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Discovery of two broad absorption line quasars at redshift about 4.75 using the Lijiang 2.4 m telescope[†]

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The ultraviolet broad absorption lines have been seen in the spectra of quasars at high redshift, and are generally considered to be caused by outflows with velocities from thousands kilometers per second to one tenth of the speed of light. They provide crucial implications for the cosmological structures and physical evolutions related to the feedback of active galactic nuclei (AGNs). Recently, through a dedicated program of optically spectroscopic identifications of selected quasar candidates at redshift 5 by using the Lijiang 2.4 m telescope, we discovered two luminous broad absorption line quasars (BALQSOs) at redshift about 4.75. One of them may even have the potentially highest absorption Balnicity Index (BI) ever found to date, which is remarkably characterized by its deep, broad absorption lines and sub-relativistic outflows. Further physical properties, including the metal abundances, variabilities, evolutions of the supermassive black holes (SMBH) and accretion disks associated with the feedback process, can be investigated with multi-wavelength follow-up observations in the future.

high-redshift, active galactic nuclear (AGN), broad absorption line quasar (BALQSO), outflow

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1 Introduction

Broad absorption line quasars (BALQSOs) are quasars whose UV/optical spectra show absorption troughs blueward from the corresponding emission lines with Balnicity Index (BI, [1]) greater than zero, which in general, occurs in the high-ionization transitions of C IV, Si IV, N V, and O IV [2]. Previous spectral studies have indicated that this sub-category comprises 10%–20% of the whole quasar population at low and intermediate redshifts (e.g., [3–6]), characterized by deep and broad absorption features associated with UV resonant lines. These BALs are at least 2000 km s^{-1} wide and can be accelerated up to velocities of $\sim 0.1c$.

Under this context, high-redshift BALQSOs may provide an unique tool to investigate the circumnuclear medium and corresponding AGN feedbacks, evolutionary phases of metal enrichment in the early Universe.

BALs with deep troughs are found only in the spectra of radio-quiet quasars, never in the spectra of strong radio sources yet [2]. The formation of broader and higher velocity absorption troughs seems more likely to be intrinsic, but the definite reason is more complicated to address. It is generally considered that only the central engine of quasars can feasibly accelerate matters to such high velocities observed in BALQSOs. The activity of BALQSOs may be powered

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by super/sub-Eddington radiation to some extent under the presumption that the huge amount of outflows are expelled and accelerated by the central radiation pressure with appearances of deep, broad absorption troughs, and sub-relativistic outflows on a long cosmological timescale. The study of broad absorption lines commonly observed in the rest-frame ultraviolet (UV) spectra of optically selected QSOs significantly advances our understanding of the structure and emission/absorption physics of AGNs.

So far, there are about 5000 quasars classified as BALQSOs [7, 8], among which only ∼ 50 BALQSOs have been confirmed with redshift larger than 4.5, and the high-redshift BALQSOs with broad, deep absorption troughs and sub-relativistic detached velocities are very rare to be seen. In this paper, we report the discovery of two high-redshift BAL quasars at redshift $z \sim 4.75$, in which both have sub-relativistic high-ionization outflows and one may have the highest BI known to date, indicating some extreme activities or unclear physics behind them. The paper is organized as follows. In sect. 2, we describe the observations from the Lijiang 2.4 m telescope (LJT) and the related data-reduction process. Through the spectra collected, we discuss the properties of the two BALQSOs in sect. 3, including the redshift uncertainties, the BI indices and the SEDs. The results are summarized in sect. 4. Throughout this paper, we adopt a Λ-dominated flat cosmology with $H_0 = 70$ km s^{-1}Mpc^{-1}, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2 Observations and data reduction

In the end of 2013, we started a quasar-identifying campaign aimed at finding luminous high redshift quasars according to the optical-IR selection criteria based on SDSS and WISE photometric data [9]. The two BAL quasars, J215216.09+104052.44 and J012247.34+121624.00 (hereafter J2152+1040 and J0122+1216), were discovered during the observational runs conducted with LJT, and the spectroscopic observations were carried out on October 1 and October 24, 2014, respectively. Among the various imaging and spectroscopic observing modes, LJT equipped with the Yunnan Fainter Object Spectrograph and Camera (YFOSC, [10]), offers a rapid switch, high sensitivity, low resolution observing mode, and we use a redward sensitive grism 5 as the dispersing element for the dedicated observations.

