THE QUASAR SDSS J105041.35+345631.3: BLACK HOLE RECOIL OR EXTREME DOUBLE-PEAKED EMITTER?

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ABSTRACT

The quasar SDSS J105041.35+345631.3 (z = 0.272) has broad emission lines blueshifted by 3500 km s$^{-1}$ relative to the narrow lines and the host galaxy. Such an object may be a candidate for a recoiling supermassive black hole, a binary black hole, a superposition of two objects, or an unusual geometry for the broad emission-line region (BLR). The absence of narrow lines at the broad line redshift argues against superposition. New Keck spectra of J1050+3456 place tight constraints on the binary model. The combination of large velocity shift and symmetrical Hβ profile, as well as aspects of the narrow line spectrum, make J1050+3456 an interesting candidate for black hole recoil. Other aspects of the spectrum suggest an extreme case of a double-peaked emitter. We discuss possible observational tests to determine the true nature of this exceptional object.

Subject headings: galaxies: active — quasars: general — black hole physics

1. INTRODUCTION

Mergers of binary black holes can result in the final black hole receiving a ‘kick’ due to anisotropic emission of gravitational radiation at coalescence. Kick velocities are predicted to range up to a maximum of 4000 km/s for certain configurations of black hole spin and mass ratio (Campanelli et al. 2007). For the case of supermassive black holes merging in a galaxy with sufficient gas to power an accretion disk around the black hole, the merger remnant will carry a portion of the disk with it and be visible as a quasar, either physically offset from the nucleus or with broad emission lines Doppler-shifted from the host galaxy velocity (Loeb 2007; Madau & Quataert 2004; Blecha & Loeb 2008). Detection of a kicked black hole would be a powerful confirmation of the predictions of numerical relativity and shed light on the cosmic evolution of supermassive black holes.

2. SPECTRAL PROPERTIES OF J1050+3456

2.1. The SDSS Spectrum

The SDSS spectrum of J1050+3456 is shown in Figure 1 and measurements are given in Table 1. The spectrum shows strong, narrow emission lines including [O III], Hβ, [Ne III], and [O II], and conspicuous stellar absorption lines. The [O III] redshift is $z_{[O III]} = 0.2720$, and the other narrow emission lines as well as the stellar absorption lines are consistent within $\sim 100$ km s$^{-1}$. The intensity ratios among the narrow lines are typical of AGN. Relative to $z_{[O III]}$, the broad Hβ line peaks at a blueshift of 3638 ± 160 km s$^{-1}$ and has a FWHM of 2170 ± 250 km s$^{-1}$. The peak of the broad Hα line shows a similar blueshift (3470 ± 150 km s$^{-1}$), but there is a more prominent red wing. (Values in Table 1 for Mg II and the [Ne v] flux and EW are from the Keck spectrum described below, with flux scaled to the SDSS spectrum using [Ne III]; other measurements are from SDSS spectrum.)

The observed flux at 5100(1 + z) Å is $F_{5100} = 10.6 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. We have estimated the galaxy...
contribution to the continuum by modeling the observed spectrum using a set of empirical galaxy spectra from SDSS (Subbarao et al. 2002), combined with a simple power-law with an adjustable spectral index for the AGN spectrum. The best fit is for an early-type galaxy. We estimate the galaxy fraction of the observed continuum at rest wavelength 5100 Å to be approximately 36% with an uncertainty of 0.1 dex. For a typical early-type galaxy energy distribution this implies an absolute magnitude \( M_H = -20.0 \) for the host galaxy. For the local black hole bulge relationship (Tremaine et al. 2002, and references therein) the expected \( M_{BH} \) is \( 10^{8.2} \pm 0.3 \) \( M_\odot \), where the uncertainty reflects the scatter in the \( M_{BH} \)-bulge luminosity relationship. Here we have assumed that the observed stellar light is all bulge and made no allowance for fading.

