The Astrophysical Journal, 696:1367–1373, 2009 May 10 doi:10.1088/0004-637X/696/2/1367

COMMENT ON THE BLACK HOLE RECOIL CANDIDATE QUASAR SDSS J092712.65+294344.0

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Received 2008 October 14; accepted 2009 January 27; published 2009 April 24

ABSTRACT

The Sloan Digital Sky Survey (SDSS) quasar J092712.65+294344.0 has been proposed as a candidate for a supermassive black hole ($\sim 10^{8.8}\ M_{\odot}$) ejected at high speed from the host galactic nucleus by gravitational radiation recoil, or alternatively for a supermassive black hole binary. This is based on a blueshift of 2650 km s^{-1} of the broad emission lines ("b-system") relative to the narrow emission lines ("r-system") presumed to reflect the galaxy velocity. New observations with the Hobby–Eberly Telescope (HET) confirm the essential features of the spectrum. We note a third redshift system, characterized by weak, narrow emission lines of [O III] and [O II] at an intermediate velocity 900 km s^{-1} redward of the broad-line velocity ("i-system"). A composite spectrum of SDSS QSOs similar to J0927+2943 illustrates the feasibility of detecting the calcium K absorption line in spectra of sufficient quality. The i-system may represent the QSO host galaxy or a companion. Photoionization requires the black hole to be $\sim$3 kpc from the r-system emitting gas, implying that we are observing the system only 10^6 yr after the recoil event and contributing to the low probability of observing such a system. The HET observations give an upper limit of 10 km s^{-1} per year on the rate of change of the velocity difference between the r- and b-systems, constraining the orbital phase in the binary model. These considerations and the presence of a cluster of galaxies apparently containing J0927+2943 favor the idea that this system represents a superposition of two active galactic nuclei.

Key words: black hole physics – galaxies: active – quasars: general

Online-only material: color figures

1. INTRODUCTION

Simulations of binary black hole mergers show large recoil velocities ("kicks") of the final merged black hole resulting from asymmetric emission of gravitational radiation. Campanelli et al. (2007b) predict a maximum recoil velocity of 4000 km s^{-1} for equal mass black holes with maximal spin ($a_* = 1$), with the spins anti-aligned and lying in the orbital plane. Kicks as large as 3300 km s^{-1} have been found in numerical simulations (Dain et al. 2008) for $a_* = 0.92$. For $a_* = 0.9$, Baker et al. (2008) predict that as many as one-quarter of mergers will give kicks over 1000 km s^{-1} for random spin orientations and mass ratios distributed in the range 0.25 to 1. For a binary supermassive black hole ($\sim 10^8\ M_{\odot}$) formed during a galactic merger (Begelman et al. 1980), the kick may displace the black hole from the galactic nucleus or eject it entirely (Merritt et al. 2004, and references therein). For a recoil occurring in an active galactic nucleus (AGN) with an accretion disk, the inner disk will remain bound to the black hole, providing fuel for continued AGN activity (Loeb 2007). This might be observed as a QSO displaced from the galactic nucleus (Madau & Quataert 2004; Loeb 2007), as a QSO with emission lines shifted relative to the galactic velocity (Bonning et al. 2007), as thermal emission from shocked gas in the disk (Lippai et al. 2008; Shields & Bonning 2008; Schnittman & Krolik 2008), or as flares from tidal disruption of stars bound to the moving hole (Komossa & Merritt 2008). However, AGNs rarely show displaced nuclei (Libeskind et al. 2006), and Bogdanović et al. (2007) argue that accretion by the merging black holes will align their spins in a way unfavorable for large kicks.

Bonning et al. (2007) conducted a search for recoil candidates among QSOs in the Sloan Digital Sky Survey (SDSS). They looked for cases in which the velocity of the broad emission lines differed substantially from that of the narrow lines. The inner disk and broad-line region (BLR) should remain bound to the black hole, the narrow-line region (NLR) will be left behind. Photoionization of the residual nuclear gas and the general interstellar medium by the displaced QSO should give narrow emission lines at the velocity of the host galaxy. Bonning et al. (2007) found many cases of shifted broad lines (as was previously known) up to 2600 km s^{-1}, but they attributed most cases to physical processes in the BLR rather than recoil. They listed several spectroscopic criteria to be satisfied by viable candidates for true kicks, including symmetrical broad-line profiles, agreement of the velocity of the broad Hβ and Mg II lines, and agreement of the profiles of the high and low ionization narrow lines. Bonning et al. (2007) listed two candidate objects that satisfied these criteria, with velocity shifts of $\sim$500 km s^{-1}.

