DISCOVERY OF EXTREMELY BROAD BALMER ABSORPTION LINES IN SDSS J152350.42+391405.2

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ABSTRACT

We present the discovery of Balmer line absorption from Hα to Hγ in an iron low-ionization broad absorption line (FeLoBAL) quasar SDSS J152350.42+391405.2 (hereafter SDSS J1523+3914), by the quasi-simultaneous optical and near-infrared spectroscopy. The Balmer line absorption is at $z_{\text{abs}} = 0.6039 \pm 0.0021$ and blueshifted by $v = 10,353 \text{ km s}^{-1}$ with respect to the Balmer emission lines. All Balmer BALs have a uniform absorption profile with the widths of $\Delta v \sim 12,000 \text{ km s}^{-1}$. We also found the absorption trough in He $\gamma$ $\lambda$10830 with the same velocity and width in the H-band TripleSpec spectrum of SDSS J1523+3914. This object is only the 10th active galactic nucleus known to exhibit nonstellar Balmer absorption, as well as the case with the highest velocity and broadest Balmer absorption lines that have ever been found. A CLOUDY analysis shows that the absorbers require a gas density of $n_e (\text{cm}^{-3}) = 9$ and an ionization parameter of $\log U = -1.0$. They are located at a distance of $\sim 0.2 \text{ pc}$ from the central ionizing source, which is slightly farther than that of broad emission line regions. Furthermore, SDSS J1523+3914 is one of the brightest Balmer BAL quasars ever reported, with unique iron absorption variations, making it the most promising candidate for follow-up high-resolution spectroscopy, multiband observations, and long-term monitoring.

Key words: quasars: absorption lines – quasars: general – quasars: individual (SDSS J152350.42+391405.2)

1. INTRODUCTION

Evidences accumulated in the past decade point to the phenomenon that feedback from active galactic nuclei (AGNs) plays a crucial role in galaxy formation and evolution. Outflows in AGNs connect the central supermassive black holes (SMBHs) to their host galaxies and regulate their coevolution (Granato et al. 2004; Scannapieco & Oh 2004; Hopkins et al. 2008; also see Antonuccio-Delogu & Silk 2010 for a recent review). Observationally, the most direct and obvious performance of AGN outflows is the high-speed blueshifted broad absorption lines (BALs). Because of the high fraction in optically selected quasars (10%–20%), high-ionization BAL (HiBAL) quasars are widely studied, with strong absorption troughs in high-ionization ions such as N v, C iv, Si iv, and O vi, up to a velocity of $v \sim 0.2c$ (e.g., Weymann et al. 1991; Trump et al. 2006; Dai et al. 2008; Shankar et al. 2008; Gibson et al. 2009). BALs are also detected occasionally ($\sim 15\%$ in BAL quasars and $\sim 2\%$ in all quasars) in low-ionization species such as Al ii and Mg ii, known as low-ionization BALs (LoBALs; e.g., Weymann et al. 1991; Reichard et al. 2003; Zhang et al. 2010; Dai et al. 2012). Moreover, FeLoBAL quasars have been observed to exhibit the broad absorption troughs in Fe ii and/or Fe iii, which are rare and only found in $\sim 15\%$ of LoBAL quasars (Hall et al. 2002).