The AGN component of the flux at 5100(1 + \( z \)) Å is \( F_\lambda = 7.4 \times 10^{-17} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), giving \( L_\lambda(5100) = 10^{44.15} \) erg s\(^{-1}\). This implies a bolometric luminosity \( L_{bol} \approx 9 \alpha L_\lambda(5100) = 10^{45.69} \) erg s\(^{-1}\), following Kaspi et al. (2000). Objects with shifted broad lines may not conform to the usual relationship between FWHM and black hole mass. However, if we apply Eq. 2 of Shields et al. (2003), we find \( M_{BH} (H/\beta) \approx 10^{7.5} M_\odot \), for the measured H\( \beta \) FWHM of 2200 km s\(^{-1}\). For this \( M_{BH} \), the Eddington ratio of the AGN is \( L/L_{Edd} = 10^{-0.5} \), a typical value.

The FIRST survey (Becker et al. 1995) detected no radio source at 20 cm at the position of J1050+3456 down to a limit of 1 mJy. This limit corresponds to a Kellermann et al. (1989) radio loudness parameter \( \log R < 0.5 \), assuming a radio spectral index \( F_{\nu} \propto \nu^{-0.5} \) between 6 and 20 cm. Radio loud sources have log \( R > 1 \).

2.2. Keck spectra

Blue and red spectra of J1050+3456 were obtained on the morning of 2008 December 24 with the LRIS double spectrograph on the Keck I telescope (Oke et al. 1995). On the blue side, the 400/3400 grism (spectral resolution of 7.2 Å FWHM) was used, which covered a wavelength region from the atmospheric cutoff to the dichroic at \(~5500\) Å. On the red side, the 600/7500 grating (spectral resolution of 4.7 Å FWHM), centered at 6600 Å, covered a wavelength baseline of 2620 Å. The spectrum is shown in Figure 2 and measurements are given in Table 1.

One goal was to measure the wavelength and profile of the Mg II λ2796, 2803 line, noted by Bonning et al. (2007) as a test of black hole recoil in cases of shifted Balmer lines. The Mg II profile is irregular and the central wavelength somewhat ambiguous. Accordingly, we obtained a second LRIS spectrum, this time with a blue side 600/4000 grism (spectral resolution of 4.0 Å FWHM), on the evening of 2009 April 9. Though at much lower S/N, the improved spectral resolution of the newer blue spectrum makes clear that the red wing of the broad Mg II feature is affected by a narrow Mg II absorption doublet at a blueshift of 500 ± 50 km s\(^{-1}\) with respect to \( z_{[O III]} \). Because of the absorption doublet and limited S/N of the spectra, the line peak and centroid velocity of Mg II remain uncertain. The Mg II peak in the 400g spectrum falls at \(~-3151\) km s\(^{-1}\), which is 490 km s\(^{-1}\) less than the H\( \beta \) peak shift. If this peak velocity is adopted for Mg II, then the profile has a substantial red wing, more pronounced than H\( \beta \). The Mg II centroid in the 400g spectrum has a blueshift \(~2300 ± 300\) km s\(^{-1}\) relative to \( z_{[O III]} \).

A common pattern in normal AGN is for [Ne v] λ3426 to be wider than [O iii] λ5007. Bonning et al. (2007) suggest that this should not occur for an ionizing source displaced from the galactic nucleus by recoil. The SDSS spectrum lacks sufficient S/N for [Ne v]. The 600/4000 LRIS spectrum shows a FWHM for [Ne v] of 5.4 ± 0.3 Å, only slightly larger than the instrumental FWHM of 4 Å. Because of this marginal resolution, and the possibility that the QSO image did not completely fill the spectrograph slit, we derived the effective spectral resolution by forcing the corrected FWHM of [O iii] λ3727 in the 600 g/Åmm spectrum to agree with that of the SDSS spectrum, which has better spectral resolution. The result is a Keck instrumental FWHM of 3.6 Å, yielding a corrected FWHM for [Ne v] of 277 ± 30 km s\(^{-1}\). This is close to the [O iii] corrected FWHM of 273 km s\(^{-1}\) from the SDSS spectrum.

