LETTERS

A candidate sub-parsec supermassive binary black hole system

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The role of mergers in producing galaxies, together with the finding that most large galaxies harbour black holes in their nuclei[1], implies that binary supermassive black hole systems should be common. Here we report that the quasar SDSS J153636.22+044127.0 is a plausible example of such a system. This quasar shows two broad-line emission systems, separated in velocity by 3,500 km s^{-1}. A third system of unresolved absorption lines has an intermediate velocity. These characteristics are unique among known quasars. We interpret this object as a binary system of two black holes, having masses of $10^{7.3}$ and $10^{8.9}$ solar masses separated by ~0.1 parsec with an orbital period of ~100 years.

The present object is the first known with two broad-line systems, and builds on the recent interest in the quasar SDSS J092712.65+294344.0, which shows two sets of narrow emission lines (only one of which has associated broad lines) separated by 2,650 km s^{-1} from each other[2–6], as well as additional emission and absorption lines at an intermediate redshift[6]. Although these characteristics might be caused by a binary black hole system, they might also be due to chance superposition of active objects or a colliding system analogous to NGC 1275[5].

We have developed a principal components analysis technique that identifies objects having spectral characteristics inconsistent with the ensemble of quasar spectra in the SDSS (Sloan Digital Sky Survey) archive. We have applied this procedure to the rest frame spectral region 4,000–5,700 Å of ~17,500 quasars. This sample comprises all quasars having redshifts (z) less than 0.70 from the SDSS quasar catalogue, fifth release[7] (SDSSQ5 catalogue), as well as all additional objects classified as $z < 0.70$ quasars observed for the final release (DR7). Of the 17,500 objects in the entire sample, only two objects have multiple redshift systems, SDSS J092712.65+294344.0, described above, and SDSS J153636.22+044127.0 (referred to here as J1536+0441).

J1536+0441 has SDSS point-source *ugriz* magnitudes of respectively 17.72, 17.24, 16.97, 16.80 and 16.33. The image appears stellar in SDSS images. For a redshift of 0.388 and a flat cosmology with $H_0 = 71$ km s^{-1} Mpc^{-1} and $\Omega_m = 0.27$, the absolute i-band magnitude is $M_i = -24.83$. This is at the high end of the luminosity distribution for the SDSS quasar sample at this redshift. The quasar has 2MASS (Two Micron All Sky Survey) *JHK* magnitudes of respectively 15.46, 14.85 and 14.10. It was also detected by ROSAT (Röntgen satellite), with a count rate of 0.03124 s^{-1}. This is typical for SDSS quasars at this redshift. The quasar is not in the FIRST (Faint Images of the Radio Sky at Twenty Centimeters) or NVSS (NRAO VLA Sky Survey) catalogues.

The spectrum of J1536+0441 shows two broad-line emission systems and one system of narrow absorption lines. The higher redshift 'r-system' at $z = 0.3889$ shows broad Balmer lines (Hα, Hβ and Hγ) and the usual narrow lines seen in low redshift quasars. The lower redshift 'b-system' at $z = 0.3727$ shows broad Balmer lines (Hα through to Hδ) and broad Fe II emission, seen most strongly around 3,000 Å in the rest frame. A strong narrow absorption-line 'a-system' is also present, including six unresolved resonance lines, at $z = 0.38783$, which, in the quasar rest frame, is 240 km s^{-1} less than that of the r-system and 3,300 km s^{-1} greater than that of the b-system. The full SDSS spectrum is shown in Fig. 1. The lines are listed in Table 1.

The r-system shows the typical features of a low-redshift quasar. The strengths and widths of the forbidden lines are normal. The somewhat larger width of the high ionization forbidden lines ([Ne V]) compared to that of the low ionization forbidden lines ([O II]) is not unusual[8,9]. The Balmer line profiles, to the extent that they can be separated from the b-system, look normal.

The b-system has no narrow or forbidden-line emission, making it extremely unusual. An upper limit on the equivalent width of its [O III] line at 5,007 Å is ~0.5 Å, about 2% of the measured strength of the r-system [O III] 5,007 Å line. Although there are a few quasars known with no detectable [O III] lines, they are exclusively infrared-luminous objects that have extremely strong optical Fe II emission[10]. Thus, they are quite rare and show features not seen in this object.