These two quasars were found to be BALQSOs with striking broad absorption lines (BALs) at first glance after the spectral extraction. Wavelength calibration was performed by using Neon and Helium lamps. The telluric absorption feature at ∼7600 Å is obvious in all of the spectra. Using the spectrum of a spectrophotometric standard star, absolute flux calibration was obtained under a photometric night observed at similar airmass. Considering some technical details of LJT and the effects of the unstable seeing, differential atmospheric refraction will cause a target's centroid to be extended a little in the vertical direction of the sky, so the dewar (dispersion components and CCD attached) was rotated at 90 degrees to make sure our targets' photon energy being fallen into the slit as much as possible.

During the observations of J2152+1040 and J0122+1216, the 1.8" slit and grism 5 with a dispersion of 3.6 Å pixel^{-1} were used to take their spectra from YFOSC, providing a typical resolution of $R = \lambda/\Delta\lambda \approx 550$ in the spectral range from 5500 to 9200 Å [12]. The blue and red magnitudes released from the SDSS DR10 are $r = 20.17$ and $i = 18.5$ for J2152+1040, $r = 22.35$ and $i = 19.44$ for J0122+1216, respectively. We also note that both quasars are radio quiet for their radio flux below the threshold of the FIRST radio survey [13]. Details of photometric magnitudes of the two BALQSOs can be obtained from the literature, including the SDSS, 2MASS, *WISE* [14–16], which are listed in Table 1.

3 Discussion

3.1 Redshift uncertainties

After extracting the spectra from the raw data, redshifts of the two quasars were initially identified by the strongest emission line peaks in the spectra, which yielded redshifts of 4.84 and 4.83 for J2152+1040 and J0122+1216 at first. While it has been found that there appears large discrepancies on redshifts when we check all the emission lines in the spectra, which leads to the re-identifications of their redshifts using the SDSS non-BALs composite template (the green dashed line) as shown in Figure 1. Among the two BALQSOs, mainly due to their strong Lyα forest absorption effects and highly luminous continua, it is relatively easy to find the unabsorbed emission peaks and hence the redshifts, even though

Table 1 Photometric data from multiple surveys and derived observational results

Name	J0122+1216	J2152+1040
SDSS-u	23.43±0.59	22.97±0.27
SDSS-g	24.29±0.37	24.28±0.32
SDSS-r	22.35±0.14	20.17±0.03
SDSS-i	19.44±0.03	18.51±0.02
SDSS-z	19.32±0.06	18.32±0.03
J	–	16.86±0.14
H	–	16.29±0.21
K	–	15.13±0.00
W1	15.58±0.05	14.64±0.04
W2	15.03±0.09	14.00±0.05
W3	11.50±0.16	10.73±0.08
W4	8.62±0.00	7.94±0.17
$A_V^{a)}$	0.09	0.19
BI(CIV)$^{b)}$	15320	5100
$z^{c)}$	4.76	4.75
$L_{1350}^{d)}$(erg s^{-1})	9.1×10^{46}	1.3×10^{47}

a): Galactic dust reddening and extinction [11]
b): Balnicity index defined by the revised calculation (1) in sect. 3.2
c): Redshift value
d): The monochromatic luminosity at 1350 Å