Komossa et al. (2008) proposed the QSO SDSS J092712.65+294344.0 as a promising candidate for black hole recoil. The object shows broad emission lines of Hβ and Mg II at $z_b = 0.6977$ (b-system) and narrow emission lines at $z_r = 0.7128$ (r-system). Portions of the spectrum are shown in Figures 1 and 2; see Komossa et al. (2008) for the full SDSS spectrum with line identifications. The Hβ and Mg II lines have symmetrical profiles with closely consistent blue shifts of 2650 km s^{-1} relative to the narrow lines. Komossa et al. (2008) identify the narrow lines with the host galaxy and the broad lines with a recoiling black hole ejected from the nucleus with a line-of-sight velocity of 2650 km s^{-1} toward the observer. The narrow lines have normal AGN line intensity ratios, with unusually narrow profiles (FWHM = 170 km s^{-1}). There is no indication of broad lines at the redshift of the narrow lines. Unusual for QSOs with shifted broad lines, there is an additional set of narrow emission lines at the peak velocity of the broad lines. Komossa et al. (2008) suggest that the narrowness of the r-system line profiles is consistent with photoionization of gas

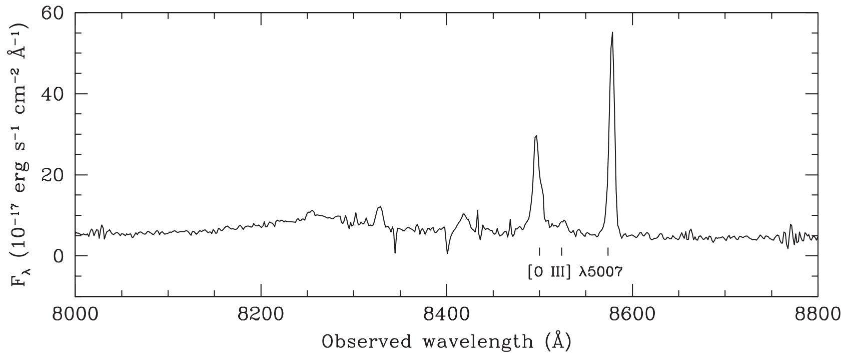

Figure 1. SDSS spectrum of J0927+2943 in the Hβ region. Note [O III]λ5007 emission line in the r-system at λ8578 and in the proposed i-system at λ8526. The emission feature at λ8500 is a blend of [O III]λ4959 in the r-system and λ5007 in the b-system. See text for discussion.

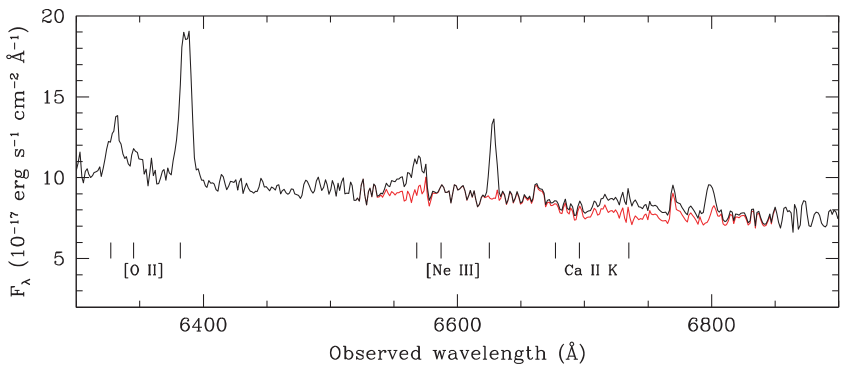

Figure 2. SDSS spectrum of J0927+2943 in the region of the stellar calcium H and K lines with (red) and without subtraction of [Ne III]λ3968 and Hϵ at the b- and r-system redshifts. Indicated are the wavelengths of [O II]λ3727, [Ne III]λ3968, and Ca IIλ3933 at the three redshifts. Note the weak i-system [O II] emission line. See text for discussion.

(A color version of this figure is available in the online journal.)

in a galactic disk by an ionizing source displaced from the nucleus, and that the b-system narrow lines may represent weakly bound gas moving with the black hole. They further argue that a chance superposition of two AGNs with these properties is unlikely, and that the velocity difference is too large for a merger of two active galaxies in a cluster of galaxies. More recently, Bogdanović et al. (2008) and Dotti et al. (2008) have proposed the alternative hypothesis that J0927+2943 represents a supermassive binary black hole system whose orbital velocity leads to the velocity of the b-system while the r-system represents the host galaxy.

Here we present a new Hobby–Eberly Telescope (HET) spectrum of J0927+2943 that confirms the basic features of the system and sets limits on variability. We note the presence of a third redshift system in J0927+2943, which is closer to the broad-line velocity and has implications for the interpretation of the system. We emphasize the importance of identifying the stellar absorption lines and discuss their possible presence at the intermediate redshift. We also consider photoionization constraints on the geometry and age of the system on the recoil hypothesis. Finally. we comment on the relative merits of the recoil, binary, and superposition hypotheses and potential tests.