Ultraviolet Fe II emission is unambiguously indicated by the 'notch' between about 3,950 and 4,300 Å. To determine to which

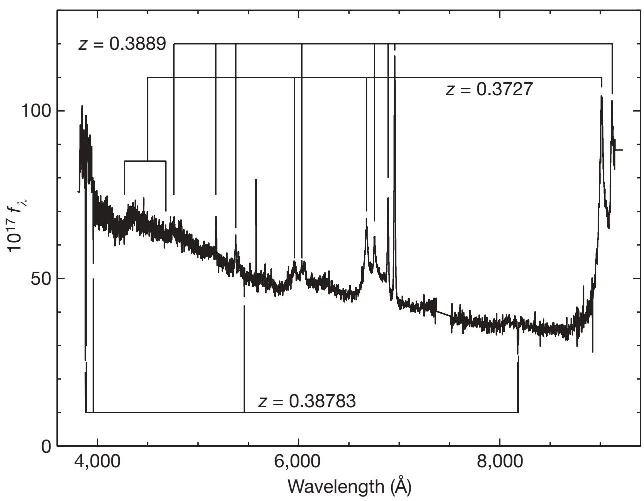

Figure 1 | The observed spectrum from the SDSS archive of the quasar SDSS J1536+0441. The three redshift systems discussed in the text are indicated with identified features marked. The r-system, at $z = 0.3889$, shows typical broad and narrow lines seen in low-redshift quasars, including the Balmer lines and the strong forbidden lines of [O II], [O III], [Ne III] and [Ne V]. The b-system, at $z = 0.3727$, shows only broad Balmer lines and ultraviolet Fe II emission. The a-system (at $z = 0.38783$) shows six unresolved absorption lines: the Mg II doublet (2,796 and 2,803 Å), the Mg I 2,852 Å line, the Ca II K line (3,934 Å), and the Na D doublet (5,891 and 5,897 Å). The strong unmarked emission feature is an artefact from poor subtraction of the night-sky line at 5,577 Å.

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Table 1 | Spectral line properties of J1536+0441

System	Line (Å)	z	FWHM (km s^{-1})	EW (Å)
r-system (emission)*	Hα	0.38890	ND	ND
r-system (emission)	[O III] 5,007	0.38889	550	24
r-system (emission)	[O III] 4,959	0.38889	530	8
r-system (emission)	Hβ	0.38894	6,000:	43
r-system (emission)	[O III] 4,363	0.38820	ND	0.8
r-system (emission)	Hγ	0.38914	ND	5.1
r-system (emission)	[Ne III] 3,968	0.38941	340:	0.5
r-system (emission)	He I 3,889	0.38960	920	1.5
r-system (emission)	[Ne III] 3,869	0.38872	680	2.1
r-system (emission)	[O II] 3,727	0.38908	ND	1.8
r-system (emission)	[Ne V] 3,426	0.38912	1,030	0.9
b-system (emission)†	Hα	0.37303	2,100:	165
b-system (emission)	Hβ	0.37247	2,400:	35
b-system (emission)	Hγ	0.37253	ND	8:
b-system (emission)	Hδ	0.3717:	ND	0.4:
a-system (absorption)‡	Na D 5,896	0.38782	Unresolved	0.8
a-system (absorption)	Na D 5,890	0.38794	Unresolved	1.2
a-system (absorption)	Ca II K 3,934	0.38776	Unresolved	0.4
a-system (absorption)	Mg I 2,852	0.38784	Unresolved	0.9
a-system (absorption)	Mg II 2,796	0.38781	Unresolved	2.1
a-system (absorption)	Mg II 2,803	0.38779	Unresolved	2.5

EW, equivalent width of line. Measurements marked with colon (:) are of lower precision. Entries of ND (not determined) indicate that the data quality was too low to determine a measurement.
* $<z> = 0.3889$.
† $<z> = 0.3727$.
‡ $<z> = 0.38783$.

system the Fe II emission should be attributed, the spectral region between 4,200 and 4,450 Å was cross-correlated with a composite quasar spectrum[11] (Fig. 2). It is clear that the Fe II belongs to the b-system, with a derived redshift of 0.375. Although this is slightly higher (500 km s^{-1}) than that of the b-system, Fe II emission in quasars is typically redshifted by 400 km s^{-1} relative to the Hβ line[12].

The absorption line system is also atypical. The lines are unresolved in the SDSS spectra, and are almost certainly due to neutral or low-ionization gas in the line of sight rather than stars in the host galaxy. There is no evidence of stellar absorption features. Absorption such as this is very unusual in low-redshift quasars. Only 6 of the 1,000 high signal-to-noise spectra of SDSS quasars that were used for constructing the eigenspectra show Na I D absorption at the strength seen in J1536+0441, and of these, three are clearly cases of self-absorption from dense material associated with the nucleus. It is possible that this absorption arises in a gas cloud unrelated to the presence of activity in the host galaxy—even in some other object in the line of sight. It is also possible that this absorption is seen because

