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A RECOILING SUPERMASSIVE BLACK HOLE IN THE QUASAR SDSS J092712.65+294344.0?

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ABSTRACT

We present SDSS J092712.65+294344.0 as the best candidate to date for a recoiling supermassive black hole (SMBH). SDSS J0927+2943 shows an exceptional optical emission-line spectrum with two sets of emission lines: one set of very narrow emission lines, and a second set of broad Balmer and broad high-ionization forbidden lines which are blueshifted by 2650 km s^{-1} relative to the set of narrow emission lines. This observation is most naturally explained if the SMBH was ejected from the core of the galaxy, carrying with it the broad-line gas while leaving behind the bulk of the narrow-line gas. We show that the observed properties of SDSS J0927+2943 are consistent with predictions and expectations from recent numerical relativity simulations which demonstrate that SMBHs can receive kicks up to several thousand km s^{-1} due to anisotropic emission of gravitational waves during the coalescence of a binary. Our detection of a strong candidate for a rapidly recoiling SMBH implies that kicks large enough to remove SMBHs completely from their host galaxies do occur, with important implications for models of black hole and galaxy assembly at the epoch of structure formation, and for recoil models.

Subject headings: galaxies: active — galaxies: evolution — galaxies: individual (SDSS J092712.65+294344.0) — quasars: emission lines

1. INTRODUCTION

The merging of two galaxies will produce a binary black hole at the center of the newly formed galaxy. If the two black holes do not stall, they will ultimately merge due to emission of gravitational wave radiation. The gravitational waves carry away linear momentum, causing the center of mass of the coalescing BH system to recoil in the opposite direction (Peres 1962; Bekenstein 1973). Early analytical calculations predicted that mergers of nonspinning black holes can attain kicks with velocities of up to a few hundred km s^{-1} (e.g., Fitchett & Detweiler 1984; Favata et al. 2004; Blanchet et al. 2005; Damour & Gopakumar 2006), recently confirmed by numerical simulations (e.g., Baker et al. 2006; Herrmann et al. 2007a; González et al. 2007b). These velocities are above the escape velocity of dwarf galaxies, low-mass spirals, and high-redshift dark matter halos. If many BHs were removed from their hosts in the early history of the universe, this would have profound consequences for galaxy assembly and BH growth in the early universe, and would give rise to a population of interstellar and intergalactic BHs (e.g., Madau et al. 2004; Merritt et al. 2004; Madau & Quataert 2004; Haiman 2004; Yoo & Miralda-Escudé 2004; Volonteri & Perna 2005; Volonteri & Rees 2006; Libeskind et al. 2006).

Recent numerical relativity simulations of certain configurations of merging, *spinning* BHs have produced much higher recoil velocities, up to several thousand km s^{-1} (Campanelli et al. 2007a, 2007b; González et al. 2007a; Tichy & Marronetti 2007; Herrmann et al. 2007b; Dain et al. 2008; Schnittman et al. 2008), scaling to an expected maximum around 4000 km s^{-1} (Campanelli et al. 2007a, 2007b; Baker et al. 2008) for maximally spinning equal-mass binaries with antialigned spins in the orbital plane. These kick velocities exceed the escape velocities of even massive elliptical galaxies (Fig. 2 of Merritt et al. 2004) and therefore the new results reinforce and enhance consequences studied earlier for the smaller kicks, with potentially far-reaching implications for the early phases of BH growth from early stellar-mass precursors or later intermediate-mass precursors (Schnittman 2007; Volonteri 2007) and consequently for the frequency of gravitational wave signals detectable with *LISA* (Sesana 2007), for the scatter in the M-σ relation (Libeskind et al. 2006), and for the offsets and oscillations of recoiling BHs in galaxy cores (Gualandris & Merritt 2008).

The recoiling black holes will carry a fraction of nuclear gas and stars with them (Merritt et al. 2004, 2006; Madau & Quataert 2004; Loeb 2007). They would be detectable spatially in the form of Seyfert or quasar activity offset from the galaxy core (Madau & Quataert 2004), or in the form of broad emission lines kinematically offset from the narrow emission lines (Bonning et al. 2007; Komossa et al. 2008). Because of the broad astrophysical implications, the search for and actual identification of such recoiling black holes is of great interest, and will place important constraints on BH growth during the epoch of structure formation, on predictions of maximum recoil velocity, and on arguments suggesting that the BH spin configurations leading to maximal recoil velocities should be rare in gas-rich mergers (Bogdanović et al. 2007).

