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Serendipitous Discovery of a Physical Binary Quasar at $z = 1.76$

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Abstract

Binary quasars are extremely rare objects, used to investigate clustering on very small scales at different redshifts. The cases where the two quasar components are gravitationally bound, known as physical binary quasars, can also exhibit enhanced astrophysical activity and therefore are of particular scientific interest. Here we present the serendipitous discovery of a physical pair of quasars with an angular separation of $\Delta\theta = (8.76 \pm 0.11)''$. The redshifts of the two quasars are consistent within the errors and measured as $z = (1.76 \pm 0.01)$. Under the motivated assumption that the pair does not arise from a single gravitationally lensed quasar, the resulting projected physical separation was estimated as (76 ± 1) kpc. For both targets we detected Si IV, C IV, C III], and Mg II emission lines. However, the two quasars show significantly different optical colors, one being among the most reddened quasars at $z > 1.5$ and the other with colors consistent with typical quasar colors at the same redshift. Therefore it is ruled out that the sources are a lensed system. This is our second serendipitous discovery of a pair of two quasars with different colors, having a separation $\lesssim 10''$, which extends the catalog of known small-separation quasar pairs.

Unified Astronomy Thesaurus concepts: Double quasars (406); Quasars (1319); Cosmology (343); Redshifted (1379)

1. Introduction

Over the past decade, several studies focused on characterizing and selecting quasars, using both optical and near-infrared (NIR) data from the *u* band to the *Wide-field Infrared Survey Explorer* (*WISE*) *W2* band. The astrometric surveys within the *Gaia* mission significantly contributed to the determination of the extra-galactic nature of several quasar candidates, which are expected to show a parallax consistent with zero (see Heintz et al. 2018a; Geier et al. 2019, and references therein for further information on the selection principles). The present work is based on the identification of three objects along the slit of the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS) instrument at the Gran Telescopio Canarias (GTC), used for the spectroscopic follow-up observations of quasar candidates (Geier et al. 2019). The primary source, identified as GQ 1114+1549A in the present paper, is a confirmed quasar candidate located at R.A. = 11:14:34.26, decl. = +15:49:44.80 (J2000.0) (Heintz et al. 2018a). The second source, hereby identified as GQ 1114+1549B with coordinates R.A. = 11:14:33.77, decl. = +15:49:49.8 (J2000.0), had not been included by any previous survey and its quasar nature was confirmed in the present work. The object is, however, listed as a high-probability photometrically classified quasar in the catalog of Richards et al. (2009) and both GQ 1114+1549 A and B appeared in binary quasar searches conducted on the Sloan Digital Sky Survey (SDSS) data set (Richards et al. 2004, 2009). The spectrum of the B object yielded a redshift compatible with that of GQ 1114+1549A, while having significantly different *g*-, *r*-, and *i*-band magnitudes compared to its companion. Ultimately, the spectrum of the third source was found to be reliably compatible with that of a foreground star.

The present paper aims at presenting the serendipitous discovery of GQ 1114+1549B and complementing it with archival and follow-up observations, analyzed with the aim of characterizing the nature of the quasar pair. The small angular separation of this pair of quasars warrants further analysis, particularly with the objective of establishing whether the pair constitutes a gravitationally bound system. The present document is divided into three sections. Section 2 covers the observations conducted on the quasar pair, Section 3 describes the main results, while in Section 4 we place our work in the context of previous studies of the binary quasar population. We assume a ΛCDM cosmological model with $H_0 = 67.4$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.32$, and $\Omega_\Lambda = 0.68$ (Planck Collaboration et al. 2018).

2. Observations

The first spectroscopic observations of the quasar pair were obtained with the OSIRIS instrument at the GTC. The candidate quasar GQ 1114+1549A, selected according to optical data, NIR photometry, and astrometry, was observed on 2018 December 4, when two 400 s integrations were obtained. Using

