongoing (see [2] for a review of electromagnetic signatures). When the two SMBHs ultimately coalesce, they are a source of strong gravitational waves. These are emitted anisotropically during coalescence and carry away linear momentum (e.g., [3]). As a result, the newly formed single SMBH recoils. Configurations of coalescing black holes can lead to kick velocities up to several thousand km/s (e.g., [4–16]; review by [17]). In the initial computations, kick velocity was highest for maximally spinning equal-mass black hole binaries with antialigned spins in the orbital plane (“superkicks”). More recently, based on a new recoil formula, Lousto and Zlochower [18] have estimated that recoil velocities up to 5000 km/s can be reached in configurations with spins partially aligned with the orbital

angular momentum. In unbound encounters (not likely to occur in astrophysical environments), the kick velocity can exceed 15 000 km/s [19, 20].

After the kick, the recoiling SMBH will oscillate about the core of its host galaxy [21, 22] or will even escape, if its kick velocity exceeds the escape velocity of its host. In a “typical,” gas-poor galaxy, a black hole kick velocity of 500 km/s will result in an initial amplitude of ~200 pc, and an oscillation timescale of order  $10^7$  yrs (Figure 1 of [23]). The kicks, including those large enough to remove SMBHs from their host galaxies, have potentially far-reaching astrophysical consequences, including for SMBH and galaxy assembly and AGN statistics. Upon recoil, the most tightly bound gas will remain bound to the recoiling black hole, and therefore high-velocity kicks imply the existence of interstellar and intergalactic quasars (e.g., [21–30]). Identifying recoiling SMBHs through observations is of great interest. Several key electromagnetic signatures of kicks have been predicted in the last few years, and first candidate recoiling SMBHs have emerged. This chapter is structured as follows. In Section 2, an overview of the predicted electromagnetic signatures of

recoiling SMBHs is given. In Section 3 the event frequency is discussed, while Sections 4 and 5 provide a review of the published candidate recoiling SMBHs. Section 6 explores consequences of recoil for unified models of AGN. Section 7 concludes with some astrophysical consequences and important future studies.

## 2. Electromagnetic Signatures of Recoiling SMBHs

**2.1. Broad Emission-Line Shifts.** After the kick, matter remains bound to the recoiling SMBH within a region whose radius  $r_k$  is given by

$$r_k = \frac{GM_{\text{BH}}}{v_k^2} \approx 0.4 \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right) \left( \frac{v_k}{10^3 \text{ km s}^{-1}} \right)^{-2} \text{ pc}, \quad (1)$$

where  $v_k$  is the kick velocity [31]. This region is on the order of the size of the broad line region (BLR) of AGN [32]. The accretion disk and BLR will therefore typically remain bound to the SMBH while the bulk of the host galaxy's narrow-line region (NLR) will remain behind. The accreting recoiling SMBH will therefore appear as an off-nuclear "quasar" as long as its accretion supply lasts. However, spatial offsets are challenging to detect even with the *Hubble Space Telescope* (HST) except in the nearby universe. The kinematic Doppler shifts of the broad emission lines are, in principle, easy to measure out to high redshifts. Spectroscopically, recoiling SMBHs will appear as AGN which have their broad emission lines kinematically shifted by up to  $\sim 5000$  km/s with respect to their NLRs.

Bonning et al. [33] suggested several criteria, how to identify a recoiling SMBH spectroscopically. Apart from (1) the kinematic shift of the BLR, a candidate recoiling SMBH should (2) show symmetric broad line profiles, it should (3) lack an ionization stratification of its narrow emission lines, and it should (4) not show any shift between broad MgII and the broad Balmer lines. (In practice, individual recoil candidates may show some (temporary) deviations from this scheme, or exhibit extra features. For instance, just after recoil, the BLR emission profiles would likely be asymmetric. Feedback trails from partially bound gas and disk winds would produce emission-line signatures at various kinematic shifts between zero and the recoil velocity. Once the SMBH has travelled beyond the extent of the classical NLR of a few kpc extent, low-density "halo" gas would dominate the optical narrow-line spectrum, with emission-line ratios characteristically different from the classical NLR.) One object, the quasar SDSSJ092712.65+294344.0, fulfills all of these four criteria and is therefore an excellent candidate for a recoiling SMBH [34]. It will be further discussed in Section 4, together with several other candidate recoiling BHs. More candidates may hide in large samples of peculiar broad-line emitters recently identified in the Sloan Digital Sky Survey (SDSS; [35]).