3. THE NATURE OF J1050+3456
3.1. Superposition in a Cluster?

Based on the SDSS field images around the QSO, as well as an examination of photometric redshifts of nearby bright galaxies, it is clear that J1050+3456 is not in a rich cluster environment. However, the nearest bright galaxy to the QSO does have a comparable photometric redshift, and has colors and a derived absolute magnitude \( M_B \sim -21.7 \) consistent with a massive early-type system. Since luminous red galaxies are generally found in relatively clustered environments (Zehavi et al. 2005), J1050+3456 could possibly reside within a sparse cluster or galaxy group. Deeper imaging and spectroscopy of faint galaxies around the QSO may resolve this issue.

In a discussion of J0927+2943, Shields et al. (2009) estimate a probability of order \( 10^{-4} \) of superposition within 1 arcsec of two AGN with a velocity difference of order...
For the SDSS spectrum (dated 2005.17), the H/β shift is \( \Delta v = -3638 \pm 160 \) km s\(^{-1}\), relative to the redshift of [O III] \( \lambda 5007 \), where the uncertainty is based on extreme cursor settings. For the Keck spectrum (2008.98), we find \( \Delta v = -3546 \pm 120 \) km s\(^{-1}\). This gives a rate of change of \( dv/dt = +31 \pm 60 \) km s\(^{-1}\) per rest-frame year. In the simple approximation that the AGN \((m_2)\) is in circular orbit around \( m_1 \) in a plane containing the observer, the rate \( dv/dt \) of change of line-of-sight velocity \( u_2 \) is given by

\[
\frac{dv}{dt} = \frac{350 M_1^{1/2} u_2^{3/4} \phi_0}{m_2} \text{ km s}^{-1} \text{ yr}^{-1},
\]

where \( M_1 \equiv M_\odot / 10^8 \) \( M_\odot \), \( u_2 = 2500 \) km s\(^{-1}\), and \( \phi_0 \) and \( \phi_0 \) are the sine and cosine of the azimuth \( \phi \). For more detailed expressions (but with coefficients tailored to \( J0927+2943 \)), see \textit{Bogdanović et al.} (2009).

If we interpret our measurement as an upper limit on \( dv/dt \) of 70 km s\(^{-1}\) yr\(^{-1}\) and take \( m_1 = 10^{8.2} M_\odot \) and \( m_2 = 10^{7.5} M_\odot \) (see Fig. 2), then \( \phi \) is constrained to be within \( \pm 15^\circ \) of quadrature, a fraction 17% of the entire orbit. For orbital inclination \( i < 90^\circ \) or for smaller masses, the constraint is tighter. The combined mass of the black holes cannot be much larger, if the normal \( M_{\text{BH}} \)-bulge luminosity relationship applies.

### 3.3. A Recoiling Black Hole?

\( J1050+3456 \) is in several ways an interesting candidate for recoil. (1) The combination of large velocity shift and relatively narrow symmetrical profile, especially for H/β, is just the signature proposed by \textit{Bonning et al.} (2007) for recoil candidates. (2) Our Keck spectrum shows a similar width for [Ne v] and [O III], another criterion suggested by \textit{Bonning et al.} (see discussion in § 2.2). (3) \textit{Shields et al.} (2009) suggested that the narrow emission lines of refractory elements might be weak in recoiling QSOs. A displaced ionizing source might preserve the order-of-magnitude depletion of Fe and other elements in the ISM, whereas these elements typically have normal gas-phase abundances in the NLR (Nagao et al. 2003 and references therein). Nagao et al. give a mean value of \( I([\text{Fe v}]\lambda 6087)/I([\text{Ne v}]\lambda 3425) = 0.52 \) for type I AGN (broad lines) and 0.34 for type II AGN, whereas we find an upper limit of 0.12 in \( J1050+3456 \). Similarly, the composite Type II quasar spectrum of \textit{Zakamska et al.} (2003) gives a value \( I(\text{Mg ii}\lambda 2800)/I(\text{H/}\beta) = 0.81 \), whereas for \( J1050+3456 \) we find an upper limit of 0.16. These results suggest that depletion of Fe and Mg into grains in the NLR of \( J1050+3456 \) may be more severe than in most AGN.