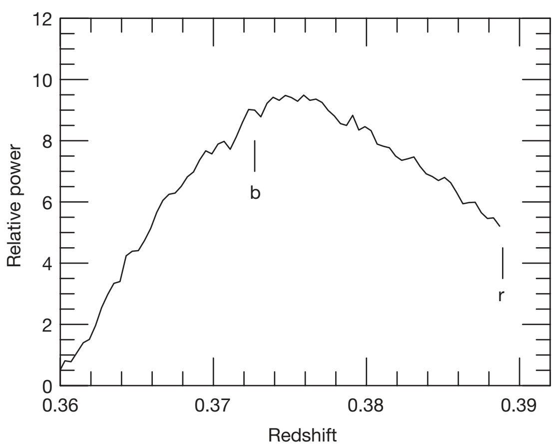

Figure 2 | Cross-correlation between the 4,200–4,450 Å region of the spectrum of J1536+0441 and the corresponding region of a composite quasar spectrum[12]. The peak indicates the presence of ultraviolet Fe II at, or slightly above, the redshift of the b-system. Note that the cross-correlation is quite inconsistent with the Fe II emission being at the redshift of the r-system ($z = 0.3889$).

of the presence of the second continuum source, presumably the b-system nucleus, seen through a part of the r-system that, normally, a line of sight to the nucleus would not pass.

If the two broad-line redshifts represent broad-line emission regions around separate supermassive black holes in a single galaxy, then the simplest model would be one in which they are in a gravitationally bound system. We estimate the masses of the two black holes using the Hβ full-width at half-maximum (FWHM) values and assuming that a fraction, proportional to the mass, of the continuum luminosity at 5,100 Å comes from each quasar. Adopting a standard calibration[13], we derive masses of $10^{8.9}$ and $10^{7.3}$ solar masses for the red and blue systems, respectively.

Derivation of the full orbital velocity, V, radius, R, and period, T, of the binary system depends on unknown geometrical factors. If a random circular orbit is assumed, the mean angle between the line-of-sight and the radial vector between the two black holes is 60°. Random orientation of the velocity vector implies an additional mean projection angle of 45°. The projected velocity is then $\sim 0.61V$, which gives $V \approx 6 \times 10^3$ km s^{-1}. This implies $R \approx 3 \times 10^{17}$ cm and $T \approx 100$ years. In contrast, upper limits of $T \approx 500$ years and $R \approx 9 \times 10^{17}$ cm are derived if no projection factors are assumed. In either case, the separation is approximately the size of the broad line region and very much smaller than the narrow line region. Thus, in this model, the two black holes and their broad line regions are orbiting well within a single narrow line region. It is notable that the derived characteristics of this system are similar to those proposed for OJ 287 based on its long term photometric variations[14,15].

For fixed black hole masses, the decay time of the binary due to gravitational radiation, t_D, is $\propto V^{-8}$, and is thus extremely sensitive to the assumed projection factors. For no projection corrections, $t_D \approx 3 \times 10^{11}$ years, whereas $t_D \approx 7 \times 10^9$ years under the model above[16]. This timescale is interesting, as it implies that the binary has evolved past the 'final parsec' scale at which decay due to energy exchange with stars becomes inefficient, but where gravitational radiation decay remains too weak to carry the evolution further[17]. Theoretical studies of the effects of gas dynamical friction indicate that the timescale for that process to cause the orbit to decay is much longer for such massive black holes[18,19], though this is an area of continuing study.

It is intriguing that the two derived black hole masses would put the systemic velocity closer to the r-system, consistent with the idea that the narrow emission lines and absorption lines are more likely to be associated with the host galaxy. Note that the masses are highly uncertain, because of both the difficulty of measuring the width of the blended lines and the uncertainty about how to split continuum flux between the two objects. This interpretation is further complicated by the fact that the narrow forbidden emission lines agree precisely with the redshift of the r-system.

A second possibility is that these are two separate quasars that are by chance seen in the same line of sight. Integrating the SDSS quasar luminosity function[20] yields a probability of 1.8×10^{-7} of finding a second quasar within a volume centred on a first quasar corresponding to a conservative one-arcsecond radius circle on the sky and a redshift range of $\pm 10{,}000$ km s^{-1}. Multiplying this by the 17,500 objects in our sample gives a probability of 3.2×10^{-3} of one chance occurrence. This calculation does not account for the possibility of an enhanced density due to the presence of a cluster of galaxies; two galaxies near the quasar on the SDSS image have photometric redshifts close to that of the quasar. The strongest, though admittedly *a posteriori*, argument against the chance superposition hypothesis is the unique lack of narrow lines in the b-system.

The most obvious interpretation of the presence of absorption at a redshift close to that of the r-system is that the b-system is background to the r-system. This would be inconsistent with an explanation involving ejection of one of the black holes, though it would be consistent with an infall interpretation, analogous with NGC 1275[21].