Statistical studies are widely used to explain the BAL phenomenon. BAL quasars on average have red continua (Weymann et al. 1991; Reichard et al. 2003 Zhang et al. 2010, 2014) and weak X-ray emission (e.g., Green et al. 1995; Brinkmann et al. 1999; Wang et al. 1999; Brandt et al. 2000; Gallagher et al. 2002, 2006; Fan et al. 2009) and are more frequently detected in quasars with higher Eddington ratio and higher luminosity (Ganguly et al. 2007; Zhang et al. 2010, 2014). Furthermore, the outflow velocity and strength are tied to the properties of quasars. Observed outflow velocities increase with the blueness of UV spectral slope, the enhancement of black hole accretion, and the equivalent width of He $\alpha$ emission (Hamann 1998; Laor & Brandt 2002; Ganguly et al. 2007; Misawa et al. 2007; Baskin et al. 2013; Zhang et al. 2014). In particular, the minimum velocity of absorption is even more strongly correlated with UV spectral slope than the maximum velocity (Zhang et al. 2014). These findings indicate the primary role of radiatively driven winds in the outflow phenomenon and the importance of the spectral energy distribution (SED) shape in governing the dynamics of outflows. Meanwhile, all outflow parameters dramatically and monotonically increase with hot dust emission. These correlations can be more naturally interpreted as the dusty outflow scenario rather than the dust-free outflow scenario, where the dust is intrinsic to the outflows or interaction with torus clouds (Wang et al. 2013; Zhang et al. 2014).

On the other hand, the study of variation of BAL troughs and the associated rare absorption systems, i.e., LoBALs, and unusual BALs (mostly FeLoBALs) can provide a new and more effective perspective to understand the physical conditions, locations, and origins of the absorbers and constraints on the outflow mechanism, which gradually becomes a hot topic of BAL research (e.g., Hall et al. 2002, 2011; Zhou et al. 2006; Lundgren et al. 2007; Gibson et al. 2008, 2010; Krongold et al. 2010; Zhang et al. 2011, 2015a, 2015b; Capellupo et al. 2012; Vivek et al. 2012, 2014; Filiz Ak et al. 2013; Welling et al. 2014). Currently, one of the rarest known BALs is nonstellar Balmer line absorption. It has previously been...
reported only in nine objects: NGC 4151\(^6\) (Hutchings et al. 2002), SDSS J112526.12+002901.3 (Hall et al. 2002; X.-H. Shi et al. 2015, in preparation), SDSS J083942.11+380526.3 (Aoki et al. 2006), SDSS J125942.80+121312.6 (Hall 2007; X.-H. Shi et al. 2015, in preparation), SDSS J102839.11+450009.4 (Wang et al. 2008), SDSS J172341.10+555340.5 (Aoki 2010), LBQS 1206+1052 (Ji et al. 2012), SDSS J222045.95+010931.2 (Ji et al. 2013), and SDSS J112611.63+425246.4 (Wang & Xu 2015). However, strictly speaking, more than half of them cannot be classified as Balmer BALs based on the criteria for BALs (see Table 1 of Zhang et al. [2010] for a summary and comparison), as their absorption widths are narrower than 1000 km s\(^{-1}\).

In this paper, we report on a quasar (SDSS J152350.42+391405.2, hereafter SDSS J1523+3914) with an emission redshift of \(z_{\text{em}} = 0.6612 \pm 0.0022\). This object shows the broadest and highest blueshifted velocity Balmer BALs known so far in the quasars, suggesting the strong, high-speed, and high column density outflow materials in the nuclear region.

The organization of this paper is as follows. The data we used will be described in Section 2. We will fit the spectrum and analyze the Balmer BALs in Section 3 and discuss the properties and possible origins of BALs in Section 4. A summary of our results will be given in Section 5. Throughout this paper, we adopt the cold dark matter “concordance” cosmology with \(H_0 = 70\) km s\(^{-1}\)Mpc\(^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\).

2. OBSERVATIONS

SDSS J1523+3914 is very bright with a Galactic-extinction-corrected magnitude of 16.59 at \(r\) band. The FIRST (Faint Images of the Radio Sky at Twenty-Centimeters; Becker et al. 1995) and NVSS (NRAO VLA Sky Survey; Condon et al. 1998) surveys show that there is no radio variation at 1.4 GHz, with the peak flux of 4.06 \(\pm\) 0.13 and 4.25 \(\pm\) 0.26 mJy, respectively. At the high-energy band, its X-ray emission is very weak and not detected by XMM-\textit{Newton} and \textit{Chandra}. The SED from ultraviolet (UV) to middle-infrared (MIR) comes from the data taken with the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), and the 

