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A quasar companion to the puzzling quasar SDSS J0927+2943*
(Research Note)

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ABSTRACT

We report the discovery of a quasar close to SDSS J0927+2943 ($z = 0.713$), which is a massive binary/recoiling black hole candidate. The companion quasar is at a projected distance of 125 h_{70}^{-1} kpc and exhibits a radial velocity difference of ∼1400 km s^{-1} with respect to the known quasar. We discuss the nature of this peculiar quasar pair and the properties of its environment. We propose that the overall system is caught in the process of ongoing structure formation.

Key words. quasars: general – quasars: emission lines – quasars: individual: SDSS J092712.65+294344.0

1. Introduction

Quasar pairs are usually divided in: *i)* physical pairs, in which the two quasars have similar redshift and belong to the same cosmological structure (e.g., Foreman et al. 2009); *ii)* gravitational lenses, where the light of a single quasar is split into two or more images due to the light bending of an intervening massive object (e.g. Wittman et al. 2000; Chieregato et al. 2007); *iii)* apparent pairs, resulting from chance projected associations. Each of the three classes has great importance for probing the galactic halos of quasar host galaxies (column density, metal and dust abundances, ionization, etc.), the distribution of matter from galactic to super-cluster scales, and the role of galaxy interactions in triggering nuclear activity. For instance, Kirkman & Tytler (2008) and Gallerani et al. (2008) used absorption features in the spectra of apparent quasar pairs to study the ionization properties of the gas in the halos of quasar hosts and to constrain the duty cycle of the nuclear activity. Zhdanov & Surdej (2001), Myers et al. (2007) and Hennawi et al. (2006, 2009) used close, physical quasar pairs to show that the quasar correlation function gets progressively steeper at sub-megaparsec scales, where gravitational interactions among galaxies become stronger.

Quasar pairs are very rare: Only few tens of quasar pairs are known with sub-arcmin separation (Veron-Cetty & Veron 2006; Hennawi et al. 2006). In a previous work (Decarli et al. 2009a), we estimated that, given a quasar, the chance probability of finding a companion quasar with $m_b \lesssim 20$ within $\approx 10''$ is 4×10^{-4} (assuming the quasar number density by Croom et al. 2004). On the other hand, quasars belonging to the same physical structure show significant clustering (see, e.g., Coil et al. 2007; Bonoli et al. 2009; Shen et al. 2009). At very small angular separations, the surface density of quasars within dense environments is up to 3 orders of magnitude higher than in the field (see, for instance, Hennawi et al. 2006; Wrobel & Laor 2009). Wide-field surveys, such as the Sloan Digital Sky Survey (SDSS; see York et al. 2000) collected spectra of ∼100 000 quasars, but missed most of close pairs because of the finite physical dimension of the spectroscopic fibers. On the other hand, the enormous, multi-band imaging database of the SDSS allows the search for quasar candidates starting from their photometry. For instance, Hennawi et al. (2009) employed colour-selection techniques and spectroscopic follow-up observations to discover 24 new physical quasar pairs at $3.0 < z < 4.5$.

In this framework, we started a programme to search for low-redshift quasar pairs with small separations, starting from the SDSS photometric dataset (Decarli et al., in preparation; see also Decarli et al. 2009a,b). Low-redshift quasars have optical Spectral Energy Distributions (SEDs) similar to those of blue stars (see, e.g., Richards et al. 2002). Starting from the $z < 1$ quasars in the spectroscopic catalogue by Schneider et al. (2007), we searched for quasar companions in the SDSS photometric database with projected separation below 200 h_{70}^{-1} kpc (at the redshift of the known quasar). Quasar companion candidates are selected on the basis of their colours, independently of the properties of the reference quasars. We limited our study to Galactic latitude $b > 45°$ to minimize contaminations from stars. About one hundred quasar pairs are selected in this way. For twenty of them the companion object was also detected by the GALaxy Evolution EXplorer (GALEX; Siegmund et al. 2004) in the *FUV* and *NUV* bands. For these systems, we designed a plan of follow-up spectroscopic observations at the Asiago Telescope, in order to confirm the quasar classification and to study the properties of the quasar pair.