Bonning et al. (2007) searched for recoiled SMBHs in the Sloan Digital Sky Survey (SDSS) database, looking for systematic kinematic offsets between broad-line gas attached to the recoiling BH and narrow-line gas left behind. They did not find any promising candidate and concluded that SMBH recoil with large kick velocities is relatively rare.

Here we present the best candidate to date for a recoiling SMBH, the quasar SDSS J092712.65+294344.0 (SDSS J0927+2943 hereafter). Its unusual emission-line spectrum matches key predictions from the recoiled-SMBH scenario. We use a cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ throughout this Letter.

2. OBSERVATIONS OF SDSS J0927+2943

2.1. *Optical Spectroscopy*

SDSS J0927+2943 at redshift $z = 0.713$ is a luminous quasar, observed in the course of the SDSS (Adelman-McCarthy et al. 2007), and was found by us in a systematic search for active galactic nuclei (AGNs) with high [O III] velocity shifts. The SDSS spectrum, corrected for the Galactic reddening

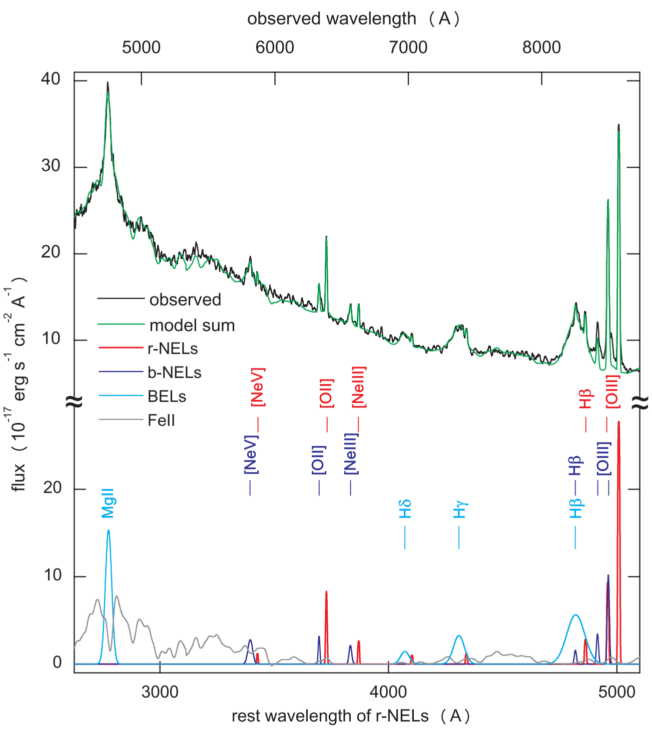

FIG. 1.—SDSS spectrum of SDSS J0927+2943, showing two sets of emission lines separated by a velocity of $v \approx 2650$ km s^{-1}. *Red*: Red set of narrow emission lines (r-NELs). *Blue and light blue*: Blue set of emission lines (b-NELs and BELs, respectively). *Gray*: Fe II spectrum.

of $E(B-V) = 0.021$ mag, is displayed in Figure 1. The underlying continuum spectral energy distribution (SED) was modeled as a power law with a best-fit slope of $\alpha = -0.1$ (where $f_\nu \propto \nu^\alpha$). Each emission line was fit by a single Gaussian except the Fe II multiplets, which were modeled by templates built from I Zw 1 ($\lambda > 3500$ Å, Véron-Cetty et al. 2004; $\lambda < 3500$ Å, Tsuzuki et al. 2006). The redshifts of the Fe II lines were tied either to Mg II (the UV multiplets) or to broad Hβ (the optical multiplets).

Two systems of strong emission lines can be identified in the spectrum, which we refer to as the "red" (r) and "blue" (b) systems. The red system consists of very narrow emission lines (red NELs, r-NELs hereafter) of [O III] λ5007, [O II] λ3727, [Ne III] λ3869, faint [Ne V] λ3426, and Balmer lines, all of them almost unresolved [FWHM,obs([O III]) = 230 km s^{-1}; the widths of the narrow lines are all very similar and were therefore all fixed to the same value in order to derive fluxes]. The blue system shows classical broad Balmer and Mg II λ2798 emission lines (BELs), plus unusually broad NELs (blue NELs, b-NELs hereafter). All lines of the blue system are blueshifted by about 2650 km s^{-1} relative to the r-NELs[1] (see Table 1 for redshifts; the value of 2650 km s^{-1} is the shift between broad Hβ and r-[O III]). The b-NELs show broad [Ne V] with a width of FWHM([Ne V]) = 2080 km s^{-1}, and broad [Ne III] with FWHM([Ne III]) = 1020 km s^{-1}. [O III] and [O II] are present, too, with widths of 460 km s^{-1}. The BELs appear in Balmer lines and in Mg II with FWHM(Hβ) = 5740 km s^{-1} and FWHM(Mg II) = 3530 km s^{-1}. Line ratios indicate AGN-like excitation in both systems, r-NELs and b-NELs. Emission-line properties are summarized in Table 1.