\[\text{Table 1}\]

| Band   | FLUX/Magnitude | Date of Observation | Survey/Telescope |
|--------|----------------|---------------------|------------------|
| 20 cm  | 4.07 \(\pm\) 0.13 mJy | 1994 Aug 13 | FIRST           |
| 20 cm  | 4.25 \(\pm\) 0.26 mJy | 1998 Apr 16 | NVSS            |
| \(u\)  | 18.234 \(\pm\) 0.026 mag | 2003 Feb 11 | SDSS            |
| \(g\)  | 16.938 \(\pm\) 0.032 mag | 2003 Feb 11 | SDSS            |
| \(r\)  | 16.680 \(\pm\) 0.023 mag | 2003 Feb 11 | SDSS            |
| \(i\)  | 16.468 \(\pm\) 0.031 mag | 2003 Feb 11 | SDSS            |
| \(z\)  | 16.339 \(\pm\) 0.023 mag | 2003 Feb 11 | SDSS            |
| \(J\)  | 15.362 \(\pm\) 0.053 mag | 1999 May 24 | 2MASS           |
| \(H\)  | 14.875 \(\pm\) 0.066 mag | 1999 May 24 | 2MASS           |
| \(K_s\) | 13.866 \(\pm\) 0.059 mag | 1999 May 24 | 2MASS           |
| \(W1\) | 12.011 \(\pm\) 0.027 mag | 2010 Jan 19, Jul 17 | WISE  |
| \(W2\) | 10.819 \(\pm\) 0.026 mag | 2010 Jan 19, Jul 17 | WISE  |
| \(W3\) | 8.431 \(\pm\) 0.033 mag | 2010 Jan 19, Jul 16, Jul 22 | WISE  |
| \(W4\) | 6.505 \(\pm\) 0.038 mag | 2010 Jan 19, Jul 16, Jul 22 | WISE  |
| \(V\)  | ... | 2005 Apr 20-2013 Sep 28 | Catalina  |
| \(V\)  | ... | 2015 Apr 20, May/13 | BSST  |

The apparent change in the optical continuum for SDSS J1523+3914. The photometric data are summarized in Table 1.

The optical spectrum of SDSS J1523+3914 was first taken with the 3.5 m telescope on Apache Point Observatory (APO) at 1997 May 26 in the FIRST Bright Quasar Survey (FBQS; White et al. 2000). The APO spectrum has a wavelength coverage from 3650 to 10000 Å at \(\sim 10\) Å resolution. SDSS J1523+3914 was also considered as a quasar candidate from the spectroscopy taken with the SDSS 2.5 m telescope on 2003 May 6 and 2012 May 28. The first observation was recorded in the SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2007). Two 5400 s exposures were taken with the original SDSS spectrographs, which provide a high signal-to-noise ratio (S/N) spectrum at the resolution \(R \sim 1800\) and the wavelength coverage from \(3800\) to \(9200\) Å (Stoughton et al. 2002). The second observation was taken in the Baryon Oscillation Spectroscopic Survey (BOSS;
Dawson et al. 2013) and published in the SDSS Tenth Data Release (DR10; Ahn et al. 2014). The BOSS spectrum has a wider wavelength range, covering 361–1014 nm with a resolution of 1300 at the blue side and 2600 at the red side, respectively. This instrument is fed by smaller optical fibers, each subtending 2″ on the sky (Smee et al. 2013).