2. HET SPECTRUM

In order to confirm the basic features of the spectrum and to search for possible stellar absorption lines (see below), we observed J0927+2943 using the HET at McDonald Observatory. Spectra were obtained with the Low Resolution Spectrograph (LRS) with the G2 grism and a 2 arcsec slit giving a spectral resolution of FWHM $=$ 410 km s^{-1} as measured from the night sky lines. Integrations of 40 minutes were obtained on the evenings of 2008 May 8 and May 9 (civil), each divided into two cosmic ray splits. The data were reduced using standard procedures. The relative flux calibration as a function of wavelength should be accurate, but absolute calibration is not precise because of the nature of the HET, which has a changing effective aperture during the integration. The flux-calibrated spectrum is shown in Figure 3. The spectrum covers the observed wavelength range from 4300 to 7250 Å, which includes Mg II through Hγ but not the Hβ-[O III] region. The HET spectrum confirms the basic features of the SDSS spectrum, including the r- and b-redshift systems representing the strong narrow lines and the broad lines, respectively. The equivalent widths for the HET and SDSS spectra, measured with a Gaussian profile with the IRAF task SPLOT[3] respectively are 11.0 Å and 10.1 Å for [O II]λ3727 and 3.7 Å and 3.3 Å for [Ne III]λ3869, consistent within an estimated 10% error due to blending and continuum level. This sets a corresponding limit on continuum variability during the 3.3 yr interval between the dates of the SDSS (2005 January 19) and HET spectra.

The binary black hole model of (Bogdanović et al. 2008) and (Dotti et al. 2008) predicts a secular shift of the b-system narrow lines because of the orbital motion (see discussion below). In this interpretation the r-system narrow lines represent the host galaxy and should be a stable frame of reference. We have measured the velocity difference between the peaks of the r-system and

[3] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

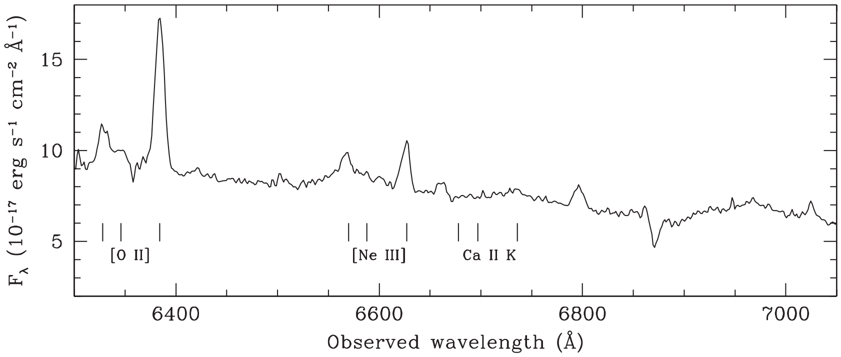

Figure 3. Optical spectrum of J0927+2943 obtained with the Hobby Eberly Telescope at McDonald Observatory. Indicated are the wavelengths of [O II]λ3727, [Ne III]λ3968, and Ca IIλ3933 at the three redshifts. The dip at 6870 Å is an artifact.

b-system narrow lines in the SDSS and HET spectra. The results in km s^{-1} for (SDSS, HET) are (2565 ± 30, 2575 ± 20) for [O II]λ3727,(2679 ± 20, 2694 ± 30) for [Ne III]λ3869, and (2811 ± 30, 2756 ± 40) for [Ne V]λ3426 (the errors are based on the extreme reasonable cursor positions and on a comparison of cursor settings by eye with Gaussian fits in SPLOT constrained to fit the line core and exclude the blue wing). The corresponding velocity change in the sense $\Delta v_{rb} \equiv v_r - v_b$ is $+10 \pm 36$, $+14 \pm 26$, and -55 ± 50 for [O II], [Ne III], and [Ne V], respectively. Note that this refers to the full 3.3 year interval. The mean weighted by the inverse square error is Δv_{rb} =–2 ± 23 for all three lines and $\Delta v_{rb} = +12 \pm 25$ for [O II] and [Ne III] only. The annual rates of change are $dv_{rb}/dt =$ –1 ± 7 km s^{-1} per year for all three lines and $dv_{rb}/dt = +4 \pm 8$ km s^{-1} per year for [O II] and [Ne III] only. Implications for the binary model are discussed below.

3. THE THIRD REDSHIFT

Motivated by the suspected presence of a stellar Ca K line at an intermediate redshift between z_b and z_r (see below), we examined the spectrum of J0927+2943 for possible emission lines at such a redshift. The SDSS spectrum (Figure 1) does indeed show a weak, narrow emission line at $\lambda 8525.5 \pm 1.0$ ($z = 0.7028 \pm 0.0002$). This feature has a flux of $(23 \pm 5) \times 10^{-17}$ erg cm^{-2} s^{-1} and an observed-frame equivalent width (EW) of 4 ± 1 Å. The corresponding [O III]λ4959 line may be present at the expected wavelength and intensity but is obscured by noise and night sky lines. There is also a weak, narrow emission line at $\lambda 6347.0 \pm 1.0$ (Figure 2) that corresponds to [O II]λ3727.4 at $z = 0.7028 \pm 0.0003$. This feature has a flux of $(16 \pm 4) \times 10^{-17}$ erg cm^{-2} s^{-1} and an observed-frame equivalent width (EW) of 1.7 ± 0.4 Å. The close agreement of the [O III] and [O II] redshifts indicates the reality of the system. We call this intermediate redshift system the "i-system" and take $z_i = 0.7028$. The HET spectrum confirms the presence of the i-system [O II] line at a velocity and intensity (EW 2.8 ± 0.7 Å) consistent with SDSS. The upper limit on any narrow Hβ emission line at z_i is about one third the flux in λ5007. These line intensities are consistent with emission from a low luminosity AGN or with H II region emission corresponding to a star formation rate of about one solar mass per year (Kennicutt 1998).