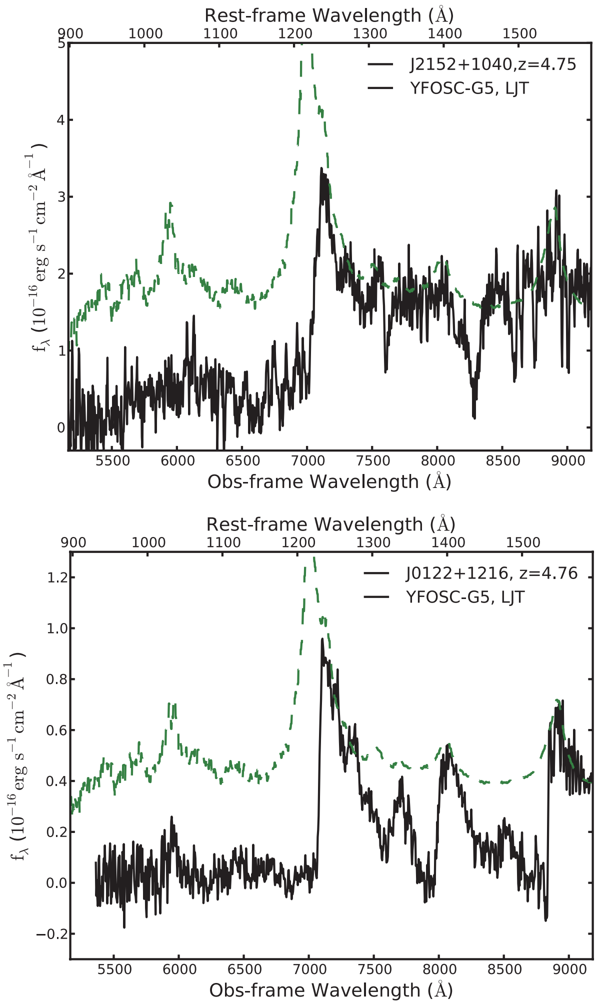

Figure 1 (Color online) The optical spectra of the two BALQSOs (solid black). The top panel presents the spectrum of J2152+1040 obtained by the 2.4 m telescope with YFOSC spectrograph on October 1, 2014. The bottom panel presents the spectrum of J0122+1216 obtained with the same instrument on October 24, 2014. The scaled composite spectrum (dashed green) of SDSS QSOs in each panel is presented as a comparison to show the absorption features in the observed spectrum.

their true values cannot be accurately established. Furthermore, considering it is difficult to ascertain an accurate position of the N V peak, we believe the complexity of the blended Lyα+N V in the two BALs makes it risky to deconvolve the two lines. The average SDSS non-BALs quasar spectrum was carefully shifted on each observational spectrum until we found the best consistency of these emission lines' positions. Then, the most likely redshifts of the two BAL quasars were corrected to be 4.75 and 4.76 compared to the previous ones mentioned above. While the redshift of J2152+1040 has larger uncertainty since the peaks of Lyβ and C IV are not in good agreement with each other, so we took another higher resolution spectrum ($\lambda/\Delta\lambda \approx 700$ at 7000 Å) by the LJT to double check this discrepancy, but found no difference except for their intensity level. In addition, the relatively narrow absorption lines sparsely located at two sides of the C IV peak may be related to the intervening clouds associated with the intergalactic medium (IGM), which could be further confirmed by the near-IR spectroscopy in the future.

It seems that the two BALQSOs have similar absorption features in the position of the Lyα emission line, suggesting the two quasars might experience a special phase or a sudden coincidence during the coevolution of BAL outflows and their powering engines. Although the possible relationship of the BAL gas with the BLR is still unclear, we could obtain useful clues based on the studies of some disappearing emission lines. One case is the strong NV 1240 absorption in BAL QSOs, which often nearly obliterates the Lyα emission line hence adds more uncertainties of their redshifts. The other case is that dust extinction may be an important factor affecting the escape of Lyα photons, while at low extinctions, other factors such as neutral hydrogen covering factor and gas kinematics could also be effective at inhibiting the escape of Lyα photons. These obvious absorption troughs, in turn, argues that the BAL gas lies outside the BLR and covers nearly all of the line-emitting region as seen along the line of sight. In order to highlight the absorption regions, the non-BALQSO composite spectrum is also used as a comparison in Figure 1.

3.2 The C IV balnicity indices

The first large sample of BALQSOs was analyzed by Weymann [1], who defined BALQSOs as quasars exhibiting C IV absorption troughs broader than 2000 km s^{-1}. Determining whether a quasar is a BALQSO, actually may be more complicated since BI indicates not only the presence of one or more broad absorption troughs but also the amount of absorption. In particular, how does one define the true continuum level mixed with emission lines and the systematic redshift when there is significant absorption? Moreover, the obvious drawback of the ideal BI is that it requires exact knowledge of the quasar's systemic velocity and continuum level. However, absorption troughs should evidently arise in BAL outflows (of C IV, Si IV or other species) as opposed to being intervening absorbers or intrinsic systems unrelated to the BAL outflows. Among the two quasars, there is no difficulty to classify them as BALQSO according to their extremely broad and deep absorption troughs. We retain the traditional BALQSO definition as both quasars with the balnicity index (BI) > 0 shown as follows:

$$\mathrm{BI} = \int_{-3000}^{-25000} \left[1 - \frac{f(v)}{0.9}\right] C \mathrm{d}v, \tag{1}$$