[1] Since the r-NELs are all very narrow and are all consistent with the same redshift, we assume henceforth that they define the rest frame of the system.

TABLE 1
EMISSION-LINE PROPERTIES OF SDSS J0927+2943

Line	z	FWHM[a]	Line Ratio
r-NEL:			
[O III] λ5007	0.71279	170	10.1
Hβ	0.71279[b]	170[b]	1.0[c]
Hγ	0.71279[b]	170[b]	0.4
[Ne III] λ3869	0.71279[b]	170[b]	0.7
[O II] λ3727	0.71279[b]	170[b]	2.6
[Ne V] λ3426	0.71279[b]	170[b]	0.3
b-NEL:			
[O III] λ5007	0.69713	460	6.7
Hβ	0.69713[b]	460[b]	1.0[c]
[Ne III] λ3869	0.69678	1020	1.8
[O II] λ3727	0.69801	460[b]	1.5
[Ne V] λ3426	0.69709	2080	4.0
BEL:			
Hβ	0.69770	5740	30.7
Hγ	0.69970	3880	10.7
Hδ	0.69996	3260	3.8
Mg II λ2798	0.69832	3530	29.5

[a] Corrected for instrumental resolution.
[b] Fixed.
[c] Normalized to 1.0.

In order to see whether any (faint) broad-line emission is also accompanying the r-NELs, we have performed the following test. We have first subtracted the best-fit continuum, Fe II multiplets, and NELs from the observed spectrum, and then fit the Hβ regime with two broad Gaussians. The redshift of the second Gaussian was fixed to that of the r-NELs, and its width constrained to be in the range 1000–5000 km s^{-1}. No successful fit could be obtained if a contribution of the second Gaussian is enforced; its contribution is always consistent with zero. We therefore conclude that only the b-NELs are accompanied by broad-line gas at the same redshift.

The broadband SED of SDSS J0927+2943 is rather blue with SDSS magnitudes of $u = 18.71 \pm 0.02$, $g = 18.36 \pm 0.02$, $r = 18.40 \pm 0.02$, $i = 18.43 \pm 0.02$, $z = 18.31 \pm 0.02$, and *GALEX*[2] (Martin et al. 2005) magnitudes of NUV = 18.57 ± 0.06 and FUV = 19.49 ± 0.15.

Assuming that the standard broad-line region (BLR) scaling relations (Kaspi et al. 2005) hold, we expect a BLR radius of ~0.1 pc and estimate a SMBH mass of SDSS J0927+2943 of $M_{\rm BH} = 6 \times 10^8\ M_\odot$ from the width of Hβ and the luminosity at 5100 Å.

2.2. *X-Ray Detection*

We have searched the X-ray archives for observations of SDSS J0927+2943. The quasar is serendipitously located close to the edge of two *ROSAT* HRI images. The deeper exposure, of 19 ks duration, was performed in 1995 April–May. X-ray emission from SDSS J0927+2943 is detected with a count rate of 0.0037 ± 0.0007 counts s^{-1}, which translates into a soft X-ray luminosity of $L_{\rm X} = 5 \times 10^{44}$ ergs s^{-1} (assuming an X-ray spectrum with no intrinsic absorption, and with photon index $\Gamma_{\rm X} = -2.5$). The second HRI image was taken in 1994 November with a duration of 10 ks. SDSS J0927+2943 is detected with a count rate of 0.0047 ± 0.0012 counts s^{-1}, consistent with the other measurement. The X-ray detection demonstrates the presence of an inner accretion disk (relevant for the discussion in § 3.2).

[2] See http://galex.stsci.edu/GR2/.

3. DISCUSSION

3.1. *The Most Unusual Quasar Pair Known?*

Several pairs of quasars have been detected at projected separations of 3″–10″. While some of them can be explained by lensing, others very likely represent real pairs (e.g., Kochanek et al. 1999; review by Komossa 2003).[3] Is SDSS J0927+2943 actually a binary quasar? We temporarily refer to this hypothetical system as SDSS J0927+2943A,B. The difference in velocity of the two sets of emission lines exceeds the peculiar velocities observed in galaxy clusters, and is too large for the two galaxies to form a bound merger. Their redshift difference corresponds to ∼100 Mpc, if their redshifts are cosmological. Consequently, we would then have a very unlikely projection effect, including not just one, but two intrinsically extremely unusual AGNs: SDSS J0927+2943A with exceptionally broad neon lines of [Ne III] and [Ne V], and SDSS J0927+2943B as one of the rare type 2 quasars with, in addition, exceptionally narrow emission lines (their observed width of ∼230 km s^{-1} is below that typically observed in quasar narrow-line regions [FWHM ≈ 400–800 km s^{-1}; Zakamska et al. 2003]). This rare source would have to be projected by chance behind the other unusual AGN.