Within this line of research, which at the moment had covered only few objects, here we present the discovery of a companion quasar of the peculiar quasar SDSS J092712.65+294344.0 (hereafter, S0927), a promising massive black hole binary / recoiling black hole candidate (see Sect. 2). The present discovery of a second quasar with $\Delta v \sim 1400$ km s^{-1}

* Based on observations collected at Asiago observatory.

along the line of sight and projected separation ~125 h_{70}^{-1} kpc adds new, unexpected elements for our comprehension of S0927.

In Sect. 3 we present our observations and the data reduction. Results are given in Sect. 4. In Sect. 5 we discuss the nature of this quasar pair, focussing in particular on its environment. Throughout the paper, we adopt a concordance cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, Ω_m = 0.3, Ω_Λ = 0.7.

2. The unusual quasar SDSS J0927+2943

S0927 (RA(J2000): 09^{h}27^{m}12^s.6, Dec(J2000): +29^{d}43^{m}44^s; u = 18.69, g = 18.42, r = 18.40, i = 18.40, z = 18.34) is a puzzling quasar, discovered by Komossa et al. (2008) out of the enormous SDSS spectroscopic database. It shows two sets of narrow emission lines at different redshifts (hereafter, the "blue" system at z_b = 0.698 and the "rest-frame" system at z_{rf} = 0.713; $\Delta v \approx$ 2650 km s^{-1}), and a set of broad emission lines at z_b. The existence of another set of emission lines at $z \approx$ 0.703 was claimed by Shields et al. (2009), mainly based on the detection of an emission line at 8526 Å, identified with the [O III]$_{\lambda 5007}$. We note however that this line is also consistent with the Fe II$_{\lambda 5014}$ at $z = z_b$, a common feature in quasar spectra.

Three scenarios have been proposed to explain the velocity difference between z_b and z_{rf}: Komossa et al. (2008) suggested that the active black hole (BH) in this object is recoiling as the result of the coalescence of two massive BHs; Dotti et al. (2009) and Bogdanovic et al. (2009) proposed that the active black hole is part of a massive BH binary with sub-parsec separation; finally Heckman et al. (2009) proposed that the velocity difference in the two systems in S0927 is due to the ongoing merger event between a massive galaxy, hosting the quasar, and a satellite (responsible of the emission of narrow lines at z_{rf}). This last scenario relies on the assumption of a close alignment between the two galaxies, which is statistically acceptable only if S0927 resides in a rich cluster. Furthermore, the potential well of a rich galaxy cluster would explain the velocity difference between the two emission line systems in S0927. On the other hand, Decarli et al. (2009c) showed that the field of this object is not as rich as the cluster scenario requires, the number of possible galaxy candidates being consistent with a rich group in the best case.

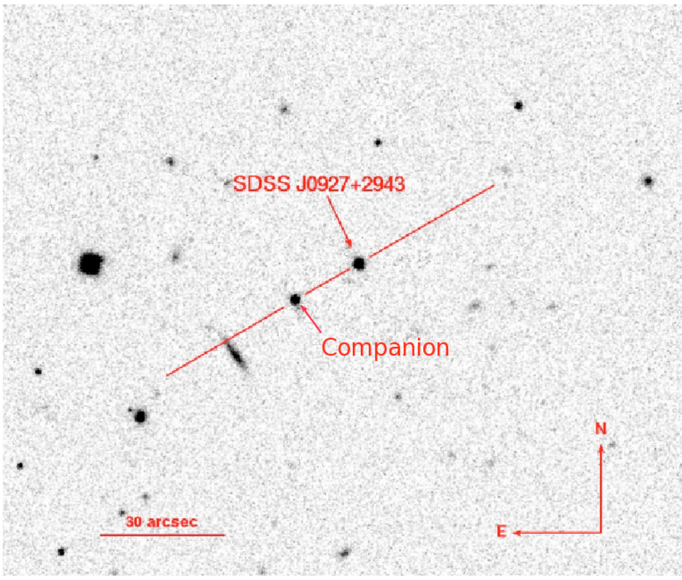

Fig. 1. The field of S0927 as imaged in the r band from the SDSS. The slit orientation adopted in our new observation is also plotted.