The i-system offers an alternative candidate for the host galaxy of the QSO, or it may represent a close companion. In either case, the presence of a galaxy at a velocity close to the broad-line velocity lends credence to the possibility that the r-system may not represent the host galaxy and that the broad-line system may be an ordinary QSO. The i-system could also represent gas ejected from the QSO.

4. STELLAR ABSORPTION FEATURES

The presence of stellar lines at a redshift close to that of the broad emission lines of J0927+2943 would undermine the recoil hypothesis. The stellar features from the host galaxy in QSO spectra are typically quite weak, particularly at higher redshifts, because of the predominance of the AGN continuum. The Ca II K line at λ3933 is often the most visible feature (Greene & Ho 2006). If the black hole mass is proportional to the host galaxy luminosity (Lauer et al. 2007, and references therein), the ratio of galaxy to QSO continuum should scale inversely as the Eddington ratio $L/L_{\rm Ed}$. From the width of the broad emission lines and the continuum luminosity, Komossa et al. (2008) find $M_{\rm BH} = 10^{8.8}$ $M_\odot$ for the black hole in J0927+2943, giving $L/L_{\rm Ed} = 10^{-1.0}$. As a guide to the expected strength of the Ca II lines in J0927+2943, we constructed a composite spectrum using QSOs from SDSS Data Release 5 (DR5) having $0.6 \leqslant z \leqslant 0.8$ and $-1.4 < \log L/L_{\rm Ed} <$ –0.6, similar to z and $L/L_{\rm Ed}$ for J0927+2943. The spectra were processed in the manner described by Salviander et al. (2007) for their "HO3" sample, shifted to the rest wavelength scale using the SDSS redshift, and scaled to a common value of F_λ at λ4000. Figure 4 shows the region of the Ca II lines in the composite spectrum for the 2181 QSOs selected in this fashion. The Ca II K line is evident at λ3933, with a depth of about 5% below the total continuum. This is consistent with the composite QSO spectrum of Vanden Berk et al. (2001).

The companion line in the Ca II doublet at λ3968 is masked by the narrow [Ne III]λ3968 and broad Hϵ at λ3970 emission lines, but an approximate subtraction is possible. We subtracted [Ne III] using $I(\lambda 3968) = 0.31 I(\lambda 3869)$ (Osterbrock & Ferland 2006) and a Gauss–Hermite fit to the profile of λ3869. For Hϵ, we examined the Balmer decrement in a generic model for a BLR cloud computed with version 07.02.00 of the photoionization code CLOUDY, most recently described by Ferland et al. (1998). This was a plane–parallel model with solar abundances, gas density $N = 10^{10}$ cm^{-3}, ionization parameter $U = 10^{-2}$, the "table power law" ionizing continuum, and a stop column density of 10^{22} cm^{-2}. The model gave $I(\mathrm{H}\epsilon)/\mathrm{I}(\mathrm{H}\delta) = 0.60$, compared with 0.62 for low density "Case B" and 0.53 to 0.55 in several other CLOUDY models with the same density but different ionizing continua and larger column densities. We subtracted Hϵ using a Gaussian profile with a wavelength-integrated flux of $0.6F(\mathrm{H}\delta)$ and the same FWHM as Hδ. The subtraction reveals the Ca H line. The depth of the K

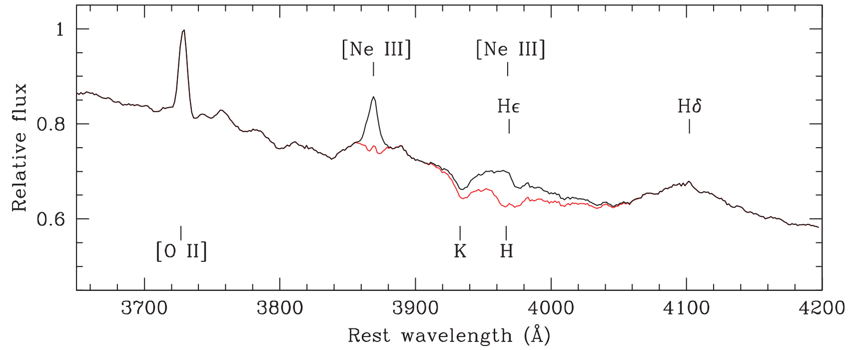

Figure 4. Composite spectrum of SDSS quasars with values of $L/L_{\rm Ed}$ similar to that of J0927+2943 (see text). The region of the stellar calcium H and K lines is shown with and without subtraction of [Ne III]λ3968 and Hϵ. The calcium K line at λ3933 is clearly visible.