We are therefore let to consider the alternative hypothesis that we actually see only one AGN, its SMBH and bound emission-line region having been ejected from the core with a line-of-sight speed of 2650 km s^{-1}, while the bulk of the narrow-line region (NLR) and other interstellar medium (ISM) was left behind and shines in narrow emission lines. This is the scenario actually predicted in the context of the recent black hole recoil simulations discussed in § 1, and it is the observational signature Bonning et al. (2007) searched for, and Komossa et al. (2008) paid attention to, but did not detect.

3.2. *A Recoiling SMBH in SDSS J0927+2943*

In this picture, SDSS J0927+2943 underwent a merger in the past. Upon merging, its central SMBH recoiled, taking with it the BLR and perhaps other very high ionization gas, leaving behind the NLR. Gas with a velocity larger than the recoil velocity will remain bound to the SMBH, and a trail of partially bound gas may form. Accretion activity may have switched off temporarily in the course of the binary SMBH merging, once the orbital decay time due to emission of gravitational waves had become smaller than the viscous timescale of the disk (e.g., Liu 2003; Milosavljević & Phinney 2005). After coalescence, the inner disk will reform quickly (Loeb 2007) and the accreting SMBH will then illuminate the bound gas, a trail of partially bound gas and swept-up ISM, the surrounding ISM/halo, and the left-behind bulk of the NLR gas.

The NLR gas left behind will retain memory of the original ionization from the premerger accretion phase for only limited time, given by the light-travel time and the hydrogen recombination timescale $t_{\rm rec} \approx 130 T_4^{0.8} n_3^{-1}$ yr, where T_4 is the gas temperature in 10^4 K and n_3 is the gas density in units of 10^3 cm^{-3}. [O III] will fade away more quickly than hydrogen lines (Binette & Robinson 1987). However, once the recoiling SMBH reforms its inner accretion disk, it will reilluminate parts of the NLR left behind (from larger distance than before) and any surrounding ISM. Emission-line ratios would depend on the average density which would be higher in the classical NLR than in other ISM/halo gas, and on metal abundances which will be lower in the halo.

Which aspects of this scenario do we observe in SDSS J0927+2943? The blue system of emission lines, the BELs and b-NELs, represents gas bound to the recoiling SMBH, seen in broad Balmer lines, broad Mg II, and broad forbidden lines, especially [Ne V]. After coalescence and recoil, matter orbiting the SMBH with a velocity much larger than the recoil velocity will remain bound to the SMBH (Merritt et al. 2006), i.e., matter within a region whose size is given by $r_b < GM_{\rm BH}v^{-2}$. In our case, $r_b < 10^{18}$ cm, which is about a factor of 3 larger than the BLR of SDSS J0927+2943. The width of [Ne III] (of the b-NEL system) of 1020 km s^{-1} is too narrow for this gas to be originally bound to the SMBH (except in case of projection effects), but as the disk keeps accreting onto the recoiling SMBH, it will spread radially and will also drive some outflows. The semibroad [O II] and [O III] most likely have this same origin, and/or are from swept-up ISM in front of the path of the recoiling SMBH.[4]

The red system of emission lines, the r-NELs, represents the NLR gas left behind and/or ISM surrounding the recoiling SMBH, not bound to it but illuminated by its accretion disk. All r-NELs have the same profiles and are very narrow, and the emission-line ratios imply an AGN ionizing continuum. Can we distinguish between NLR and other ISM/halo gas, in terms of line ratios and line profiles? Line *ratios* would depend on density and distance. As the recoiling SMBH moves away from the galaxy core, illumination of the NLR from an on average larger distance would decrease the degree of ionization, while illumination of low-density ISM surrounding the recoiling SMBH would increase the degree of ionization of the line-emitting gas. It is possible that we see a mix of these two processes. We do not expect to see pure very low density halo gas. Its high ionization parameter would lead to a much higher degree of ionization than we actually observe, as we have also verified by test calculations with Ferland's photoionization code Cloudy (S. Komossa et al., in preparation). The density-sensitive [S II] doublet is outside the observed wave band, but will be accessible with NIR spectroscopy.

