Co-Evolution of Central Black Holes and Galaxies
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Electromagnetic Signatures of Recoiling Black Holes

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Abstract. Recent numerical relativity simulations predict that coalescing supermassive black holes (SMBHs) can receive kick velocities up to several thousands of kilometers per second due to anisotropic emission of gravitational waves, leading to long-lived oscillations of the SMBHs in galaxy cores and even SMBH ejections from their host galaxies. Observationally, accreting recoiling SMBHs would appear as quasars spatially and/or kinematically offset from their host galaxies. The presence of these "kicks" and "superkicks" has a wide range of exciting astrophysical implications which only now are beginning to be explored, including consequences for black hole and galaxy growth at the epoch of structure formation, modes of feedback, unified models of AGN, and the number of obscured AGN. SMBH recoil oscillations beyond the torus scale can be on the order of a quasar lifetime, thus potentially affecting a large fraction of the quasar population. We discuss how this might explain the long-standing puzzle of a deficiency of obscured type 2 quasars at high luminosities. Observational signatures of recoiling SMBHs are discussed and results from follow-up studies of the candidate recoiling SMBH SDSSJ0927+2943 are presented.

Keywords. black hole physics, quasars: emission lines, quasars: general, quasars: individual (SDSSJ092712.65+294344.0), galaxies: Seyfert

1. Introduction

Gravitational waves emitted anisotropically during gravitational collapse carry away linear momentum (Peres 1962). As a result, when two SMBHs coalesce the newly formed single SMBH recoils. Configurations of coalescing black holes can lead to recoil velocities up to 3800 $\mathrm{km\,s^{-1}}$ (e.g., Campanelli *et al.* 2007, 2009; González *et al.* 2007, 2009; Herrmann *et al.* 2007; Baker *et al.* 2008; Brügmann *et al.* 2008; Dain *et al.* 2008; Miller & Matzner 2009; Lousto & Zlochower 2009; Le Tiec *et al.* 2009; Lousto *et al.* 2009), for maximally spinning equal-mass black hole binaries with anti-aligned spins in the orbital plane. The kick velocity can be as large as $\sim 10^4$ $\mathrm{km\,s^{-1}}$ in hyperbolic encounters (Healy *et al.* 2009).

Kicks large enough to remove SMBHs from their host galaxies have potentially far-reaching astrophysical consequences, including for SMBH and galaxy assembly. 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., Madau *et al.* 2004; Merritt *et al.* 2004; Madau & Quataert 2004, Haiman 2004; Libeskind *et al.* 2006; Schnittman 2007; Sesana 2007; Volonteri 2007; Loeb 2007, Gualandris & Merritt 2008; Volonteri & Madau 2008; Tanaka & Haiman 2009). Identifying recoiling SMBHs through observations is of great interest and several key electromagnetic signatures of kicks have been predicted in the last few years. We will briefly summarize these signatures and then discuss implications of recoil oscillations of SMBHs for unified models of AGN.

2. Emission-Line Signatures of Recoiling SMBHs

After binary SMBH coalescence, the newly formed recoiling SMBH will oscillate about the core of its host galaxy (Madau & Quataert 2004; Gualandris & Merritt 2008) or will even escape its host if the kick velocity exceeds the escape velocity. After the kick, matter remains bound to the recoiling SMBH within a region whose radius is given by

$$r_{\rm k} = \frac{GM_{\rm BH}}{v_{\rm k}^2} \approx 0.4 \left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{v_{\rm k}}{10^3\,{\rm km\,s^{-1}}}\right)^{-2}\ {\rm pc}, \tag{2.1}$$