(A color version of this figure is available in the online journal.)

line is about 7% in the subtracted spectrum, in rough agreement with the expected value for this range of $L/L_{\rm Ed}$ on the basis of the black hole–galaxy luminosity relationship of Lauer et al. (2007) for bright ellipticals.

We initially suspected the presence of a weak Ca K absorption line at a redshift similar to z_i, based on visual inspection of the SDSS spectrum. We performed a subtraction of the r-system and b-system [Ne III] and Hϵ lines from the SDSS spectrum of J0927+2943 in the manner described above. The resulting spectrum (Figure 2) shows no convincing K line at any of the three redshifts. The K line is not evident in the HET spectrum (Figure 3), which has higher signal to noise. We estimate an upper limit of 10% on the depth of the K-line, consistent with the expected depth as discussed above. Detection of host galaxy absorption lines is an important goal for future observations.

5. GEOMETRICAL CONSTRAINTS

The likelihood of observing a high velocity recoil such as proposed for J0927+2943 depends on the length of time during which it would have the current appearance. Komossa et al. (2008) suggest an upper limit of $\sim 10^9$ yr for the postkick duration of AGN fueling, if the mass of the bound disk is close to that of the black hole and the efficiency of luminosity production is as high as expected for a rapidly spinning hole. Blecha & Loeb (2008) estimate a bound disk mass of $\sim 10^7$ $M_\odot$, based on a disk model that takes account of the disk's self gravity, giving a lifetime of $\sim 10^7$ yr. The object likely would not maintain its current appearance over even this shorter time. At the observed velocity, the black hole would reach 30 kpc from the galactic nucleus in $10^{7.1}$ yr, by which time the r-system narrow lines would fade as the galactic ISM intercepted a diminishing fraction of the ionizing continuum from the recoiling AGN.

A still tighter constraint follows from the ionization equilibrium of the gas emitting the r-system narrow lines. The r-system [O II]$\lambda\lambda$3728.8, 3726.0 doublet is marginally resolved in the SDSS spectrum, with equal intensities. Given the [O III] redshift, the observed wavelength of 6386.0 ± 0.2 Å of the [O II] doublet also supports equal intensities. For $r = I(3728.8)/I(3726.0) = 1.0 \pm 0.2$, based on the appearance of the doublet and the mean wavelength, the "NEBULAR" software[4] (Shaw & Dufour 1995) gives $N_e = 380$ cm^{-3} (range 140 to 670 cm^{-3}). The corresponding value of the [S II] doublet ratio $I(6717)/I(6730)$ is 1.12, a typical NLR value (Salviander et al. 2007). In the recoil model, the ionizing source for the r-system lines is the broad-line AGN. The observed AGN continuum flux at λ5100 rest wavelength corresponds to $\lambda L_\lambda(5100) = 10^{44.96}$ erg s^{-1}, giving $L_{\rm bol} \approx 9\lambda L_\lambda(5100) = 10^{45.92}$ erg s^{-1} following Kaspi et al. (2000). If we take an ionizing luminosity of $0.3L_{\rm bol}$ and a mean ionizing photon energy of 2 Ryd, then the ionizing photon luminosity is $Q = 10^{55.76}$ s^{-1}, consistent with the broad Hβ luminosity of $10^{45.25}$ erg s^{-1}. The uncertainty in Q may be $\sim$0.3 dex, based on the assumptions. NLR models with CLOUDY (solar abundances, density $N = 10^3$ cm^{-3}, and either a $L_\nu \propto \nu^{-1}$ or "Table AGN" ionizing continuum) reproduce the [O II]/[O III] line ratio of J0927+2943 for an ionization parameter $U \equiv \phi/Nc = 10^{-2.5\pm0.2}$, where $\phi = Q/4\pi R^2$. For $N = 380$ cm^{-3} and $Q = 10^{55.76}$s^{-1}, this places the ionizing source at a distance of 3.5 kpc from the gas. This is a plausible distance in terms of allowing gas in a galactic disk to intercept a substantial fraction of the ionizing radiation and give the strong narrow lines of the r-system. The derived radius depends on parameters as $R \propto Q^{1/2}N^{-1/2}U^{-1/2}$. This gives an uncertainty of $\pm$0.23 dex in R if we add the three contributions in quadrature, or $\pm$0.8 dex if we force each uncertainty toward the small R or large R extreme.

At 2650 km s^{-1}, the recoiling black hole requires only $10^{6.1}$ yr to reach 3 kpc from the galactic nucleus. Thus, we are catching this object at a fortuitous moment, if it is indeed a recoil event. A similar photoionization argument is given by Bogdanović et al. (2008) and Heckman et al. (2009).