On the other hand, there are reasons for caution. (1) A common pattern, illustrated by \textit{Bonning et al.} (2007), is that when the broad H/β peak is blueshifted, the red wing of the line profile is more extended than the blue wing, and vice versa (see discussion in § 5.4). This pattern is evident in the Ha and Mg II profiles of \( J1050+3456 \) (Figs. 1 & 2) and is characteristic of double-peaked broad-line AGN (§3.4). (2) The Mg II centroid is 2200 km s\(^{-1}\) blueshifted, smaller than for H/β. \textit{Bonning et al.} (2007) noted a pattern for Mg II to have a smaller shift than H/β. (3) \textit{Shields et al.} (2009) estimated a probability of only \( \sim 10^{-4.9} \) for a line-of-sight kick velocity of 2650 km s\(^{-1}\) as observed for \( J0927+2943 \). For \( J1050+3456 \), the shift of 3500 km s\(^{-1}\) is closer to the theoretical maximum of 4000 km s\(^{-1}\), resulting in an even lower probability. This argument is sensitive to the ex-
act value of the maximum recoil velocity, currently based on extrapolation (Campanelli et al. 2007). (4) The [S ii] doublet is marginally resolved with a typical line ratio of I(λ6717)/I(λ6731) = 1.2 ± 0.1, implying an electron density 240 ± 130 cm$^{-3}$ from the “NEBULAR” software’ (Shaw & Dufour 1993). This resembles the situation for the r-system narrow lines of J0927+2943, and the photoionization argument of Shields et al. (2009) carries over to J1050+3456 (given the similar [O ii]/[O iii] intensity ratio). With allowance for the electron density and continuum luminosity of J1050+3456, the result is a distance of $10^{0.3±0.2}$ kpc for the ionizing source from the narrow emission-line gas. This indicates an age of $10^{2.5±0.2}$ yr, contributing to the low probability of catching a recoil in this stage. (5) The narrow line spectrum of J1050+3456 appears quite normal and conforms to the pattern of strong [O iii] with weak Fe ii. The question of whether the ionizing continuum from a displaced QSO would produce normal AGN narrow-line ratios in the host galaxy ISM requires investigation (Komossa et al. 2008).

3.4. A Double-Peaked Emitter?

Double peaked broad Balmer lines are sometimes seen, and a number of cases have been interpreted in terms of line emission from a Keplerian disk (Eracleous & Halpern 1994 and references therein). Occasionally, the broad Balmer lines may have a single peak shifted relative to the narrow lines. Often in such cases, the profile is asymmetric, with red wing more extended in the case of a blue-shifted peak, and vice versa, as discussed by Bonning et al. (2007). This class is often considered a subset of the double-peaked emitters.

The 3500 km s$^{-1}$ blueshift of the Balmer line peak of J1050+3456 is large but not unprecedented for a double-peaked emitter. In Table 3 of Strateva et al. (2003), among 138 double-peaked emitters, the shift of the blue peak W$_{b}$ ranges from $-6700$ to $+800$ km s$^{-1}$, with 21 objects blueshifted 3500 km s$^{-1}$ or more. However, the combination of the large shift and the dominance and symmetry of the blue peak of J1050+3456 is exceptional. In Strateva et al., FHWM for H$\alpha$ ranges from 3700 to 20,700 km s$^{-1}$; and the centroid at half-maximum, FHWM$_{c}$, ranges from $-2200$ to $+1500$ km s$^{-1}$, with only 5 objects more blueshifted than $-1500$ km s$^{-1}$. The low FHWM of $2200$ km s$^{-1}$ and large FHWM$_{c}$ of $-3500$ km s$^{-1}$ for J1050+3456 stand apart among known double-peaked emitters.