where $v_{\rm k}$ is the kick velocity (Merritt *et al.* 2006). This region is on the order of the size of the broad-line region (BLR) of AGN (Peterson 2007), which will therefore typically remain bound to the SMBH while the bulk of the host galaxy's narrow-line region (NLR) will remain behind. Recoiling SMBHs will therefore appear as AGN which have their broad emission lines kinematically shifted by up to $\sim 3800\,{\rm km\,s^{-1}}$ with respect to their NLRs. Bonning *et al.* (2007) formulated several criteria, how a recoiling SMBH should appear spectroscopically. Apart from (1) the kinematic shift of the BLR, a candidate ejected SMBH should (2) exhibit symmetric broad-line profiles, it should (3) lack stratification of high- versus low-ionization narrow emission lines, and it should (4) not show any shift between broad Mg II and the broad Balmer lines†. One object, the quasar SDSSJ092712.65+294344.0 (SDSSJJ0927+2943 hereafter), fulfills all four of these criteria and is therefore an excellent candidate for a recoiling SMBH (Komossa *et al.* 2008). It will be further discussed in §9.

3. 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 (Liu *et al.* 2003; Milosavljević & Phinney 2005; Loeb 2007). 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., Lippai *et al.* 2008; Shields & Bonning 2008; Schnittman & Krolik 2008; Megevand *et al.* 2009; van Meter *et al.* 2009; Rossi *et al.* 2009; Corrales *et al.* 2009). These flares may last for $\sim 10^4$ yrs and should be searched for in current and future sky surveys.

4. Tidal Disruption Flares from Stars Bound to Recoiling SMBHs

Even in the absence of an accretion disk, ejected SMBHs will always carry a retinue of bound stars. These stars are subject to tidal disruption, leading to powerful X-ray flares of quasar-like luminosity (Komossa & Bade 1999), which would appear off-nuclear or even intergalactic (Komossa & Merritt 2008a; KM08a hereafter). We determined disruption rates for the bound, and the unbound, stellar populations, under recoil conditions (see KM08a for details). In the resonant relaxation regime, we find that the rates are of order $10^{-6}\ {\rm yr}^{-1}$ for a typical postmerger galaxy (Figure 2 of KM08a), which is smaller than, but comparable to, rates for non-recoiling SMBHs. Another signature related to the stars bound to the recoiling SMBH is episodic X-ray emission from accretion due to stellar mass

† 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 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.

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. All these signals would be generically 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 ~ 10 Gyr.

5. Hypercompact Stellar Systems

While the "tidal recoil flares" are very luminous and could 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 $M_{\rm BH}$ (Komossa & Merritt 2008a). Merritt *et al.* (2009) explored the properties of these "hypercompact stellar systems" (HCSS) in great detail, and related the structural properties (size, mass, 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 (Merritt *et al.* 2009), while O'Leary & Loeb (2009) predict hundreds of low-mass HCSSs in the halo of our Milky Way.

6. Other Recoil Signatures

A recoiling SMBH with a bound gas disk that passes through the dense molecular torus in the core of an AGN might cause local shocks leading to temporary electromagnetic radiation. Further, during the long-lived "Phase II" recoil oscillations (Gualandris & Merritt 2008), when the SMBH oscillation amplitude is on the scale of the torus, the SMBH might efficiently accrete from the dense molecular gas at *each* turning point, causing repeated flares of radiation (Komossa & Merritt 2008b). 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 could also 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 (Kornreich & Lovelace 2008), their imprints on the hot gas in early-type galaxies (Devecchi *et al.* 2009), accretion from the ISM (Fujita 2009), and the possibility of star formation in the wake of the SMBH trajectory (de la Fuente Marcos & de la Fuente Marcos 2008).