Table 1. Properties of the detected emission lines.

Line (1)	λ_{peak} [Å] (2)	z (3)	*FWHM* [Å] (4)	*EW* [Å] (5)
S0927, blue system				
Mg II (broad)	4750 ± 5	0.697	68 ± 17	85 ± 11
[O II]	6335 ± 5	0.699	18 ± 10	7 ± 4
[Ne III]	6565 ± 6	0.697	30 ± 8	6 ± 3
Hγ (broad)	7379 ± 9	0.700	100 ± 20	39 ± 8
S0927, rest frame system				
[O II]	6382 ± 1	0.712	17 ± 6	13 ± 2
[Ne III]	6628 ± 3	0.713	17 ± 10	4 ± 3
Companion quasar				
Mg II (broad)	4772 ± 8	0.706	55 ± 20	45 ± 20
Hγ (broad)	7395 ± 15	0.704	30 ± 20	22 ± 15

Notes. (1) Line. (2) Peak wavelength from the line fit. (3) Redshift corresponding to λ_{peak}. (4) Fitted *FWHM* in the observed frame. (5) Line equivalent width in the observed frame.

3. Observations and data reduction

The optical spectrum of S0927 was collected with the 1.82 m Cima Ekar telescope at the Asiago Observatory on January, 4, 2009. The Asiago Faint Object Spectrograph Camera was mounted in long-slit spectroscopy configuration with grism #4, yielding a spectral resolutions of $R \sim$ 300 (2.10″ slit) in the spectral range 3500–7800 Å ($\Delta\lambda$/pixel = 4.24 Å). At $\lambda \approx$ 5000 Å the spectral instrumental resolution is ~17 Å. The slit was oriented with Position Angle = 30.5°, so that the spectrum of the blue source placed 17.5″ south-west of the main target could be simultaneously acquired (see Fig. 1). The total integration time was 100 min.

The standard IRAF[1] procedure was adopted in the data reduction. The `ccdred` package was employed to perform bias subtraction, flat field correction, frame alignment and image combination. Cosmic rays were eliminated with the `cosmicrays` task in the `crutils` package. The spectra extraction, the background subtraction and the calibrations both in wavelength and in flux were performed with `doslit` task in `specred` package, using a Hg-Cd lamps and the spectrophotometric standard star Feige 34 as reference. Wavelength calibration residuals are around 0.2 Å (sub-pixel). Absolute calibration of spectra was optimized through the photometry of field stars, by comparing corollary imaging with Johnson's R filters to the magnitudes published in the US Naval Observatory catalogue. The uncertainty in the flux calibration is 0.1 mag. Galactic extinction was accounted for according to the Galactic H I maps by Schlegel, Finkbeiner & Davis (1998) and assuming R_V = 3.1.

The spectra of the two sources are shown in Fig. 2.

4. Results

The blue object selected as a quasar candidate 17.5″ far from S0927 (SDSS J092713.82+294335.5; RA(J2000): 09^{h}27^{m}13^s.8, Dec(J2000): +29^{d}43^{m}35^s; u = 19.38, g = 19.18, r = 19.14, i = 19.01, z = 19.13) appears in the USNO-A2 catalogue (Monet et al. 1998). The GALEX All-Sky Survey provides estimates

[1] 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.