At a distance of 3 kpc from the galactic nucleus, the projected angular separation is $0\farcs4 \sin\theta$. The angle θ of the recoil velocity to the line of slight may be small, since the radial velocity of 2650 km s^{-1} is close to the maximum theoretical kick velocity of 4000 km s^{-1}. Thus, the angular offset of the AGN from the host galaxy nucleus may or may not be resolvable by HST in the recoil picture.

6. DISCUSSION

6.1. Superposition in a Cluster?

The possibility of chance superposition of a second AGN was rejected as improbable by (Komossa et al. 2008). The SDSS image of J0927+2943 appears pointlike, and the SDSS spectrograph fibers have a diameter of 3 arcsec. The alignment must be within $\sim$1 arcsec on the sky. From the overall QSO luminosity function (Croom et al. 2005; Richards et al. 2006), the odds of a chance superposition within 1 arcsec and within 2650 km s^{-1} is only $\sim 10^{-8}$ for a given QSO. This assumes that

4 http://stsdas.stsci.edu/nebular

narrow-line QSOs have similar abundance to their broad-line counterparts. However, the probability is substantially enhanced by clustering. Given the existence of a broad-line QSO in a cluster in the first place, what is the likelihood of a second, superimposed narrow-line AGN? A massive cluster is needed to support the observed velocity difference. Given an incidence of AGN per galaxy at this redshift of $\sim 10^{-2}$ (Shi et al. 2008, and references therein), it may be reasonable to assume that there typically is one additional narrow-line QSO in the cluster. For a cluster radius of 1 Mpc, the probability of a superposition within 1 arcsec is $10^{-4.3}$. This suggests that several such superpositions may be present among the $\sim 10^5$ QSOs in SDSS, or even the subset with $z < 0.8$ having [O III] in range.

The SDSS images show a number of galaxies in the vicinity of J0927+2943 whose photometric redshifts (Csabai et al. 2003), given by the SDSS data server,[5] are consistent with J0927+2943 within the errors of ~ 0.2. The SDSS photometric query server gives four galaxies of magnitude $i = 20.0$ to 22.2 within 0$'$.5 (200 kpc). One, with $i = 21.6$ and photometric redshift 0.63 ± 0.25, is only 4$'$.7 (33 kpc) from the QSO. Other apparent companions within a few arcsec are visible in the images. An apparent cluster of galaxies lies about 0$'$.5 to the southwest of J0927+2943. On the eastern edge of this group, 33 arcsec south–southwest of the QSO, is SDSS J092711.93+294312.3 with $i = 20.3$, M_i =-22.8, and $z_{\rm phot} = 0.66 \pm 0.02$, close to the redshift of J0927+2943.

Consistent with the presence of close companions is the intermediate redshift system that we have identified in J0927+2943. The broad lines have a line-of-sight velocity of only 900 km s^{-1} with respect to this redshift, reasonable for orbital motion in a galactic merger or a collision or superposition in a cluster of galaxies. The black hole mass of $10^{8.8}$ $M_\odot$ corresponds to a stellar velocity dispersion of $\sigma_* = 300$ km s^{-1} by the local $M_{\rm BH} - \sigma_*$ relationship (Tremaine et al. 2002). Orbital velocities of several times σ_* can occur in mergers (Merritt et al. 2004). The velocity of the r-system narrow lines is 1700 km s^{-1} relative to z_i. This is large for a galactic merger but is possible in a cluster of galaxies (Hayashi & White 2006).

While this manuscript was in preparation, a preprint by Heckman et al. (2009) appeared suggesting that J0927+2943 is a high-redshift analog of the nearby active galaxy NGC 1275. This object has two sets of narrow emission lines separated by 3000 km s^{-1} representing two interacting galaxies. These authors also note the apparent cluster in the vicinity of J0927+2943, and they suggest that the r-system lines of J0927+2943 may be gas in an interacting galaxy photoionized by the QSO continuum.

6.2. *A Recoiling Black Hole?*

Komossa et al. (2008) note that the b-system narrow lines are rather broad and asymmetrical and suggest that this supports a special nature for the object as opposed to a superposition. However, wider forbidden lines are associated larger $M_{\rm BH}$ and L. The b-system [O III] widths of 460 km s^{-1} (Komossa et al. 2008) resemble the average value of 444 km s^{-1} for the QSOs of Salviander et al. (2007) having $\nu L_\nu(5100) > 10^{45}$ erg s^{-1} and $M_{\rm BH} > 10^{8.5}$ $M_\odot$, similar to J0927+2943. Blue wings on [Ne V] do occur at velocities similar to J0927+2943 (-1500 km s^{-1} from the line peak). Our composite SDSS QSO spectrum shows such a blue wing, although not as strong as in J0927+2943.