In this case, however, the two broad-line systems must represent two active nuclei.

New observations could test the binary black hole hypothesis. A spectrum with higher signal-to-noise ratio may allow the detection of stellar absorption features from the host galaxy, as well as setting better limits on any narrow emission lines associated with the b-system. Detection of such features at both b- and r-system redshifts would provide compelling evidence that this is a chance superposition or a colliding pair. High spatial resolution imaging could also rule out the close binary hypothesis. Monitoring over several years could reveal changes due to the orbital motion of the system. Our simple projection model predicts a velocity change in the b-system of $\sim 10^2\,\mathrm{km\,s^{-1}}$ in a single year.

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1. Magorrian, J. *et al.* The demography of massive dark objects in galaxy centers. *Astron. J.* **115**, 2285–2305 (1998).
2. Komossa, S., Zhou, H. & Lu, H. A recoiling supermassive black hole in the quasar SDSS J092712.65+294344.0? *Astrophys. J.* **678**, L81–L84 (2008).
3. Bogdanovic, T., Eracleous, M. & Sigurdsson, S. SDSS J092712.65+294344.0: Recoiling black hole or a sub-parsec binary candidate? Preprint at ⟨http://arxiv.org/abs/0809.3262⟩ (2008).
4. Dotti, M. *et al.* SDSSJ092712.65+294344.0: A candidate massive black hole binary. Preprint at ⟨http://arxiv.org/abs/0809.3446⟩ (2008).
5. Heckman, T. M., Krolik, J. H., Moran, S., Schnittman, J. & Gezari, S. SDSSJ092712.65+294344.0: NGC 1275 at z=0.7? Preprint at ⟨http://arxiv.org/abs/0810.1244⟩ (2008).
6. Shields, G. A., Bonning, E. W. & Salviander, S. Comment on the black hole recoil candidate quasar SDSS J092712.65+294344.0. Preprint at ⟨http://arxiv.org/abs/0810.2563⟩ (2008).
7. Schneider, D. P. *et al.* The Sloan Digital Sky Survey quasar catalog. IV. Fifth data release. *Astron. J.* **134**, 102–117 (2007).
8. Appenzeller, I. & Wagner, S. J. Forbidden high-ionization lines in QSO spectra. *Astron. Astrophys.* **250**, 57–61 (1991).
9. Moore, D. & Cohen, R. D. Narrow-line region kinematics in Seyfert nuclei. *Astrophys. J.* **433**, 602–624 (1994).
10. Boroson, T. A. & Meyers, K. A. The optical properties of IR-selected and Mg II broad absorption line quasars. *Astrophys. J.* **397**, 442–451 (1992).
11. Vanden Berk, D. E. *et al.* Composite quasar spectra from the Sloan Digital Sky Survey. *Astron. J.* **122**, 549–565 (2001).
12. Hu, C. *et al.* A systematic analysis of Fe II emission in quasars: Evidence for inflow to the central black hole. *Astrophys. J.* **687**, 78–96 (2008).
13. Denney, K. D., Peterson, B. M., Dietrich, M., Vestergaard, M. & Bentz, M. C. Systematic uncertainties in black hole masses determined from single epoch spectra. Preprint at ⟨http://arxiv.org/abs/0810.3234⟩ (2008).
14. Sillanpää, A., Haarala, S., Valtonen, M. J., Sundelius, B. & Byrd, G. G. OJ 287: Binary pair of supermassive black holes. *Astrophys. J.* **325**, 628–634 (1988).
15. Valtonen, M. J. *et al.* A massive binary black-hole system in OJ 287 and a test of general relativity. *Nature* **452**, 851–853 (2008).
16. Peters, P. C. Gravitational radiation and the motion of two point masses. *Phys. Rev.* **136**, 1224–1232 (1964).
17. Milosavljevic, M. & Merritt, D. Long term evolution of massive black hole binaries. *Astrophys. J.* **596**, 860–878 (2003).
18. Gould, A. & Rix, H. Binary black hole mergers from planet-like migrations. *Astrophys. J.* **532**, L29–L32 (2000).
19. Cuadra, J., Armitage, P. J., Alexander, R. D. & Begelman, M. C. Massive black hole binary mergers within sub-pc scale gas disks. *Mon. Not. R. Astron. Soc.*. (in the press).
20. Richards, G. T. *et al.* The Sloan Digital Sky Survey quasar survey: Quasar luminosity function from Data Release 3. *Astron. J.*131 2766–2787 (2006).
21. Conselice, C. J., Gallagher, J. S. & Wyse, R. F. G. On the nature of the NGC 1275 system. *Astron. J.* **122**, 2281–2300 (2001).

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