$f(v)$ is the normalized flux distribution, $C = 1$ at trough velocities more than 2000 km s^{-1} from the start of a continuous trough with flux density less than 90% of the continuum, and $C = 0$ elsewhere. The 25000 km s^{-1} blue limit is set to avoid ambiguities associated with the Si IV emission and absorption (here we actually set the upper limit up to 26000 km s^{-1} considering all of the C IV troughs extending to the right edge of the Si IV line), and 3000 km s^{-1} red limit is chosen to avoid contamination from absorption that might not be caused by outflows.

Low-redshift BALQSOs would be better for the quantitative analysis because their BI values are easy to normalize while the continuum fitting of high-redshift spectra can be problematic due to significant absorptions [8]. In order to avoid this problem, the best-fit template is manually adjusted to prevent overestimation or underestimation of the BI, especially for the quasar owning unusual emission/absorption line profiles. In addition, since the Fe emission lines make negligible contributions for the Si IV and C IV lines in the rest-frame wavelengths, we took a power-lower function to roughly fit the unabsorbed continua as shown in Figure 2, and the continuum level is set according to the seemingly unabsorbed parts of the whole continuum. Therefore, it will give the lower limits of their BI values. Moreover, the continuum slope and the BI of the C IV that is similar to the equivalent width expressed in km s^{-1}, are determined by the improved method [17].

As a result, the calculated BI of J2152+1040 should be close to the true value since its continuum is not absorbed much. For J0122+1216, which is conspicuous for its extremely broad and deep absorption troughs, we roughly obtained its BI according to the unabsorbed continua in the scaled template. If the continua level of the composite template is higher than the seemingly true continua shown in the observational spectra, these scaled continua will be abandoned in the calculation. Thus, the estimated BI indices of the two BALQSOs are close to their lower limits, which are tabulated in Table 1. For example, after different fittings of the C IV trough for J0122+1216, the results give a lower BI limit of 15320 km s^{-1}, which is possible among one of the highest BI BALQSOs known to date. Furthermore, Balnicity indices higher than 8000 km s^{-1} are only found among low ionization BALQSOs (LoBAL). As a comparison, the absorption profile of J0122+1216 is well resolved, in which it not only owns the deepest and broadest absorption troughs, but also displays a clear peak in the middle of the C IV double troughs. This phenomenon, again, is a typical feature commonly observed in LoBALs, so it would be particularly helpful to further confirm their nature through near-IR spectroscopic observations in the future.

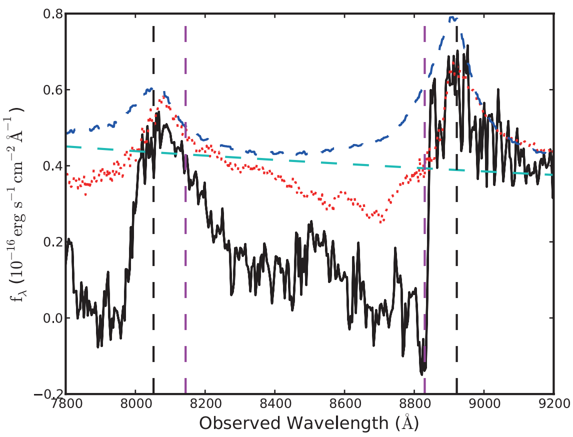

Figure 2 (Color online) A demonstration of the calculation of C IV BI index for J0122+1216, in which the blue dashed and red dotted lines are scaled to find a better continuum level and represent non-BAL and BAL composite spectra, respectively. The cyan dashed line shows the well-consisted continua fitting with a power law slope of −1.1. The velocity scale is based on the systematic redshift z = 4.76. The vertical magenta dashed lines represent the detached velocities from 3000 to 26000 km s^{-1}, and the vertical black dashed lines give the observed wavelengths of the C IV and Si IV lines.