Independent evidence for the origin of the r-NELs comes from their *profiles* which are very narrow. Their width is below the stellar velocity dispersion of $\sigma_* = 260$ km s^{-1} predicted from the $M_{\rm BH}$-σ_* relation (Ferrarese & Ford 2005). This indicates that the r-NEL gas illuminated by the recoiling SMBH either does not feel the full bulge potential, or the local velocity field of the illuminated gas does not reflect the full velocity dispersion. This latter situation is expected if the recoiling SMBH was in a disk where the velocity pattern is predominantly rotational, so that we only see a fraction of the full pattern.

The whole parameter space of BH recoil velocities is still

[3] In this context, it is interesting to mention HE 0450−2958, a system consisting of an ultraluminous infrared galaxy (ULIRG) and a narrow-line Seyfert 1 (NLS1) galaxy. The host galaxy of the NLS1 was not detected in *HST* imaging, suggesting it was a "naked quasar" (Magain et al. 2005). Merritt et al. (2006) then revised downward the SMBH mass of the NLS1 by a factor 10; the nondetection of the host galaxy is then consistent with the observed upper limit. Merritt et al. (2006) argued that the emission-line properties of the NLS1 are incompatible with the scenario that the NLS1 was actually ejected from the ULIRG, whether the mechanism of ejection was gravitational wave recoil or three-body interaction of a binary BH with a third BH (Haehnelt et al. 2006; Hoffman & Loeb 2006). Finally, Kim et al. (2007) pointed out that the ultraluminous IR emission is more likely associated with the NLS1 galaxy.

[4] Based on photoionization models (e.g., Komossa & Schulz 1997) we expect little [O II] emission from the gas bound to the recoiling SMBH, even though shielding geometries might be constructed in which this actually becomes possible.

being explored (e.g., Baker et al. 2006, 2007; Campanelli et al. 2007a, 2007b; Choi et al. 2007; González et al. 2007a, 2007b; Herrmann et al. 2007a, 2007b; Pollney et al. 2007; Schnittman et al. 2008 and references therein; see Pretorius 2008 for a review). Several recent calculations focused on (almost) equal-mass BHs with specific spin configurations such that kick velocities are maximized. The line-of-sight velocity we measure is comparable to the recoil velocities predicted by the runs of Gonzáles et al. (2007a; $v_{\rm kick} \approx 2500$–$2650$ km s^{-1}) and by Dain et al. (2008; 3300 km s^{-1}). The scaling formulae of Campanelli et al. (2007a) and of Baker et al. (2008) predict maximal recoil velocities of $\sim$3800 km s^{-1}. In order to reach a high kick velocity, the premerger BHs of SDSS J0927+2943 must have been rapidly spinning and of nearly equal mass; i.e., the galaxy hosting SDSS J0927+2943 must have undergone a major merger.

Assuming that the recoiling SMBH carried with it an amount of mass which is not larger than its own mass, and that most of that gas is ultimately available for accretion, we can estimate an upper limit on the duration of the quasar activity, t_q. We further assume that the gas continues to accrete at its current rate of $L/L_{\rm Edd} \simeq 0.1$, where $L_{\rm Edd}$ is the Eddington luminosity, and we use a radiative efficiency of $\eta = 0.37$ which is appropriate for rapidly spinning BHs. This implies an upper limit on the lifetime of quasar activity of $t_q \approx 10^9$ yr. If the space velocity of the recoiling SMBH was close to the maximum possible velocity, it would reach a projected separation from the core on the order of a few kiloparsecs within $\sim 10^6$ yr.

Future *HST* imaging of SDSS J0927+2943 will be valuable to distinguish whether the host galaxy shows a distorted morphology as would be expected if the merger was recent. With its spatial resolution of 0.1″, *HST* would allow resolution of a spatial scale of $\sim$1 kpc in the galaxy and measurement of a corresponding offset of the accreting SMBH from the galaxy core. The X-ray detection of SDSS J0927+2943 holds promise for a deep *Chandra* study of SMBH and host galaxy. If the recoiling SMBH is a radio emitter, high-resolution radio observations would provide even more precise measurement of its location.

In summary, SDSS J0927+2943 is the best candidate to date for a recoiling supermassive black hole. Its spectrum shows the characteristic signature of two separate emission-line systems, kinematically offset by $\sim$2650 km s^{-1}: broad lines from gas bound to the recoiling hole, and narrow lines from gas left behind. Further study of this source and detection of similar ones will provide important information on BH recoil, relevant timescales, and the frequency of BHs removed from their host galaxies, and therefore on simulations of galaxy formation and evolution and on the question how many BHs grew early by merging.

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