**2.2. Flaring Accretion Disks.** In gas-rich mergers, an accretion disk is likely present, even though the inner part of the disk may only re-form after binary coalescence [27, 36–38]. UV, soft X-ray, and IR flares could result from shocks in the

accretion disk surrounding the SMBH just after recoil, or when the inner disk reforms (e.g., [38–46]). These flares may last  $\approx 10^4$  yrs and may be detectable in current and future sky surveys.

**2.3. Tidal Disruption Flares from Stars Around Recoiling SMBHs.** Even in the absence of an accretion disk, ejected SMBHs will always carry a retinue of bound stars. Observable effects related to these stars are therefore perhaps the most universal signature of recoil. As the SMBH moves through the galaxy, the bound, and unbound, stars are subject to tidal disruption, leading to powerful X-ray flares of quasar-like luminosity [47, 48], which would appear off-nuclear or even intergalactic. Komossa and Merritt [49] computed disruption rates for the bound, and the unbound, stellar populations under recoil conditions. In the resonant relaxation regime, they showed that the rates are of order  $10^{-6}$  yr<sup>-1</sup> for a typical postmerger galaxy (Figure 2 of [49]); smaller than, but comparable to, rates for nonrecoiling SMBHs. At an early phase of recoil, the tidal disruption rate can be much higher, when the SMBH experiences a full loss cone, and travels through the clumpy core environment of a recent merger [49]. The flare rate may temporarily reach values as high [50] as during the peak of the premerger binary phase [51].

Another signature related to the stars bound to the recoiling SMBH is episodic X-ray emission from accretion due to stellar mass loss. Mass loss provides a reservoir of gas, and therefore also *optical emission lines from gas at the recoil velocity* even in the initial absence of a gaseous accretion disk. Other consequences include the presence of intergalactic planetary nebulae and supernovae, after the ejected SMBH has left its host galaxy [49].

All these signals would generically be associated with recoiling SMBHs, whether or not the galaxy merger is gas-rich or dry, and whether or not an accretion disk is present initially, and they would continue episodically for a time of  $\sim 10$  Gyr [49].

**2.4. Hypercompact Stellar Systems.** While the "tidal recoil flares" are very luminous and can be detected out to very large distances, the compact system of bound stars itself will be detectable in the nearby universe, and would resemble a globular cluster in total luminosity, but with a much greater velocity dispersion due to the large binding mass  $M_{\text{BH}}$  [49]. Merritt et al. [52] worked out the properties of these "hypercompact stellar systems" (HCSSs), and related the structural properties (mass, size, and density profile) of HCSSs to the properties of their host galaxies and to the amplitude of the kick. Since the kick velocity is encoded in the velocity dispersion of the bound stars, future detection of large samples of HCSSs would therefore allow us to determine empirically the kick distribution, and therefore the merger history of galaxies in clusters. Nearby clusters of galaxies are best suited to search for and identify HCSSs, and  $\sim 100$  of them should be detectable within 2 Mpc of the center of the Virgo cluster [52]. Depending on the merger history of our Milky Way [53], and the merger history of black holes in its globular clusters [54], 100s of low-mass HCSSs and rogue black holes

may reside in the halo of our Milky Way, and a search for them is underway [55].

*2.5. Other Observable Effects of Recoil.* During the long-lived “Phase II” recoil oscillations [22], when the SMBH oscillation amplitude is on the torus scale, the SMBH might efficiently accrete from the dense molecular gas at *each* turning point, causing repeated flares of radiation [23]. Such flares would locally destroy the dust, while photoionization of the dense surrounding gas would produce a strong emission-line response. Such a signal would not only help in identifying kicks but also could be used as a new probe of the properties of the torus itself.

Other signatures of recoiling SMBHs include effects on the morphology and dynamics of the gaseous disk of the host galaxy [56], their imprints on the hot gas in early-type galaxies [57], accretion from the ISM [58], the possibility of star formation in the wake of the SMBH trajectory [59], and their influence on the jet structures in radio galaxies [30].

### 3. The Frequency of Recoiling SMBHs in Astrophysical Environments

Several factors affect the distribution of SMBH kick velocities and their observability; the system parameters of the SMBH binary on the one hand (mass ratio, spin magnitudes and spin directions), and the astrophysical environment on the other hand.