3.3 Luminosity properties based on SEDs

Since radio surveys have demonstrated that the decreasing number of quasars at high redshift is not due to dust obscuration [18], the UV/optical spectral energy distribution (SED) remains a powerful diagnostic tool to advance the understanding of luminous QSOs. Thanks to the photometric data from SDSS, UKIDSS and WISE, the SEDs of the two BALQSOs can be plotted in the rest-frame after K-correction and Galactic extinction. We note that the radio flux at 1.4 GHz of the two BALQSOs are below 1 mJy limit of the FIRST survey, in common sense, which means they belong to radio-quiet quasars and the bolometric luminosity should dominate their observational phenomena. Based on the optimized shifts using the average radio-quiet quasar template (the solid blue line, [19]) for each source between the UV/optical and infrared bands, the most likely positions were plotted by differently dashed color lines as shown in Figure 3.

Apart from apparent dropouts caused by the strong Lyα forest absorption in the higher redshift BALQSOs, the

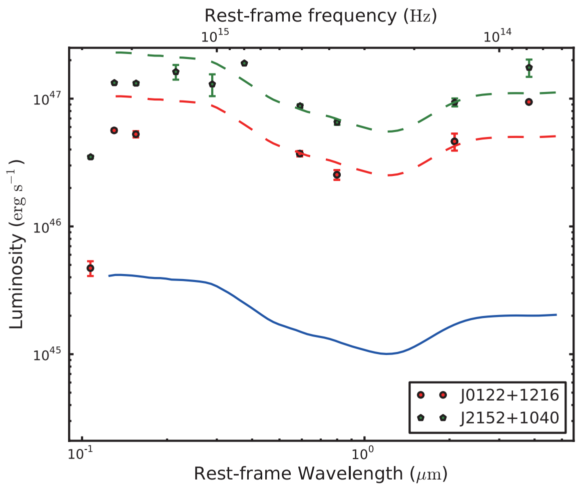

Figure 3 (Color online) Rest-frame SEDs of the two BALQSOs at $z \approx 4.75$, which are compiled from multiple photometric surveys (2MASS, WISE and SDSS). These data points are all calibrated in the rest-frame after K-correction and Galactic extinction correction. The blue solid line at the bottom is the composite SED template of radio-quiet quasars in the local Universe [19], which is much less luminous than the two high-redshift BALQSOs. Two dashed lines, shifted upward from the blue solid line, present the match of the template to the SEDs of two BALQSOs between 1200 Å($10^{15.398}$ Hz) and 4 μm ($10^{13.875}$ Hz) in the rest-frame wavelengths.

spectral profiles between 1200 Å and 1600 Å of the two BALs are also deviated much to the up-shifted composite template, in which the discrepancies may be largely due to their evident absorption features, including the Lyα+N V, Si IV and C IV or potential continua absorptions. Furthermore, this observational evidence, in part, accounts for the missing of their Lyα emission lines mentioned above.

4 Summary

Broad absorption line (BAL) outflows are observed as blueshifted wide troughs in the rest-frame spectrum of ∼20% of quasars [3, 4, 20]. The energy, mass, and momentum carried by the outflows are thought to play a crucial role in forming the early universe and leading to its evolution (e.g., [21–25]). This has been further corroborated from the finding of a strong dependence between redshift and the BALQSO fraction, especially for the intrinsics C IV BAL phenomenon [26]. Based on the two BALQSOs discovered by us, their observational implications can be concluded as follows:

(1) The detached velocities of the C IV and SiIV lines are close to or might be beyond 0.1c, in combination with their very deep and broad absorption troughs, which strongly suggest spectacular outflow activities being violent during their evolution in the early Universe. The huge amount of outflows, in turn, should exert significant impact on the formation of black hole and host galaxy.

(2) All of their Lyα emission line peaks are obliterated to large extent in the spectra, which could be associated with the strong H I or N V absorptions around the inner circumnuclear region.

(3) The extremely fast outflows among the two luminous BALQSOs, which are potentially driven by the super/sub-Eddington radiation, may be fundamental to or even dominate the process of their feedbacks. A better understanding of the kinematics through the combination of multi-wavelength data could shed light on the physical basis of the sub-relativistic activities among AGNs.

The discovery of two BALQSOs, according to their observational properties, would be particularly valuable to do some follow-up observations, especially for the near-IR spectroscopy, which can be fully used to investigate their true continua shapes, chemical abundances and AGN feedbacks, or more fundamental physics including the accretion disk and formation of black holes.

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