SDSS J092712.64+294344.0: recoiling blackhole or merging galaxies?

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ABSTRACT

We report long-slit spectroscopic observations of SDSS J092712+294344 carried out at the recently commissioned 2-m telescope in IUCAA Girawali Observatory, India. This active galactic nuclei like source is known to feature three sets of emission lines at \( z_{\text{em}} = 0.6972 \), 0.7020 and 0.7128. Different scenarios such as a recoiling black hole after asymmetric emission of gravitational waves, binary black holes and possible merging systems are proposed for this object. We test these scenarios by comparing our spectra with that from the Sloan Digital Sky Survey, obtained 4 years prior to our observations. Comparing the redshifts of [O\text{III}] \( \lambda 4960,5008 \), we put a 3σ limit on the relative acceleration to be less than 32 km s\(^{-1}\) yr\(^{-1}\) between different emitting regions. Using the two-dimensional spectra obtained at different position angles (PAs), we show that the [O\text{III}] \( \lambda 5008 \) line from the \( z_{\text{em}} = 0.7128 \) component is extended beyond the spectral point spread function. We infer the linear extent of this line emitting region is \( \sim 8 \) kpc. We also find a tentative evidence for an offset between the centroid of the [O\text{III}] \( \lambda 5008 \) line at \( z_{\text{em}} = 0.7128 \) and the quasi-stellar object trace when the slit is aligned at a PA of 299\(^\circ\). This corresponds to the \( z_{\text{em}} = 0.7128 \) system being at an impact parameter of \( \sim 1 \) kpc with respect to the \( z_{\text{em}} = 0.6972 \) in the north-west direction. Based on our observations, we conclude that the binary black hole model is most unlikely. The spatial extent and the sizes are consistent with both black hole recoil and merging scenarios.

Key words: galaxies: active – galaxies: individual: SDSS J092712.64+294344.0 – quasars: emission lines.

1 INTRODUCTION

The availability of several thousands of quasi-stellar object (QSO) spectra in the Sloan Digital Sky Survey (SDSS) data base has allowed astronomers to find various interesting and peculiar active galactic nuclei (AGN). In particular, the discovery of unresolved point sources with two sets of emission lines that are powered by AGN-like continuum sources [SDSS J092712+294344 at \( z = 0.713 \) (Komossa, Zhou & Lu 2008), SDSS J153636+044127 at \( z = 0.38 \) (Boroson & Lauer 2009) and SDSS J105041+345631 at \( z = 0.272 \) (Shields et al. 2009b)] has opened up possibilities to study recoiling black holes and/or binary inspiralling supermassive black holes. In this Letter, we concentrate on the first object (i.e. SDSS J092712.64+294344.0, hereafter J0927+2943). J0927+2943 is an unusual quasar with \( z = 0.713 \), identified by Komossa et al. (2008) during their search for AGN with high [O\text{II}] velocity shifts. There are two systems of emission lines identified in the SDSS spectrum with a velocity separation of about 2650 km s\(^{-1}\). One is referred as ‘red’ (with \( z_{\gamma} = 0.71279 \)) and other as ‘blue’ (with \( z_{\beta} = 0.69713 \)). The red system consists of narrow emission lines (NELs) of [O\text{III}] \( \lambda 5008, [\text{O\text{II}}] \lambda 3727, [\text{Ne\text{II}}] \lambda 3869, [\text{Ne\text{\text{I}}} \lambda 3426 \) and narrow Balmer lines. The blue system shows classical Balmer and Mg\text{II} broad emission lines, plus unusually broad NELs. The line ratios indicate AGN-like excitation in both systems. Shields, Bonning & Salviander (2009a) re-observed this object with the Hobby–Eberly Telescope and reported a third redshifted set of narrow lines at \( z \sim 0.7020 \). They also put a bound on the line-of-sight acceleration between the red and blue systems (i.e. a 3σ limit of \( \Delta v / \Delta t \leq 24 \) km s\(^{-1}\) yr\(^{-1}\)).