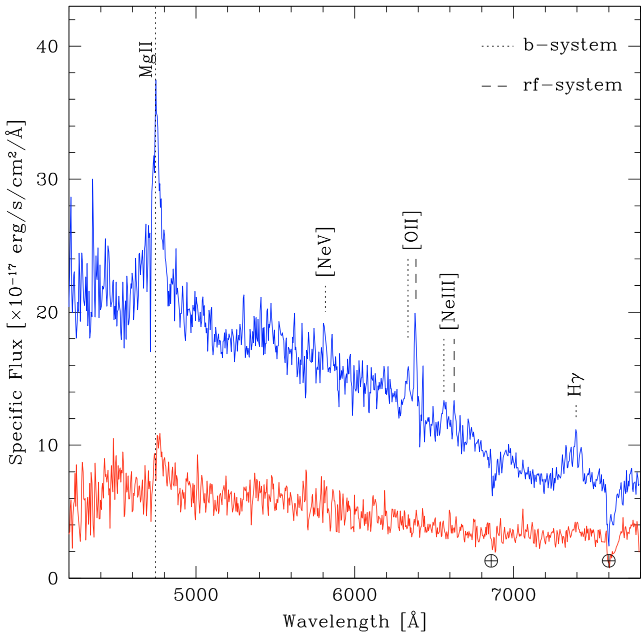

Fig. 2. Our new spectra of S0927 and its (fainter) companion. Main emission lines in the spectrum of S0927 are labelled (see also Komossa et al. 2008). The Earth symbols mark relevant atmospheric absorption features. Note the detection of the Mg II line in the spectrum of quasar B and a tentative detection of Hγ, confirming the line identification. The Signal-to-Noise ratios per pixel in the two spectra are ~20 and 8.

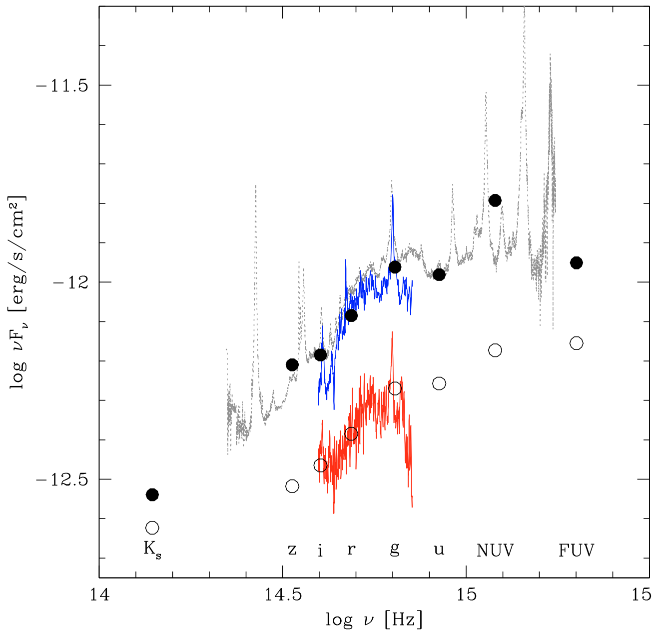

Fig. 3. The Spectra Energy Distributions of S0927 and its companion. Observed spectra are plotted as solid lines, while photometry data are reported as circles. The quasar composite spectrum derived in Decarli et al. (2010) is also shown for comparison (dotted line). *FUV* and *NUV* fluxes derived from the GALEX archives. The magnitudes in the optical bands are from the SDSS. The K_s flux is from Decarli et al. (2009c). The SEDs of the two quasars are remarkably similar.

of its UV magnitudes ($FUV = 19.94 \pm 0.19$, $NUV = 19.22 \pm 0.11$). The blue optical colours and the bright UV emission are consistent with the typical Spectral Energy Distribution (SED) of a quasar (see Fig. 3 and Decarli et al. 2009c). The spectrum shows a broad emission line at 4772 Å and another possible emission line at 7395 Å (see Fig. 2 and Table 1). We identify the former with the Mg II and the latter with Hγ, yielding $z = 0.705$. Other identifications of the 4772 Å line (e.g., with C IV) are ruled out by the lack of any correspondence with other expected bright UV lines, e.g., CIII], SiIV and Lyα.