7. The Frequency of Recoiling SMBHs

The frequency of high-velocity kicks depends on the distribution of mass ratios and spins of the binary SMBHs. In case of random spin distributions (dry mergers), the kick formula (Campanelli *et al.* 2007; Baker *et al.* 2008; Lousto & Zlochower 2009) predicts the kick fraction independent of recoil velocity (Campanelli *et al.* 2007; Schnittman & Buonanno 2007; Baker *et al.* 2008; Komossa & Merritt 2008b). Under these assumptions, kicks with velocities larger than 500 km $\rm s^{-1}$ are relatively common (Figure 1 of

Komossa & Merritt 2008b). In gas-rich mergers, the SMBH spins may align with the orbital angular momentum (e.g., Scheuer & Feiler 1996; Natarajan & Armitage 1999; Bogdanović *et al.* 2007; Perego *et al.* 2009). The timescale of alignment, in comparison to the binary coalescence timescale, then determines the fraction of high-velocity kicks in gas-rich systems (another important factor is the amount of gas accretion before versus after the merger). The whole parameter space is still being explored; Perego *et al.* (2009) estimate timescales of 10^5–10^9 yrs for spin alignment (e.g., their Figure 12), depending on accretion rate and disk properties.

8. 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 & Merritt (2008b) have computed the off-core timescale of (intrinsically type 2) quasars. We found 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., Hasinger 2008). 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 (Komossa & Merritt 2008b).

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 (Komossa & Merritt 2008b). It is also tempting to speculate that SMBH recoil might offer an explanation for observed time delays between starburst and AGN activity in galaxies.

9. The Candidate Recoiling SMBH SDSSJ0927+2943 and X-Ray Follow-Ups

The quasar SDSSJ0927+2943 (Komossa *et al.* 2008; KZL08 hereafter) shows the characteristic optical signatures of a recoiling SMBH, which were predicted by Bonning *et al.* (2007): its broad emission lines are shifted by 2650 km s^{-1} with respect to its narrow emission lines, the broad lines are symmetric, the broad Mg II line shows the same shift as the broad Balmer lines, and the narrow emission lines lack ionization stratification as expected if the accreting SMBH is no longer at the center of the system (KZL08).† 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 one arcsec, of one or *two intrinsically peculiar* AGN in a very massive cluster of galaxies (KZL08; Shields *et al.* 2009; Heckman *et al.* 2009), and a close pre-merger binary SMBH (Dotti *et al.* 2009; Bogdanović *et al.* 2009). However, a rich and massive cluster has not been detected in NIR and X-ray imaging follow-up observations (Decarli *et al.* 2009; Komossa *et al.*, in preparation). Neither was the predicted orbital motion of an SMBH binary detected in spectroscopic follow-ups (Shields *et al.* 2009; see also Vivek *et al.* 2009). This leaves us with the recoil scenario to explain the properties of SDSSJ0927+2943. This scenario is also consistent with the recent measurement of an *offset* between the QSO and the host galaxy as traced by [O III] emission (Vivek *et al.* 2009).

We have obtained a *Chandra* imaging observation of SDSSJ0927+2943 in order to measure its X-ray luminosity more precisely than was possible with a serendipituous off-axis *ROSAT* observation (KZL08), and to study the properties of the field around SDSSJ0927+2943, including a search for a possible massive galaxy cluster. We detect coincident with the optical position of SDSSJ0927+2943 point-like X-ray emission from the quasar. A second X-ray source is present at ∼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.* (2009), is not present. The full results of the X-ray imaging will be presented by Komossa *et al.* (in preparation).

10. Summary and Future Observations

The kicks and superkicks predicted by recent numerical relativity simulations of coalescing SMBHs have led to an active new field of research. Electromagnetic signatures of recoiling SMBHs are being predicted, and astrophysical implications of the kicks are still being explored. Apart from ongoing follow-ups of SDSSJ0927+2943, it is 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 in the optical, and eROSITA and EXIST in X-rays; and

(3) the characteristic, large stellar velocity dispersions of HCSSs in spectroscopic follow-ups of ongoing imaging surveys of nearby clusters of galaxies.

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† SDSSJ0927+2943 also shows a second system of narrow emission lines with unusual properties when compared with other known quasars. 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 (KZL08). 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 (Komossa & Merritt 2008a).

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