Simulations of binary black hole mergers predict large recoil velocities (kicks) of the final merged black hole resulting from anisotropic emission of gravitational radiation (see e.g. Campanelli et al. 2007a,b; González et al. 2007; Loeb 2007; Tichy & Marronetti 2007; Dain, Lousto & Zlochower 2008). In the discovery paper, Komossa et al. proposed J0927+2943 as a possible candidate for a supermassive black hole (with \( M \sim 10^{8} M_{\odot} \)) ejected at high speed from the host galactic nucleus by gravitational radiation recoil. However, Dotti & Volonteri (2009) and Bogdanović, Eracleous & Sigurdsson (2009) have proposed an alternate hypothesis in which the observed configuration of emission lines originate from binary black holes. The main features of this model are the prediction of

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Table 1. Log of IGO observations.

| Date         | Total exposure time | PA  |
|--------------|---------------------|-----|
| 2008/12/01   | 120 min             | 66  |
| 2008/12/01   | 90 min              | 202 |
| 2008/12/01   | 90 min              | 299 |
| 2009/01/31   | 120 min             | 100 |

1 Individual exposures are of 30 min duration.
2 Angle measured in the clockwise direction with respect to south. In IGO images, south is at the top and west is at the right-hand side.

were converted to the vacuum-heliocentric rest frame, and individual spectra were scaled within a sliding window and co-added using 1/σ² weighting in each pixel. The error spectrum was computed taking into account proper error propagation during the combining process. The achieved spectral resolution is R ~ 300 and the continuum signal-to-noise ratio (S/N) in the combined spectrum varies between 20 and 40 per pixel. The final combined one-dimensional spectrum, together with the SDSS spectrum, is shown in Fig. 1.

In order to extract the spatial information from our observations, we model the observed individual two-dimensional spectra in the wavelength range 8100–8700 Å with the sum of the QSO continuum and the [O iii] emission lines. The aim is to study the centroid shift of the emission lines with respect to the centre of the trace and the extent (FWHM) of the emission lines compared to that of the trace in the regions free from emission lines. We subtract the sky from each science frame using the mean sky spectrum extracted from the spatial bins on either side of the QSO trace.

2 OBSERVATIONS AND DATA REDUCTION

We observed J0927+2943 using the 2-m telescope at IUCAA Girawali Observatory (IGO) in India near Pune. Long-slit spectra covering the wavelength range 3700–9200 Å were obtained using the GR5 grism of the IUCAA Faint Object Spectrograph (IFOSC) and a slit width of 1.5 arcsec. A typical seeing of 1.2–1.3 arcsec was measured from full width at half-maximum (FWHM) of the images taken during the nights. The observations were carried out on 2008/12/01 and 2009/01/31 for four different PAs of the slit. The detailed log of our observations is summarized in Table 1. The raw CCD frames were cleaned using standard IRAF1 procedures. We use halogen flats for flat-fielding the frames. Since at λ > 7000 Å simple flat-fielding does not remove the fringes, the QSO was moved along the slit for different exposures of a same PA. We subsequently removed fringing by subtracting one frame from the other taken on the same night. The same procedure was applied to standard stars as well.

We then extracted the one-dimensional spectrum from individual frames using the IRAF task `DOSLIT`. Wavelength calibration of the spectra was performed using Helium Neon lamps. Wavelengths were converted to the vacuum-heliocentric rest frame, and individual spectra were scaled within a sliding window and co-added using 1/σ² weighting in each pixel. The error spectrum was computed taking into account proper error propagation during the combining process. The achieved spectral resolution is R ~ 300 and the continuum signal-to-noise ratio (S/N) in the combined spectrum varies between 20 and 40 per pixel. The final combined one-dimensional spectrum, together with the SDSS spectrum, is shown in Fig. 1.

3 ANALYSIS AND RESULTS

The SDSS observations were taken on 2005 January 19. Our observations were taken after a time interval of ~4 yr. In the rest frame of the object, this corresponds to an elapsed time of 2.35 yr. Even though our spectrum covers a wide wavelength range, we mainly concentrate on the [O iii] emission lines as they are the strongest ones seen in the spectrum. We fit the [O iii] lines with Gaussians using standard χ²-minimization techniques. The Gaussian fits to IGO and SDSS one-dimensional spectra are shown in Fig. 2 and the corresponding redshifts are given in Table 2. For individual lines, our measurement of the redshift matches well with that from the SDSS spectrum within errors. Using [O iii]λ5008 of the red system and [O iii]λ4960 line of the blue system, we estimate the 3σ limit on the acceleration at the redshift of the QSO to be less than 32 km s⁻¹ yr⁻¹. This is also consistent with the redshift of the red component measured using the [O iii]λ3727 line.