The frequency of high-velocity kicks depends on the distribution of mass ratios and spins of the binary SMBHs. In case of random distributions of spin directions, as expected in gas-poor galaxy mergers, the kick formula (e.g., [4, 9, 13]) has been used to predict the kick fraction in dependence of recoil velocity [4, 9, 23, 60]. In this case, kicks with velocities larger than 500 km/s are relatively common (Figure 1 of [23]). Spin precession further has the consequence that large kicks are deboosted if the angle  $\Theta$  between the spin of the more massive BH and the orbital angular momentum is initially small, while large kicks are boosted, if  $\Theta$  is initially large [61].

The other key factor is the astrophysical environment, which determines the spin magnitude (set by the mechanism of SMBH mass growth via random accretion, ordered accretion, or BH-BH merging; [62]) and the timescale of spin alignment with the orbital angular momentum (e.g., [63–65]) in gas-rich galaxy mergers. The latter depends on the rapidity of binary coalescence, the amount of gas accretion before versus after coalescence, the accretion rate, the disk properties (e.g., the viscosity law across the disk), and the mass of the SMBH. While the most massive black holes are more resistant to alignment, the process is generally relatively fast in gas rich environments (timescales of  $10^5$ – $10^9$  yrs or less) [66, 67].

While initial results from numerical relativity have indicated that kick velocities are low in this case, the whole parameter space is still being explored, and Lousto and Zlochower [18] have recently shown that kick velocities up to 5000 km/s can be reached in configurations with spins partially aligned with the orbital angular momentum. As a consequence, the likelihood of observing high-velocity recoils in gas-rich

environments is significantly higher than in some previous estimates (their Figure 3).

Given the large number of uncertain parameters in estimating the frequency of recoiling SMBHs, identifying them through observations is also important. Ultimately, observations will independently provide the distribution of kick velocities and the properties of the recoiling SMBHs. First candidates have emerged in recent years, and more are likely to come soon, given the number of operating or planned very large spectroscopic and time-domain surveys, like SDSS, LAMOST, LSST, and future X-ray surveys.

### 4. Candidate Recoiling SMBHs Identified by Kinematic Signatures

*4.1. SDSSJ092712.65+294344.0 and X-Ray Followups.* The quasar SDSSJ092712.65+294344.0 (SDSSJ0927+2943 hereafter) at  $z = 0.7$  shows all the characteristic optical signatures of a recoiling SMBH [34], which were predicted earlier [33]. Its broad emission lines are shifted by  $2650 \text{ km s}^{-1}$  with respect to its narrow emission lines, the broad lines are symmetric, the broad MgII line shows the same shift as the broad Balmer lines, and the narrow emission lines lack an ionization stratification as expected if the accreting SMBH is no longer at the center of the system [34]. (SDSSJ0927+2943 also shows a second system of narrow emission lines with unusual properties when compared with other known quasars, including exceptionally broad Neon emission lines. The origin of these lines is still being explored; the lower-ionization lines are too narrow to have originally been bound to the recoiling SMBH (except in case of projection effects), and their low degree of ionization is not straightforward to understand [34]. A possible reservoir of narrow-line gas at the kick velocity is stellar mass loss, as a consequence of stellar evolution of the stars bound to the recoiling SMBH [49].) Its unique properties make SDSSJ0927+2943 an excellent candidate for a recoiling SMBH.

Two alternative models have been considered in order to explain some (but not all) of the unusual properties of this system; a chance projection, within 1 arcsec, of one or two *intrinsically peculiar* AGN in a very massive cluster of galaxies [34, 68, 69], and a close premerger binary SMBH [70, 71]. However, a rich and massive cluster has not been detected in NIR and X-ray imaging follow-up observations [72], (Komossa et al. 2012, in prep.). Neither was the predicted orbital motion of an SMBH binary detected in spectroscopic followups [68]; see also [73]. This leaves us with the recoil scenario for SDSSJ0927+2943. This scenario is also consistent with the recent measurement of an *offset* between the QSO and the host galaxy as traced by [OIII] emission [73].