The near-infrared (NIR) spectrum of SDSS J1523+3914 was taken with the TripleSpec spectrograph of the Hale 200-inch telescope (P200) at Palomar Observatory on 2012 April 16. SDSS J1523+3914 was exposed four times, each for 240 s. TripleSpec (Wilson et al. 2004) is a cross-dispersed NIR spectrograph that provides simultaneous wavelength coverage from 0.9 to 2.46 μm at a resolution of 1.4–2.9 Å. The raw data were processed using IDL-based Spextool software (Vacca et al. 2003; Cushing et al. 2004). There are two gaps in the infrared spectrum around 1.35 and 1.85 μm owing to the atmosphere transmissivity. Fortunately, the redshifted Hσ emission line is detected with the TripleSpec at J band. Since the time interval between the SDSS DR10 and P200 TripleSpec observations is just 12 days in observed frame, the data are considered as quasi-simultaneous, which we will use in the following analysis.

After correcting for the Galactic reddening of $E(B-V) = 0.021$ mag (Schlegel et al. 1998), we transformed the photometric data, as well as the optical and NIR spectrum, into the rest frame with its emission redshift, which are shown in Figure 2, respectively. The TripleSpec spectrum, after correcting for the aperture effect, agrees very well with the 2MASS photometric data. The SDSS and TripleSpec continuum spectra and WISE photometric data suggest two basic components. One is a single power law, $f_{\nu} \propto \lambda^{-1.70}$, representing the nuclear spectrum from the accretion disk (the pink dashed line). It is estimated from continuum windows ($[3790, 3810]$ Å, [5600, 5630] Å, [6950, 7000] Å) that are not seriously contaminated by emission lines (e.g., Forster et al. 2001). Another is the NIR emission bump at W2 band corresponding to the blackbody radiation from the hot dust with $T = 1064$ K (green dashed line).

Figure 2. (a) We show the broadband SED of SDSS J1523+3914 from UV to MIR by red squares, the spectra of SDSS and TripleSpec by black and blue curves, the power-law continuum by pink, and the blackbody radiation by green. (b) We show the spectral details of SDSS J1523+3914 from 2300 to 7000 Å by black curves, its FBQS spectrum by blue curves, and two quasars from the SDSS by green and red curves, whose spectra follow the continuum slope and the emission peaks of Fe II multiplets of SDSS J1523+3914, except BAL troughs.

3. ANALYSIS

SDSS J1523+3914 is a typical BAL quasar and was first classified as a radio-detected BAL quasar with $B1 \sim 3700$ km s$^{-1}$ by Becker et al. (2000). It is also contained in the SDSS DR5 low-redshift Mg II BAL quasar sample (Zhang et al. 2010). The measured maximum and minimum velocities of the Mg II BAL trough are $-20,000$ and $-11,500$ km s$^{-1}$, and the absorption index AI is 3227 km s$^{-1}$. We note that the absorption intensity of the Mg II BAL listed in the above literature is likely underestimated as the absorbing troughs of Mg II and Fe II UV 62 overlap each other and cannot be discriminated easily. In Zhang et al. (2015b), SDSS J1523+3914 was reidentified to be an “overlapping-trough” FeLoBAL quasar because of almost no continuum windows below Mg II which is caused by overlapping Fe II absorption troughs.

3.1. Absorption of Balmer Lines

In panel (b) of Figure 2, we show the spectral details of SDSS J1523+3914 from 2300 to 7000 Å. Several regions of the spectrum are absorbed and significantly below the nuclear continuum. Except BALs of Mg II and Fe II, Balmer BALs can be also found by visual examination. We further selected two quasars (SDSS J082806.18+063608.3 and SDSS J125807.45+232921.6) using the pair-matching method (Zhang et al. 2014; Liu et al. 2015), which can match the continuum slope and Fe II emission multiplets of SDSS J1523+3914 except for the absorbing troughs. Compared with the spectra of the two quasars (green and red curves), BAL troughs of Hσ and Hβ are evident. We marked the potential BAL absorption regions by gray dashed lines.