Note that this is very much comparable to the constraint obtained by Shields et al. (2009a) using [O ii] and [Ne iii] lines. However, it seems that Shields et al.’s values are not computed for the rest-frame elapsed time at the redshift of the QSO and their actual value may be higher by a factor of 1.7 (i.e. a 3σ limit of 41 km s⁻¹ yr⁻¹). Note that the constraint we get is a factor of 3 less than the acceleration

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predicted by Bogdanović et al. (2009). Our good S/N spectrum also confirms the third redshift found by Shields et al. (2009a) at $z_{\text{em}} = 0.7028 \pm 0.0002$. Using the SDSS spectrum, we find that emission from this system does not show any detectable acceleration.

Shields et al. (2009a) suggested that the presence of stellar Calcium H and K lines at redshift, $z_r$, would undermine the re-coil hypothesis. These lines are not detected in our IGO spectrum. We place a 3σ upper limit on the rest equivalent width of 0.4 Å for the Ca II $\lambda$3934 line. However, this is not stringent enough to detect this line with the equivalent width ($\sim 0.2$ Å) as seen in the SDSS QSO composite spectrum (Vanden Berk et al. 2001).

Next, we perform a two-dimensional spectral analysis. We assume the flux perpendicular to the dispersion axis to distribute like a Gaussian around the central pixel [i.e. the spectral point spread function (PSF) is assumed to be Gaussian]. The continuum flux along the dispersion axis is approximated with a lower order polynomial. As the wavelength range considered is very small, we use a single FWHM for the spectral PSF. In addition to this, the unblended [O III] lines (i.e. [O III]$\lambda$5008 of the blue system, $L_b$, and [O III]$\lambda$4960 of the red system, $L_r$) are fitted with two-dimensional Gaussians, using an IDL code based on MPFIT (Markwardt 2009) which performs $\chi^2$-minimization by applying the Levenberg–Marquardt technique.

Two-dimensional spectra taken at different PAs of the slit after removing the QSO continuum and the background light are shown in the top four panels of Fig. 3. The long dashed line shows the centre of the trace used to remove the QSO continuum emission. The dotted lines mark the FWHM of the trace. The PA of the slit is also given in each panel. The bottom panel gives the extracted one-dimensional spectrum to enable identifications of different features in the two-dimensional spectra. The vertical lines are as in Fig. 2.

From Table 3, it is clear that the [O III]$\lambda$5008 line of the red component (i.e. $L_r$) has FWHM that is consistently higher ($\geq 4\sigma$) than the FWHM of the trace. Deconvolving from the spectral PSF (as obtained from the FWHM of the QSO trace), this gives the physical extent of the emitting region. $\text{FWHM}_b \approx \sqrt{\text{FWHM}(L_r)^2 - \text{FWHM(QSO)}^2}$ is $1.2 \pm 0.2$ arcsec. At $z \approx 0.7$, 1.2 arcsec corresponds to a physical extent of 8.4 kpc for a flat universe with $\Omega = 0.73$, $\Omega_m = 0.27$ and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ (Komatsu et al. 2009). The FWHM of the [O III]$\lambda$4960 line of blue component ($L_b$) is similar to that of the trace. This is consistent with the line emission being unresolved.

The last two entries in Table 3 give the relative spatial shift of the emission line centroids to that of the continuum. It is clear that we see the maximum deviation of the emission line centroids for the PA 299°. In particular, $L_b$ is shifted by 0.19 ± 0.02 arcsec from the quasar trace. The shift is confirmed by nearly the opposite value for PA = 100° while such shifts are not seen in other PAs. The small error is the reflection of the fact that the shift is consistently seen in all the individual exposures. We also note a 2σ shift (0.10 ± 0.05 arcsec) for $L_b$ with respect to the trace for PA = 299°. This is probably not statistically significant as we do not see any shift in the spectrum taken with PA = 100°.