We have obtained an imaging observation of SDSSJ0927+2943 with the *Chandra* X-ray observatory, in order to measure more precisely its X-ray luminosity (than was possible with a serendipitous off-axis ROSAT observation; [34]), and to study the properties of the field around SDSSJ0927+2943, including the search for a possible massive cluster of galaxies. We detect point-like X-ray emission from the quasar coincident with the optical position of SDSSJ0927+2943. A second X-ray source is present at a distance of

$\sim 17$  arcsec from SDSSJ0927+2943. This second source coincides with the object SDSSJ092713.8+294336 and contributed approximately 70% to the ROSAT X-ray emission from the region of SDSSJ0927+2943. Luminous extended X-ray emission from a *rich* cluster, in the form predicted by Heckman et al. [69], is not present. The full results of the X-ray analysis will be presented by (Komossa et al. 2012, in prep.).

**4.2. E1821+643.** The well-known luminous quasar E1821+643 ( $z = 0.297$ ) shows highly asymmetric broad Balmer lines which appear different in direct and in polarized light, and are strongly shifted with respect to the narrow lines. Based on their spectropolarimetric observations, Robinson et al. [74] favor a scenario where one component of the BLR is bound to a recoiling black hole, which is moving at 2100 km/s relative to its host galaxy. A second broad-line system is shifted by only 470 km/s, and its nature is currently unclear. If still related to recoil, in form of a marginally bound or unbound component of the BLR, the system is young, and Robinson et al. then estimate an age of  $\sim 10^4$  years.

**4.3. SDSSJ105041.35+345631.3.** Shields et al. [68, 75] selected the quasar SDSSJ105041.35+345631.3 at  $z = 0.272$  from the SDSS because of its large kinematic shift of the BLR of, in this case, 3500 km/s relative to the narrow emission lines. A projection effect is considered unlikely, as is a binary SMBH because of the lack of detectable orbital motion. While Shields et al. do not rule out an extreme case of a recoiling SMBH, they conclude that several aspects of the optical spectrum are best understood if this galaxy is an extreme case of a “double-peaked emitter.”

## 5. Candidate Recoiling SMBHs Identified by Spatial Offsets

**5.1. CID-42.** The galaxy CID-42 (COSMOSJ1000+0206) at redshift  $z = 0.359$  was discovered in the COSMOS survey [76], and caught attention due to its unusual morphology with two apparent optical “nuclei” [77] at a projected separation of 2 kpc, and an extended tidal tail. Initially suspected to be a binary AGN [77], it was then reinterpreted as a candidate recoiling SMBH, or alternatively, an SMBH ejection following 3-body interaction in a triple SMBH system, by Civano et al. [78]. An HST image analysis has shown that the northwestern core is slightly extended though compact, and consistent with being the nucleus of the galaxy, while only the southeastern bright source is point-like [78]. The optical spectrum of CID 42 shows a kinematic shift of 1200 km/s between the BLR and the major narrow-line component, and extra faint narrow H $\beta$  emission at the same redshift as the broad lines [78], and perhaps further faint narrow-line emission shifted by  $\sim 150$  km/s [77]. As such, the spectrum shares similarities with that of the recoil candidate SDSSJ092712.65+294344.0 [34, 68]. Another remarkable feature, not yet well understood, is the presence of a strong redshifted broad iron line with a P-Cygni profile, variable over four years, of high column density and highly ionized [78]. Follow-up optical and X-ray observations are currently

underway (Civano et al. 2012, in prep.). Their new high-resolution Chandra data show the presence of only one X-ray emitting object which coincides with the position of the southeastern optical source, supporting the recoil scenario rather than the binary SMBH (Civano et al. 2012, in prep.).

**5.2. M87.** M87 is a nearby massive galaxy with a prominent radio jet. The photocenter of the host galaxy is offset by 7 pc from the nuclear point source (i.e., presumably the location of the SMBH) [79]. The displacement is in the direction of the counterjet. Among several scenarios (acceleration by a jet, presence of massive perturbers, binary orbital motion) considered, Batcheldor et al. [79] favor GW recoil as the most plausible. The observed offset can then be explained either by a moderate kick 1 Myr ago, or residual small-amplitude oscillations of a large recoil which happened  $< 1$  Gyr ago.

**5.3. CXOJ122518.6+144545.** Jonker et al. [80] reported the detection of an unusual off-nuclear X-ray source, at a projected separation of 3 kpc from the core of the galaxy SDSSJ122518.86+144547.7 at  $z = 0.045$ . CXOJ122-518.6+144545 is X-ray luminous and has a bright optical counterpart and properties unlike those of other off-nuclear X-ray sources which were found in large numbers with *Chandra*. The authors offer three explanations of CXOJ-122518.6+144545: a supernova of type IIn, an ultraluminous X-ray source with an unusually bright optical counterpart, or a recoiling SMBH. Bellovary et al. [81] further discuss the possibility of a wandering SMBH in the galaxy halo, produced by stripping of a satellite which merged with the primary galaxy.