In order to exactly measure the absorption troughs of Balmer lines, we simultaneously fit the continuum and emission lines in the Hβ and Hσ regions using the code of Dong et al. (2008). In brief, the optical continuum from 4000 to 7000 Å is approximated by a single power law ($f_{\nu} \propto \lambda^{\beta}$). The value of the slope estimated from continuum windows is taken as the initial value of $\beta$. Indeed, we also try to use a broken power law with a break wavelength of 5600 Å, i.e., $a_1 \lambda^{\beta_1}$ for...
the Hβ region and $a_2 \times \lambda^{1.5}$ for the Hα region. However, we get almost the same values of $\beta_1$ and $\beta_2$. That means that a single power law is enough to model the continuum. Fe II multiplets, both broad and narrow, are modeled using the I Zw 1 template provided by Véron-Cetty et al. (2004). Emission lines are modeled as multiple Gaussians: two Gaussians for broad Balmer lines, one Gaussian for [O III]. There are no significant narrow emission lines in the spectra of SDSS J1523+3914; thus, we do not add Gaussians for narrow emission lines. Additionally, we assume that [O III] $\lambda\lambda4959$, 5007 doublets have the same redshift and profile, and their flux ratio is fixed to the theoretical value. We notice that the spectrum of SDSS J125807.45+232921.6 can cover the blue wing ($v \lesssim 5000$ km s$^{-1}$) and red wing of the broad Hα line in SDSS J1523+3914 (Figure 2, panel (b)), which means that Hα emission is likely unaffected by the BAL absorption. Thus, we just mask the potential BAL absorption regions (gray dashed lines) in the fitting.

In the top panels of Figure 3, we show the rest-frame spectra of the SDSS and TripleSpec in black curves and our best-fit models in red curves. A more accurate continuum around Hα and Hβ, $f_{\lambda} \propto \lambda^{-1.6816}$, is shown by the pink dashed line. The blue solid lines show the broad and narrow components of optical Fe II emission, and the green curves represent the three strong Balmer lines. In panel (a), the strong narrow Fe II 37 multiplets are present in the Hβ BAL trough. This implies that the outflow winds may only obscure the nuclear continuum and broad emission lines, but not the narrow emission lines. This speculation is consistent with our detailed calculation in Section 4.2. Furthermore, it can be seen from the normalized spectra of Hα, Hβ, and Hγ (Figure 3(c)) that the Hα trough is polluted by the sky lines. The latter is plotted as the gray line in panel (b) of Figure 3 for comparison. That is more remarkable in the normalized spectrum of Hα in velocity space; the corresponding polluted velocity regions are marked by green lines (panel (c)). The "true" normalized spectrum in these polluted regions is approximately given through interpolation of those in unpolluted regions. Absorption parameters of Balmer BAL troughs are listed in Table 2.

### 3.2. Further Confirmation of Balmer BALs

As is known, Fe II emission is unique in individual quasars and not exactly the same as the I Zw 1 template. Furthermore, the ratio of Fe II multiplets with different excitation is very sensitive to the temperature and density of the gas. The Balmer BAL troughs are unfortunately falling into the regimes of Fe II multiplets. Thus, we used a new Fe II template derived from the Keck spectrum of IRAS 07598+6508 (Véron-Cetty et al. 2006) to investigate the impact of Fe II templates. We first decompose...
the continuum emission of IRAS 07598+650 from the Keck spectrum through a single power-law fitting based on the above-mentioned continuum windows in Section 2. After subtracting the modeled continuum, the residual spectrum that includes broad and narrow Fe II and Balmer emission lines is used as the emission template. In panels (a) and (b) of Figure 3, the cyan curves show the new best-fit model, which is the sum of the power-law continuum (pink) and the scaled emission template. It can be seen that the new unabsorbed model around H\(_\alpha\) and H\(\beta\) BAL troughs is below the best-fitting I Zw 1 template, causing weaker H\(\alpha\) and H\(\beta\) absorption. Conversely, it shows a stronger H\(\gamma\) BAL than the previous measurement.