[5] http://www.sdss.org

How unlikely is a combination of parameters giving a line-of-sight recoil velocity of 2650 km s^{-1}?As noted above, extrapolation of numerical results indicates a maximum possible kick of 4000 km s^{-1} for equal mass holes with maximal spins anti-aligned and lying in the orbital plane. Baker et al. (2008) find that the recoil velocity varies as η^3, where $\eta \equiv q/(1+q)^2$ and $q = m_1/m_2 < 1$ is the black hole mass ratio. If other parameters are optimal for a 4000 km s^{-1} kick, then a kick of 2650 km s^{-1} is possible for $q > 0.5$. In the cosmological merger simulations of Sesana et al. (2007), merger mass ratios are fairly uniformly distributed in log q for their "large seeds" scenario. If a luminous QSO typically involves a major merger with $q > 10^{-1}$, then a fraction $\sim 10^{-0.5}$ of all QSOs may have a mass ratio capable of giving the required kick. Spins of black holes in AGNs are not well determined, but it is commonly believed that they are often $a_* = 0.9$ or larger (e.g., Fabian 2005), consistent with kicks of $\sim$3000 km s^{-1}or larger if the other parameters are optimal (Baker et al. 2008). Campanelli et al. (2007a) find that the kick velocity varies sinusoidally with the initial spin direction of each hole relative to its linear momentum. Assuming a distribution in q above $10^{-0.5}$ and a_* above 0.9, the typical kick for perfect spin alignment will be some average over the range 2650 and 4000 km s^{-1}. If this requires that the two spins must be anti-aligned such that $\cos\theta > 0.9$, and that the common axis lie in the orbital plane within a similar tolerance, then a fraction $\sim 10^{-2}$ of randomly aligned mergers will have the needed alignment. If objects with a true kick between 2650 and 4000 km s^{-1} have a typical value $\sim$3300 km s^{-1}, then a fraction $10^{-0.7}$ will have a kick over 2650 km s^{-1} projected onto the line of sight to the observer, assuming that redshifted or blueshifted kicks would equally attract notice. Then the fraction of QSOs whose line-of-sight kick exceeds 2650 km s^{-1} will be $\sim 10^{-0.5} \times 10^{-2} \times 10^{-0.7} = 10^{-3.2}$. We have argued that J0927+2943 is being observed in a stage of evolution lasting only 10^6 yr after the recoil event. If we assume that typical QSOs shine for a Salpeter time of $\sim 10^{7.6}$ yr, then the odds of catching a particular QSO in the J0927+2943 stage is only $\sim 10^{-1.6}$. Altogether, this gives a probability of only $\sim 10^{-4.9}$ that a QSO will show a kick of the magnitude of J0927+2943. The SDSS DR6 has 90,000 QSOs at $z < 2.3$, of which approximately one-fourth have $z < 0.8$ allowing observation of the [O III] lines. The expected number of QSOs with kicks over 2650 km s^{-1} is therefore approximately $10^{-0.4}$. This very approximate estimate suggests that finding one example of a large kick in the SDSS data base is not altogether implausible. This assumes (1) that spin orientations are random, (2) that spin magnitudes are large, and (3) that the final merger occurs during the QSO phase. If some physical process tends to align the spins, as proposed by Bogdanović et al. (2007), then large kicks will not occur.

6.3. *A Supermassive Black Hole Binary?*

The binary black hole model of Bogdanović et al. (2008) and Dotti et al. (2008) assumes that the broad lines are associated with the less massive black hole of the pair, whose orbital motion gives rise to the blueshift of the b-system lines while the r-system reflects the host galaxy velocity. The model has the advantage that the binary may be in a long lived stage of evolution. This may be as much as 10^2 times longer than the observable phase of the recoil scenario, before the QSO moves too far from the galaxy. However, the binary model is constrained by our limit $dv/dt < 10$ km s^{-1} per year on the rate of change of the velocity separation between the r- and b-systems (see Section 2). The rate of change of the line-of-sight velocity u_2 of the secondary black hole M_2, identified with the b-system spectral features, is given by Bogdanović et al. (2008) as $du_2/dt \approx (88\ \mathrm{km\ s^{-1}})(1+\mathrm{q})^2\, \mathrm{M}_{2,8}^{-1}\, \mathrm{q}_{0.1}\, \mathrm{s}_\mathrm{i}^{-3}\, \mathrm{s}_\phi^{-4}\, \mathrm{c}_\phi$, where $q_{0.1} \equiv 10M_2/M_1$, $M_{2,8} = M_2/(10^8\ M_\odot)$, i is the inclination of the orbital axis to the line of sight, $s_i \equiv \sin i/\sin 45°$, $s_\phi \equiv \sin\phi/\sin 45°$, and $c_\phi \equiv \cos\phi/\cos 45°$. There is a range of orbital phase around $\phi = 0$ (inferior conjunction) and $\phi = 180°$ for which du_2/dt exceeds the observational limit. For some parameters, this requires the orbital phase to be close to quadrature where dv/dt is zero ($\phi = 90°$ or $270°$). The severity of the constraint depends on the system parameters. For larger black hole masses, the period is longer, the orbital acceleration is smaller, and the constraint on ϕ is less severe. For small i, the orbital velocity and acceleration are large and the constraint on ϕ is severe. A modest inclination may be favored by the unified model of an AGN. Dotti et al. (2008) suggest a model with $M_1 = 6\times10^8\ M_\odot$, $M_2 = 1.7\times10^9\ M_\odot$, and $i = 40°$ (this large M_2 may stretch the upper limit on the Ca K line in Section 4). For these parameters, our constraint $du_2/dt < 10$ km s^{-1} restricts ϕ to be within $\pm12°$ of quadrature, corresponding to 13% of each orbital period. Alternatively, Bogdanović et al. (2008) argue that in the binary model, the broad emission-line width may not give a valid indication of the AGN black hole mass (M_2 in the binary model). From the observed X-ray luminosity, an assumed bolometric correction, and the Eddington limit, they argue for a lower limit of $M_2 > 5\times10^7\ M_\odot$. They also argue that M_2 should be substantially less than M_1 in order for the AGN luminosity of M_1 to be relatively unimportant, consistent with a single set of broad emission lines in the observed spectrum. For $M_{2,8} = 0.5$ and $M_{1,8} = 5$, the allowed azimuth range around quadrature is ($\pm8°$, $\pm3°$, $\pm0.9°$) for $i = 45°, 30°, 20°$, respectively. We would be observing the binary in a special portion of only $\sim10^{-1}$ of its orbital period, somewhat offsetting the advantage of the binary model as a long lived configuration.