Several studies have noted a tendency for the low ionization forbidden lines to be strong in double-peaked AGN. J1050+3456 does not conform to this pattern. Eracleous & Halpern (1994), working with radio loud objects, found that the ratio I([O I]λ6300)/I([O III]λ5007) has a median value of 0.14 for their “disk-like emitters” but only 0.05 for other broad-line radio galaxies (BLRGs). From Table 1, we measure this ratio to be 0.03±0.01, less than half the lowest value among the disk-like emitters in Table 10 of Eracleous & Halpern (1994).

4. CONCLUSION

J1050+3456 shows an unusual combination of a large velocity shift of the broad lines and a fairly symmetrical profile, especially for H$\beta$. This object is one of the most promising candidates for black hole recoil, although arguments can be made for a double-peaked emitter. Observations of the rest far-UV spectrum are needed to establish the velocity and profile of the high ionization broad lines, such as C iv, which tend to be narrower and less shifted than the Balmer lines in double-peaked emitters (Eracleous et al. 2004). Improved observations of the Mg ii line profile are needed for a definitive measurement of the peak velocity and profile, as well as the strength of narrow Mg ii. High resolution imaging can test for displacement of the AGN from the galactic nucleus and for tidal features indicative of a recent merger, as might be expected if the object is a recoil event or binary. Multi-epoch spectroscopic monitoring can tighten constraints on the binary model or search for broad-line variability. Even if J1050+3456 is confirmed as a double-peaked emitter, its extreme properties may lead to a better understanding of this class of AGN and help to develop criteria for distinguishing true cases of recoil from binary supermassive black holes.

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Shields et al.
## TABLE 1

|       | [S ii] | [S ii] | [N ii] | H$\alpha$ (n) | H$\alpha$ (b) | [O i] | [O iii] | H$\beta$ (n) | H$\beta$ (b) | Ne iii | [O ii] | Ne v | Mg ii (b) |
|-------|--------|--------|--------|---------------|---------------|-------|---------|--------------|--------------|--------|--------|------|----------|
| $\lambda_{\text{rest}}$ | 6730.8 | 6716.4 | 6583.4 | 6562.8        | 6562.8        | 6300.3| 5006.8  | 4958.9       | 4861.4       | 3869.1  | 3727.3 | 3425.9| 2799.2   |
| $\lambda_{\text{obs}}$ | 8561.8 | 8544.6 | 8374.3 | 8348.1        | 8254.5        | 8013.4| 6306.6  | 6307.6       | 6183.3       | 6109.1  | 4920.7 | 4741.4| 4357.2   |
| $z$   | 0.2720 | 0.2722 | 0.2720 | 0.2720        | 0.2578        | 0.2719| 0.2720  | 0.2720       | 0.2720       | 0.2719  | 0.2718 | 0.2718| 0.2585   |
| Flux  | 60     | 72     | 180    | 230           | 2200          | 20.3  | 760     | 270          | 63           | 700     | 70     | 220   | 35     | 520     |
| Error | 6      | 7      | 18     | 12            | 300           | 5     | 38      | 13           | 6            | 70      | 4     | 11    | 7      | 80      |
| EW    | 5.4    | 6.5    | 12.1   | 15.5          | 230           | 5.2   | 71      | 24           | 5.9          | 66      | 6.5   | 19    | 2.6     | 47      |

**Note.** — Emission-line measurements for J1050+3456; “b” and “n” denote peaks of the “broad” and “narrow” components. Wavelength (air) and equivalent width are given in Å; flux is in $10^{-17}$ erg cm$^{-2}$ s$^{-1}$. Flux and EW are in observed frame.

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