In order to further rule out the possibility that Balmer BALs are resulting from the artifacts of spectral fittings, we constructed a sample of 500 quasars whose spectra can match the slope and primary Fe II multiplets, i.e., Fe II \(\lambda\lambda4472–4731\) and Fe II \(\lambda\lambda5169–5325\) of SDSS J1523+3914. We used them to normalize the observed spectra of SDSS J1523+3914 and calculated the absorption equivalent width of Balmer BALs. The average values are 2769.7 \(\pm\) 252.6 km s\(^{-1}\), 1341.4 \(\pm\) 217.1 km s\(^{-1}\), and 138.9 \(\pm\) 39.6 km s\(^{-1}\) for H\(\alpha\), H\(\beta\), and H\(\gamma\) BALs, respectively. From the average values and dispersion of the absorption equivalent widths, it can be seen that the uncertainty of Fe II templates and/or the continuum determination can affect the measurement of BAL parameters, but the existence of Balmer BALs is unquestionable.

### 3.3. Optical Depth and Covering Factor

Percentage absorption depths of the troughs (Table 2) decrease as the upper term of the transition increases. However, the decline in depth is less than the decrease in transition oscillator strengths (~5 from H\(\alpha\) to H\(\beta\)), leading to the absorption being saturated. There is a residual intensity of \(~2/3\) of the modeled flux at the velocity of the maximum absorption depth (Figure 3, panel (c)), suggesting that the absorption materials only obscure \(~1/3\) of the total continuum region. Theoretically, the absorption depth is defined as

\[
D(\nu) = 1 - I(\nu)
\]  

for a partially obscured absorber, where

\[
I(\nu) = 1 - C_f(v) + C_v(v)e^{-\tau(v)}
\]  

is the normalized intensity in the troughs, \(C_f(v)\) is the percentage covering factor of the absorber, and \(\tau(v)\) is the optical depth for the relevant ion (e.g., Hall et al. 2003). We can calculate \(D(\nu)\) for each Balmer trough from the normalized spectrum, and the relative values of \(\tau(v)\) are determined by the known oscillator strengths.\(^{9}\) Thus, we can estimate \(C_f(v)\) and \(\tau(v)\) through the observed H\(\alpha\) and H\(\beta\) troughs. The maximum absorption depth of the Balmer lines is found to be \(\tau_{H\alpha} = 5.51 \pm 0.69\) with covering factor \(C_f = 34\% \pm 2.0\%\) at the velocity of maximum depth (Table 2).

In panel (d) of Figure 3, the covering factor \(C_f(v)\) and the optical depth of H\(\alpha\) absorption \(\tau(v)\) are shown as a function of the blueshifted velocity. The absorption materials have the maximum covering factor at the velocity of the maximum absorption depth (\(\nu \sim 10,700\) km s\(^{-1}\)) and smaller covering factors at the higher or lower velocities. The optical depths, i.e., the column densities, decrease as a function of the blueshifted velocity from \(\tau \sim 8.0\) at \(\nu = 5000\) km s\(^{-1}\) to \(\tau \sim 3.0\) at \(\nu = 16,000\) km s\(^{-1}\). In panel(c) of Figure 3, we compared the theoretical absorption troughs (blue curves) with the observed normalized spectra for Balmer BALs. We find that the observed absorption trough for H\(\gamma\) is shallower than the theoretical profile. The absorption of H\(\gamma\) is relatively weak and difficult to accurately measure.

Using the optical depths derived above, we calculate the column densities of H\(\alpha\) as a function of velocity using the general expression (e.g., Arav et al. 2001)

\[
N(\Delta\nu) = \frac{m_e c}{\pi e^2} \frac{1}{\lambda_0} \tau(\Delta\nu)
\]

\[
= 3.7679 \times 10^{14} \frac{\tau(\Delta\nu)}{\lambda_0} \text{ cm}^{-2},
\]

where \(\lambda_0 = 6564.41\) and \(f_0 = 0.6400\) are the wavelength and the oscillator strength of H\(\alpha\), respectively. The results are shown in panel (d) of Figure 3. The total column density is obtained as \(N_{H\alpha} = 5.52 \pm 0.27 \times 10^{15} \text{ cm}^{-2}\) by integrating Equation (3).