**5.4. ESO 1327–2041.** The nearby galaxy ESO 1327–2041 ( $z = 0.018$ ) shows a complex morphology indicative of a recent merger. *HST* imaging has revealed the presence of a compact source embedded in an extended “stellar stream” ([82]; their Figure 1), at a redshift similar to the core of ESO 1327–2041, and at a projected separation of 15 kpc. Keeney et al. discuss several possible interpretations of this compact object, and propose that it is the actual nucleus of the galaxy, ejected as a consequence of either tidal interaction between two galaxies or gravitational wave recoil following a past merger.

## 6. Implications of Recoil Oscillations for Unified Models of AGN

There are potentially far-reaching consequences of SMBH recoil for unified models of AGN. Spatial oscillations of the SMBHs about the cores of their host galaxies imply that the SMBHs spend a significant fraction of time *off-nucleus*, at scales beyond that of the molecular obscuring torus. An intrinsically *obscured* quasar of *type 2* with its BLR hidden by the torus will therefore appear as *unabsorbed*, *type 1* quasar during the recoil oscillations, when moving beyond the torus scale.

Assuming reasonable distributions of recoil velocities, Komossa and Merritt [23] have computed the off-core time-scale of (intrinsically type 2) quasars (These calculations are based on models of Gualandris and Merritt [22], which did not include gas. Recent simulations of recoil oscillations in

a gaseous disk show, that oscillation timescales can either increase or decrease [83] with respect to the gas-free case.). It was shown that roughly 50% of all major mergers result in a SMBH being displaced beyond the torus for a time of  $10^{7.5}$  yr or more. This is an interesting number, because it is comparable to quasar activity time scales. Since *major* mergers (i.e., quasars) are most strongly affected by gravitational wave recoil, our results imply a deficiency of luminous type 2 quasars in comparison to low-luminosity Seyfert 2 galaxies, as indeed observed (e.g., [84]). These may therefore naturally explain the long-standing puzzle, why few absorbed type 2 quasars exist at high luminosities; it would be these which are affected by the recoil oscillations, therefore appearing as type 1 rather than type 2 for a significant fraction of their lifetime [23].

Recoil oscillations further imply the presence of a fraction of quasars which lack a hot dust component, because the dusty torus is only illuminated from a distance. Such “hot-dust-poor” quasars have indeed been observed (e.g., [85]).

Recoil oscillations also have a number of other observable consequences related to AGN. For instance, they will affect the X-ray background and its modeling since a fraction of sources will be unobscured at any given time. In particular, small amplitude oscillations of the order the torus size will affect the ratio of Compton-thin to Compton-thick sources and could lead to measurable variability in the absorption and extinction of AGN spectra once the recoiling SMBH passes the individual clouds making up the torus [23].

## 7. Astrophysical Implications and Future Observations

The kicks and superkicks predicted by recent numerical relativity simulations of coalescing SMBHs have stimulated an active new field of research. Electromagnetic signatures of recoiling SMBHs are being predicted, several candidates have emerged in large data bases, and astrophysical implications of the kicks are still being explored. The fact that SMBHs will not always reside at the very cores of their host galaxies, or may even be ejected completely, has many potential implications for the topics discussed in this book; for galaxy and SMBH assembly and galaxy-SMBH (co)evolution, core structures in early type galaxies, the scatter in the host galaxy-SMBH scaling relations, the statistics of obscured quasars, and the redshift-dependence of gravitational wave signals (e.g., [26, 86–92]).

It is therefore important to identify more candidate recoiling SMBHs through observations. Promising future searches would include (1) emission-line signatures in large spectroscopic data bases such as SDSS or LAMOST; (2) recoil flares from accretion disks and stellar tidal disruptions in large-scale surveys like Pan-STARRS and LSST and in the X-ray regime; (3) the characteristic, large stellar velocity dispersions of HCSSs in spectroscopic followups of ongoing imaging surveys of nearby clusters of galaxies.

Detecting recoiling SMBHs in large numbers will open up a new window on measuring galaxy merger histories and kick amplitude distributions, and testing predictions of numerical relativity.

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