No obvious detection of the [O II] doublet is reported. We fitted the profiles of these lines and of the main lines in the spectrum of S0927 with gaussian profiles (a superposition of 2 Gaussian is used for the Mg II line; see the discussion on the fit of quasar broad emission lines in Decarli et al. 2010). Table 1 reports the best fit parameters for the peak wavelength and corresponding z, for the line width (as measured in the observed frame) and for the line equivalent width. Referring to standard techniques for single-epoch spectra of quasar (e.g., Decarli et al. 2010), we infer the BH mass of the newly discovered quasar from the continuum luminosity and the Mg II line width: $\mathcal{M}_{\rm BH} \sim 1.4 \times 10^8\ M_\odot$. The uncertainty on $\mathcal{M}_{\rm BH}$ is of a factor ~2, dominated by the dispersion on the adopted broad line region radius-luminosity relation. The corresponding Eddington ratio is $L/L_{\rm Edd} = 0.22$, assuming the bolometric correction $L/\lambda L_\lambda(3000\ \text{Å}) = 5.15$ (Richards et al. 2002).

5. Discussion and conclusions

The observations of the quasar pair presented here reveal a puzzling nature. The probability that the pair is due to a chance superposition is very small: Following Decarli et al. (2009a), we estimate that the probability to find a companion quasar with $m_b < 20$ and angular separation <20″ *at any redshift* is $\sim 10^{-3}$. If we consider pairs with redshift difference <1500 km s^{-1}, the probability drops by two orders of magnitude. Hence, at most one quasar pair with properties similar to those observed in the case of S0927 is expected among the ~77 000 quasars in the SDSS catalogue by Schneider et al. (2007). Therefore the chance superposition is very unlikely.

Alternatively, the two quasars may belong to a common physical structure, as suggested by their velocity difference (≈−1400 km s^{-1} with respect to $z_{\rm rf}$, ≈ 1200 km s^{-1} with respect to $z_{\rm b}$). Quasars show some evidence of clustering in a way that roughly resembles what observed in quiescent galaxies (Söchting et al. 2002; Coil et al. 2007; Shen et al. 2009). Different environments are observed depending on the radio loudness (Barr et al. 2003; Söchting et al. 2004) or on other AGN properties (e.g., Hickox et al. 2009). Boris et al. (2007) analyzed the environment of 4 quasar pairs at $z \sim 1$, and found evidence of rich galaxy environment in 3 of them, while one pair (QP 0114-3140) appears isolated. Djorgovski et al. (2007) discovered a quasar triplet at $z = 2.076$, with relative velocities of few hundrends km/s. The presence of many galaxies in the field around the triplet suggests that its environment may be particularly dense.

In the case of the quasar pair of S0927, if we assume that the two objects are gravitationally bound, their velocity difference and projected separation imply a dynamical mass of $\sim 10^{14}\ M_\odot$ (depending on the de-projected separation and the direction of the velocity vector). Decarli et al. (2009c) reported that the number of galaxies around this system is consistent with the presence of at most a moderately rich galaxy group. Unless extreme Mass-to-Light ratios are invoked, this would suggest that the system is not virialized. This quasar pair might thus unveil the occurrence of an ongoing structure formation, similarly to the low-redshift cases of the Blue Infalling Group (Gavazzi et al. 2003; Cortese et al. 2006), the Stephan's Quintet (Sulentic et al. 2001) or the Cartwheel's system (Taylor & Atherton 1984; Wolter et al. 1999). The main difference among these low-z counter-parts and S0927 is that none of the former examples shows quasar-like nuclear activity in any galaxies (but note that NGC 7319 in the Stephan's Quintet is a Seyfert 2). We remark here that a systematic, spectroscopic study of the galaxies observed in the field of S0927 is mandatory to definitely pin down the dynamical state of this system. Further, deep images both in the optical and X-ray bands would also provide new contraints on the mass and structure of the galactic environment of this pair.

Our results provide additional clues supporting the presence of a galaxy group surrounding S0927. This kind of structure is the ideal habitat for strong gravitational interactions to occur, which may trigger quasar-like nuclear activity (Canalizo et al. 2007; Bennert et al. 2008, 2010). Alltogether, the available information about this system support a view in which a recent or ongoing galaxy merger is present. On the other hand, the projected distance and the relative velocity of the quasar pair are too high to account per se for explaining the occurrence of two emission line systems in S0927, which appears independent of the presence of a companion quasar. Deep, high-resolution multiband images and multi-object spectroscopy of the sources in this field are required to probe the actual build-up of a galaxy group, to search for signatures of gravitational interactions, and to pin down the dynamics of the system.

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