Other issues for the binary model, as noted by Heckman et al. (2009), include the presence of strong [O II] emission in the b-system. This is difficult to account for at the densities $n_e > 10^6$ cm^{-3} derived by Dotti et al. (2008) for the tidal gap in the accretion disk that is the proposed source of the b-system narrow lines. Also of interest is how the binary model would give the observed, normal broad-line profiles and the close redshift agreement of the b-system broad and narrow lines.

More exotic interpretations of J0927+2943 can be imagined. For example, if the host galaxy is indeed at an intermediate redshift, the system might be a slingshot event in which a merging triple black hole system has ejected one black hole at +1700 km s^{-1} while the remaining binary rebounded toward the observer at −900 km s^{-1}. Problematic in such a picture is how the r-system object could retain or reacquire an NLR with line widths of only 170 km s^{-1} after experiencing a kick of 1700 km s^{-1}.

7. CONCLUSION

The key question about J0927+2943 is whether it is indeed a high velocity recoil or some other dramatic event. Confirmation of such a recoil would be an important confirmation of recent predictions of numerical relativity. Additional observations of the candidate system are needed to establish its true nature. Komossa et al. (2008) note the importance of obtaining HST imaging to resolve the recoiling AGN from its host galaxy. Most essential is to establish the velocity of the host galaxy; detection of stellar features close to the b-system (broad-line) velocity would suggest a normal QSO at rest in its host galaxy. We have argued that the Ca II lines provide an opportunity to do this with high quality spectra. Other stellar features may be more difficult, given the presence of AGN emission lines near the G-band, the Mg b-band, and the Na D lines. The infrared calcium triplet, seen in the composite AGN spectrum of Vanden Berk et al. (2001), may be an alternative.

Also important are imaging and spectroscopic studies of the environment of J0927+2943 to establish the nature of the galaxy cluster that apparently contains the QSO. If the velocities of the neighboring galaxies resemble the b-system (broad-line) redshift of J0927+2943 this will weigh against a recoil or binary model. Finally, if the narrow lines of the r-system come from the ISM of the host galaxy, photoionized by a displaced QSO, spectroscopic anomalies might be expected. For example, in the geometry deduced above, the QSO radiation flux reaching the r-system gas is similar to that in Galactic and extragalactic H II regions. Iron remains depleted into grains in these H II regions, whereas it is gaseous in the NLR of AGN. The intensity of emission lines such as [Fe VII]λ6087 in the r-system of J0927+2943 may be a diagnostic. Also, the [Ne V] lines of AGN are often broader than the lower ionization lines. Confirmation of this for the r-system lines of J0927+2943 would indicate a normal AGN with the ionizing source in the center of the NLR. This would argue against recoil and against the variant of the superposition model in which the r-system lines are the ISM of a passing nonactive galaxy photoionized by the main AGN (Heckman et al. 2009).

Pending such studies, the existence of a third velocity system in the spectrum of J0927+2943 as noted here, relatively close to the broad-line velocity, together with the presence of a substantial cluster apparently containing J0927+2943, suggests that the superposition hypothesis deserves attention.

We thank Anita Cochran, Mike Gladders, Tesla Jeltema, Stefanie Komossa, Milos Milosavljević, and David Rosario for helpful discussions and assistance. G.S. acknowledges support from the Jane and Roland Blumberg Centennial Professorship in Astronomy at the University of Texas at Austin.

Funding for the Sloan Digital Sky Survey (SDSS) has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

The Hobby–Eberly Telescope (HET) is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. The Marcario Low Resolution Spectrograph is named for Mike Marcario of High Lonesome Optics who fabricated several optics for the instrument but died before its completion. The LRS is a joint project of the Hobby-Eberly Telescope partnership and the Instituto de Astronomia de la Universidad Nacional Autónoma de México.

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