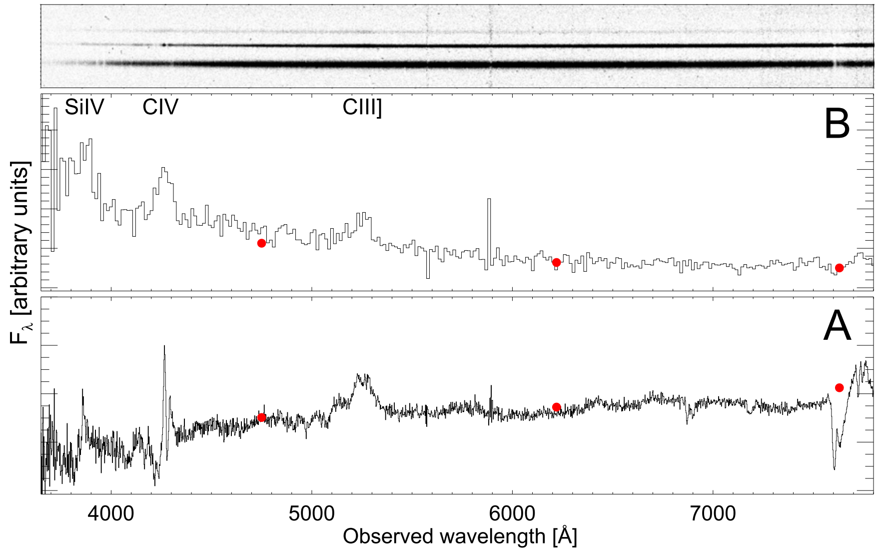

Figure 1. Here we show the GTC spectra in which the Si IV, C IV, and C III] lines are well covered. The top panel shows the two-dimensional spectra showing three objects on the slit. The lowest trace is the bright star located west of GQ 1114+1549A (see Figure 2, the central trace is the primary quasar target (GQ 1114+1549A) and the upper trace is the serendipitously discovered quasar (GQ 1114+1549B)). The two bottom panels show the quasar spectra, A (below) and B (above). The B spectrum is suppressed by about a factor of 10 (i.e., we get only 10% of the flux in the slit compared to the A spectrum). The B spectrum is binned by a factor of seven for better visibility. Overplotted is also the *g*-, *r*-, and *i*-band photometry from SDSS.

the Grism R1000B and a 1.″23 slit, the observation yielded a resolution of $\mathcal{R} = 500$, with a spectral range of 3750–7800 Å. The observing conditions were a seeing of about 1.″1, and spectroscopic sky transparency, and dark time. The target was observed at an average airmass of 1.43, at the parallactic slit angle.

While analyzing the GTC spectrum of GQ 1114+1549A, the authors found evidence for a second (adjacent) quasar on the slit. Follow-up observations of the quasar pair were obtained on 2019 July 2 and 5 with the Nordic Optical Telescope (NOT). The total integration time was 2840 s, with the aim of confirming the presence of a companion quasar in the field, aligning the slit with both quasars. Here, we used the low-resolution Alhambra Faint Object Spectrograph and Camera (AlFOSC) and a grism covering the spectral range of 3800–9000 Å with a 1.″3 wide slit providing a resolution of $\mathcal{R} \approx 280$. The pair was observed in evening twilight, as it was already setting, with the position angle being 124° east of north. As the airmass was high (1.5–1.8) the observation suffered from significant differential slit-loss, but the spectral region from 4500 to 9000 Å was well covered.

The spectroscopic data from all the observations were reduced using standard procedures in IRAF.[14] The GTC spectra were flux calibrated using observations of the spectrophotometric standard star Feige 110 observed on the same night. The NOT spectra were flux calibrated using a sensitivity function from an earlier night.

To reject cosmic rays we used La_cosmic (van Dokkum 2001). We corrected the spectra for Galactic extinction using the extinction maps of Schlegel et al. (1998). To improve the absolute flux calibration we scaled the spectra to the *r*-band photometry from the SDSS (Alam et al. 2015).