#### 3.4. Absorption of He I* \(\lambda10830\)

Only the blue wing of the redshifted He I* \(\lambda10830\) emission line is detected with the TripleSpec spectrum at H band (panel (a) of Figure 2). To obtain the unabsorbed spectral intensity around He I* \(\lambda10830\), we used the following procedure. We downloaded the high-quality near-infrared broad emission line spectra presented by Landt et al. (2008) and found four objects that can be compared with SDSS J1523+3914: 3C 273, IRAS 1750, HE 1228+013, and PDS 456. These spectra are similar to that of SDSS J1523+3914 in terms of emission lines, but different in their continuum slopes. Thus, we could use line-free spectral regions in each comparison object to determine the continuum and thus the normalized emission line profiles. We focus on a limited wavelength range between 0.7 and 1.5 \(\mu m\) and fit the line-free continuum bands of each object with a

\[ \tau_v = R \cdot \tau_o, \] where \(R = g_i f_i / g_0 f_0 \cdot \lambda_i \) is the ratio of the optical depth of H\(\beta\) to that of H\(\alpha\), the \(g_i\) are the statistical weights, the \(f_i\) are the oscillator strengths, and the \(\lambda_i\) are the wavelengths of the lines.
single power law for the accretion disk and a blackbody emission component for hot dust emission. Then the emission-line templates are obtained by dividing the observed spectra by the best-fitting continuum. Finally, we multiplied the emission-line templates by a single power-law and blackbody emission to reconstruct the NIR spectrum of SDSS J1523+3914. IRAC 1750 provided the best-matched NIR emission line template with the minimized \( \chi^2 \). In Figure 4, the left panel shows the observed spectra of the He I \(^\lambda 10830\) regime overplotted with the best-fit model for SDSS J1523+3914. The pink and orange lines represent the power-law and blackbody emission components, respectively. For comparison, we overplotted the emission-line template multiplied by a power-law component for IRAC 1750 (blue curve). The bottom right panel shows the normalized spectrum of the He I \(^\lambda 10830\) regime overplotted with the best-fitting emission-line plus continuum template. Through the comparisons of He I and Balmer BALs, the velocity structure of He I BAL (black curve) is similar to those of Balmer BALs.

4. DISCUSSION

4.1. Comparison with Other Balmer Absorption Lines

Table 3 gives outflow velocities of the absorber for various Balmer BALs, as reported in the literature. In three cases (SDSS J125942.80+121312.6, LBQS 1206+1052, and SDSS J222024.59+010931.2), the absorption widths of Balmer absorption troughs are \( \Delta v \geq 1500 \text{ km s}^{-1} \) and can be classified as Balmer BALs. However, the widths for other quasars are only several hundred kilometers per second and could be classified as Balmer narrow absorption lines (NALs). As shown in Table 2, the widths of Balmer BALs in SDSS J1523+3914 are \( \Delta v \approx 12,000 \text{ km s}^{-1} \), and they are the broadest Balmer absorption lines that have ever been found. The redshift of the Balmer absorption troughs in SDSS J1523+3914 is \( z_{\text{abs}} = 0.6039 \pm 0.0021 \), and the blueshifted velocity is \( v = 10,353 \text{ km s}^{-1} \), which can even reach \( v_{\text{max}} \approx 17,000 \text{ km s}^{-1} \) with regard to the Balmer emission lines. It is a factor of two higher than the maximum blueshifted velocity from the previously known Balmer absorption lines. In fact, the blueshifted velocities in two-thirds of the known Balmer BALs are very small (only \( \leq 1000 \text{ km s}^{-1} \)). Compared with the above two Balmer BAL quasars with strong [O III] emission in literature, we find that the [O III] line in SDSS J1523+3914 is relatively weak (\( EW_{[\text{O III}]} = 3.46 \pm 0.12 \text{ \AA} \)). SDSS J1523+3914 also has the weakest [O III] emission among nine AGNs with Balmer absorption lines. SDSS J1523+3914 and SDSS J222024.59+010931.2 are obviously inconsistent with the previous assertion that Balmer BALs are found in FeLoBAL quasars with relatively strong [O III] emission (Aoki et al. 2006; Hall 2007).