Thus, we conclude that our observations provide a tentative evidence of the gas associated with the red component having a projected separation of $\sim 1$ kpc from the quasar. This can be easily tested either with direct imaging using Hubble Space Telescope or repeating the same exercise with narrower slit under good seeing conditions.
4 DISCUSSIONS

We report the analysis of long-slit spectroscopic observations of J0927+2943. Comparing our extracted one-dimensional spectrum with the SDSS spectrum, obtained 4 years before, we place a 3σ constraint on the acceleration between the red and blue component to be less than 32 km s\(^{-1}\) yr\(^{-1}\). This is a factor of 3 smaller than the one expected for the binary black hole model (Bogdanović et al. 2009). However, this alone could not rule out the binary black hole model but rather tightens the constraints on the orbital parameters (see Shields et al. 2009a). Moreover, one of the directly testable predictions of this model is the compact sizes (sub-parsec scale) of the emitting regions (Dotti & Volonteri 2009). Here, we show that the [O\(\text{III}\)] emission from the red component originates from an extended region of size \(\sim 8\) kpc. This observation probably rules out the binary black hole model for J0927+2944.

In the frame work of recoil model with maximally spinning holes, we expect the maximum possible kick of \(\sim 4000\) km s\(^{-1}\) (Campanelli et al. 2007a). The extended emission from the red component can be understood in this model as an effect of photoionization by the accretion disc emission associated with the recoiling black hole. Off-centred emissions are also expected in these models (see Haehnelt, Davies & Rees 2006; Loeb 2007; Guedes et al. 2009). Thus extended [O\(\text{III}\)] emission from the red component or the slight offset we found for this emission with respect to the QSO trace alone cannot rule out the recoiling black hole scenario.

Heckman et al. (2009) proposed that J0927+2943 could be a high-redshift analogue of NGC 1275. Based on a simple model of infalling gas photoionized by the QSO continuum, Heckman et al. suggested that the observed emission lines could be produced by a gas of density 300 cm\(^{-3}\) at a distance of 8 kpc from the QSO with a projected area of 12 kpc\(^2\). The extent of the gas we find \((\sim 8\) kpc) for the red component is consistent with Heckman et al.'s simple picture. However, we wish to point out that in the case of NGC 1275 21-cm and X-ray absorption is seen at the higher redshift suggesting the infalling gas is in between us and the continuum source (De Young, Roberts & Saslaw 1973). In their calculation, Heckman et al. consider N(H) that will be optically thick to Lyman continuum radiation. Such gas is also expected to produce Mg\(\text{II}\) absorption if the infalling gas is well aligned with the QSO. In the SDSS spectrum, we do not detect any Mg\(\text{II}\) absorption. However, detailed photoionization modelling is needed to rule out the in falling gas model based on the absence of Mg\(\text{II}\) absorption.

Our observations confirm the [O\(\text{III}\)] 5008 from \(z_{\text{em}} = 0.7028\) reported by Shields et al. (2009a). To explain the three redshifted emission lines, Shields et al. (2009a) proposed a hypothesis in which different emission components originate from a chance alignment of galaxies that are part of a massive cluster. However, there is no clear indication of J0927+2943 residing in the centre of a galaxy cluster (see Decarli et al. 2009). In the recoil models, this third emission line component has to come from the unbound gas that got kicked also with the black hole. Future deep observations under better seeing conditions are needed to provide a strong constraint on the spatial extent of the third system.

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Table 3. Results from the two-dimensional Gaussian fits to the [O\(\text{III}\)] lines.

| Position Angle (°) | Trace | FWHM (arcsec) | \(L_n\) | \(L_v\) | Shift (arcsec) |
|------------------|-------|---------------|-------|-------|-------------|
| 66               | 1.31(0.04) | 1.55(0.09) | 1.75(0.07) | -0.06(0.13) | +0.11(0.04) |
| 100              | 1.65(0.23) | 1.72(0.45) | 2.10(0.09) | +0.00(0.08) | +0.13(0.04) |
| 202              | 1.29(0.04) | 1.21(0.09) | 1.70(0.10) | -0.02(0.03) | +0.05(0.04) |
| 299              | 1.30(0.03) | 1.36(0.20) | 1.80(0.08) | -0.10(0.05) | -0.19(0.02) |

\(^{1}\)[O\(\text{III}\)]\(\lambda4960\) blue system
\(^{2}\)[O\(\text{III}\)]\(\lambda5008\) red system
\(^{3}\)In the CCD image 1 pixel corresponds to 0.35 arcsec.