[14] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

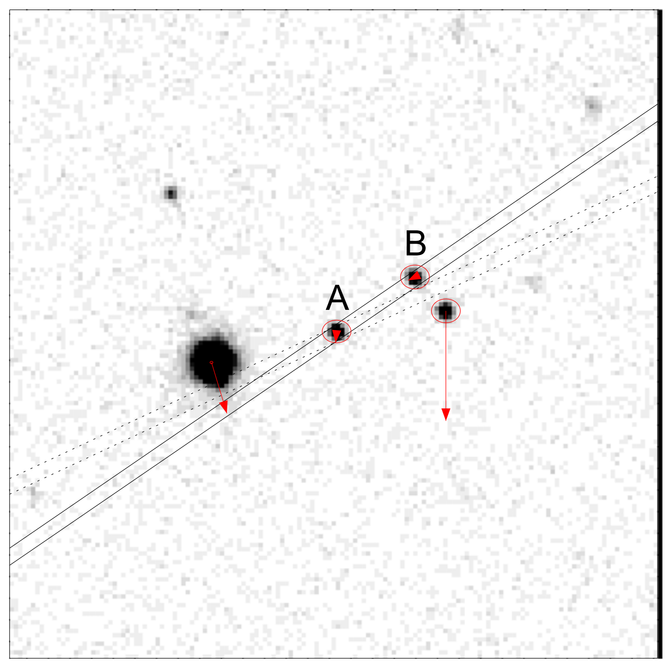

Figure 2. 1 × 1 arcmin^2 field around the two sources (marked A and B) as imaged in the *r* band by SDSS DR12. North is up and east is to the left. We have overplotted information on the proper motion from *Gaia* DR2 (Gaia Collaboration et al. 2018) with red arrows and red error ellipses showing the 2σ uncertainty on the proper motion. The quasars both have proper motions consistent with zero, whereas the two other objects are moving significantly and are hence unrelated. We also plot a schematic view of the slit during the GTC observation (dotted lines), which was centered on source A and aligned with the parallactic angle, oriented at 115° east of north (EoN) at the time of the observation. The position angle between the two objects is 124° EoN, and this was the slit angle used during the NOT observation (full drawn lines).

3. Results

In Figure 1 we show the discovery spectroscopy from GTC. The top panel shows the two-dimensional spectra with the trace of GQ 1114+1549A in the middle. Below that there is the trace of a bright star (see Figure 2). Above the trace of GQ

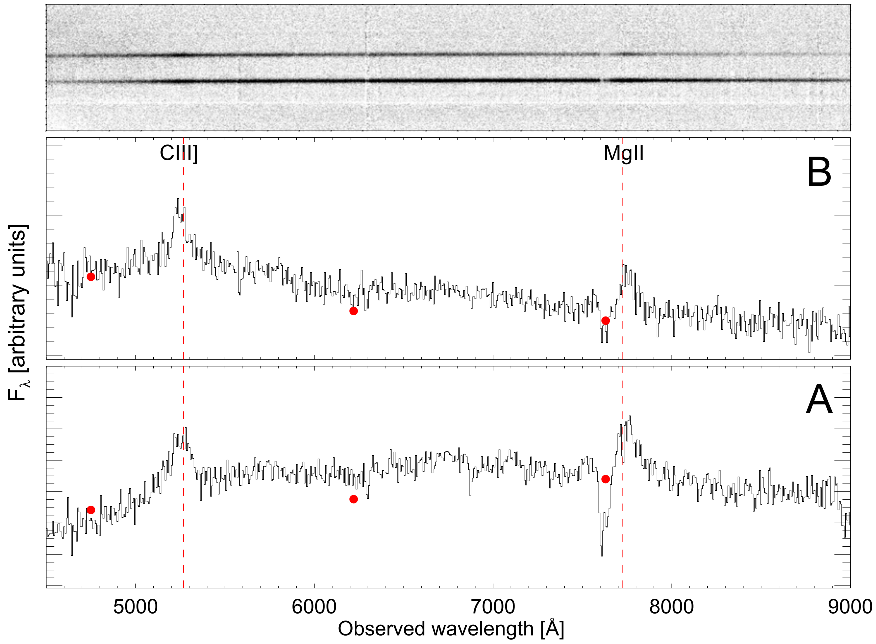

Figure 3. Here are shown the spectra from NOT obtained using a slit properly aligned with both quasars. The top panel illustrated the two-dimensional spectrum with the traces of both quasars separated by 8.″76. The two bottom panels show the one-dimensional spectra covering the region from C III] to Mg II (marked with dashed red lines). The spectra are not corrected for telluric absorption. The red dots show the *g*-, *r*-, and *i*-band photometry from SDSS.

1114+1549A there is the weak trace of another source. In this trace, we noted the presence of possible broad emission lines indicative of this source also being a quasar. The two lower panels in Figure 1 show the extracted one-dimensional spectra of GQ 1114+1549A and this possible second quasar on the slit (referred to as GQ 1114+1549B). As the trace is very weak we had to bin the spectrum significantly to properly bring the emission lines out of the noise for visibility.

In Figure 2 we show a 1×1 arcmin^2 field around the two sources (marked with A and B) as imaged in the r band by SDSS in DR12 (Alam et al. 2015). We also indicate the slit orientations. From this image it is clear that the slit position covering GQ 1114+1549A at the parallactic angle grazes another point source with similar brightness west of GQ 1114 +1549A, which must be GQ 1114+1549B.

The projected angular separation between the two objects is 8.″76 ± 0.″11 as measured from the SDSS r-band image.[15]

The purpose of the NOT spectroscopy was to obtain a spectrum with both GQ 1114+1549A and GQ 1114+1549B properly aligned. As the source was already setting in evening twilight the observation was difficult, but the authors still managed to capture a useful spectrum, as shown in Figure 3. Here we again show both the two-dimensional spectrum (top) and the extracted one-dimensional spectra of both quasars. It is clear that both objects are quasars at a very similar redshift of 1.76 ± 0.01.

By accounting for both GTC and NOT data, there is no doubt that a new physical binary quasar pair has been serendipitously discovered. Remarkably, this is the second time that by chance we discover a quasar pair using a random slit angle (for the first discovery see Heintz et al. 2016).

4. Discussion and Conclusions

For two quasars at the same redshift at such a low projected separation the first question to answer is if this is a lensed source or a physical quasar pair. An overview of more than 200 known lensed quasars can be found in Ducourant et al. (2018), but unfortunately the separations are not included in the list. Currently, a handful of lensed systems are known with separation larger than 10″ (Inada et al. 2003, 2006; Dahle et al. 2013; Shu et al. 2018), so a separation of 8.″76 does not exclude that the pair under study here is a lensed system.

The redshifts of the two quasars in our case are also consistent within the errors. However, the spectra and spectral energy distributions, as mapped out by the photometry (see Table 1), are remarkably different with one of the pair members (A) being strongly reddened and the other not (B). As an example, source A has a color excess in the $r - z$ bands (which is found to be a good tracer of reddening due to dust in high-z quasars; Heintz et al. 2018b) of $r - z = 0.73 \pm 0.01$ mag, which is at the 95th percentile of the full sample of quasars from the SDSS data release 14 (Pâris et al. 2018). Source B, with $r - z = 0.11 \pm 0.01$ mag, falls well within one standard derivation from the mean compared to the same sample. Therefore, the system is most likely a physical pair of quasars with a projected proper distance of 75 kpc in the assumed cosmology.

There is a substantial literature on binary quasi-stellar object (QSO) systems based primarily on the SDSS (York et al. 2000; Richards et al. 2004, 2009) and the 2dF quasar survey (2QZ) QSO catalogs. The binary quasar statistics are studied in particular in Hennawi et al. (2006, 2010), Myers et al. (2007, 2008), Eftekharzadeh et al. (2017), and Findlay et al. (2018).

The number of known physical quasar pairs includes many hundreds, but most of these have substantially larger separations than 10″ (Findlay et al. 2018). Eftekharzadeh et al. (2017) list 58 pairs with separations between 2.9 and 7.″7 in the SDSS footprint where there are about half a million confirmed quasars (Findlay et al. 2018; Pâris et al. 2018). It is known that the number of quasar pairs with small separation (here $\lesssim$30″) can be underestimated in catalogs only based on the SDSS/Baryon

[15] http://skyserver.sdss.org/dr12/en/tools/explore/Summary.aspx?

Table 1
The Optical and Near-infrared Magnitudes of Object A and B (All on the AB Magnitude System) from the SDSS and UKIDSS Catalogs (Warren et al. 2007; Alam et al. 2015)

Object	u (mag)	g (mag)	r (mag)	i (mag)	z (mag)	Y (mag)	J (mag)	H (mag)	K_s (mag)
A	21.58	20.51	19.78	19.11	18.99	18.05	17.60	17.22	16.39
B	19.99	19.83	19.86	19.68	19.75	18.96	18.75	18.24	18.48

Oscillation Spectroscopic Survey (BOSS) spectroscopic sample, primarily due to fiber collisions (see Ross et al. 2013; Li et al. 2016, and references therein).

A new study, based only on a selection of point sources without significant proper motion based on *Gaia* astrometric data next to known quasars, would be an interesting way to further explore the population of binary quasars. As seen in Figure 2, astrometry is a very efficient method for rejecting stars in searches for quasars (see also Heintz et al. 2018a). We ultimately note that such a study is already underway for lensed quasars (Delchambre et al. 2019).

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