Among the 10 objects in the literature and this work, absorption lines are usually detected in He I and Fe II. He I absorption lines arise from the metastable triplet level He I \(^2\Sigma\), which is populated by recombination from He II with electrons. Transitions from this level will generate a series of absorption lines at 3189, 3889, and 10830 \( \text{\AA} \), which are detected in seven quasars, except for SDSS J112611.63+425246.4, SDSS J125942.80+121312.6, and SDSS J172341.10+55340.5. Another interesting fact is that 7 out of 10 Balmer absorption AGNs show abundant absorption lines arising from the excited Fe II. The co-occurrence may indicate that it is probable that these three absorption phenomena are closely related. Combined diagnostics of them can determine the density and the ionization state of the absorption gas and put constraints on the geometry and physical conditions of outflows. For example, the absorbers in SDSS J112525.12+002901.3 are considered to have the parameters of \( \log_{10} n_e (\text{cm}^{-3}) = 9.25^{+0.5}_{-0.25}, \log_{10} N_{\text{Ly}} (\text{cm}^{-2}) = 22^{+0.5}_{-0.25}, \) and \( \log_{10} U = -1.75 \pm 0.25 \). The derived distance from the central engine is about 1.8-1.4 \( \text{pc} \), which is about 10 times the size of the broad emission line region (BELR) and similar to the radius of the inner edge of the dusty torus (X.-H. Shi et al. 2015, in preparation). These estimations provide some enlightenment about the physical properties of the absorbers in
### Table 3
Absorption Parameter Comparison

| Target                  | $V_{\text{blue-shift}}$ | Absorption Width | Inferred Density | Inferred Distance | References         | Notes       |
|-------------------------|-------------------------|------------------|------------------|-------------------|--------------------|-------------|
|                         | (km s$^{-1}$)           | (km s$^{-1}$)    | (cm$^{-3}$)      | (pc)              |                    |             |
| NGC 4151                | ∼1000                   | ∼350             |                  |                   | Hutchings et al. (2002) |             |
| SDSS J112526.12+002901.3$^b$ | 71.9 ± 7.2, - 651.2 ± 13.7$'$ | 199.4 ± 16.4$'$, 398.6 ± 32.6$'$ | $10^{9.25_{-0.23}}$ | $1.8^{+1.4}_{-1.6}$ | Hall et al. (2002) | mmtFeLoBAL |
| SDSS J083942.11+380526.3$^b$ | 520                     | ∼340             |                  | 10$^{8.23}$       | Aoki et al. (2006)  |             |
| SDSS J125942.80+121312.6$^b$ | 3400                    | 2000 ± 200       | $10^{9}$         | 1                 | Hall (2007)        | BAL        |
| SDSS J102839.11+450009.4 | 670                     | 149 ± 7          | ...              | ...               | Wang et al. (2008) |             |
| SDSS J172341.10+555340.5 | 5370                    | 450 ± 130        | ...              | ...               | Aoki (2010)        | mmtFeLoBAL |
| LBQS 1206+1052          | 726                     | 2000             | $10^{6.8}$       | ...               | Ji et al. (2012)   | BAL        |
| SDSS J222024.59+010931.2 | 0                      | ∼1500            | $10^{9}$         | ...               | Ji et al. (2013)   | BAL        |
| SDSS J112611.63+425246.4 | 300 ± 70                | 290 ± 40         | ...              | ...               | Wang & Xu (2015)   |             |
| SDSS J152350.42+391405.2 | 10,353                  | ∼12,000          | $10^{9}$         | 0.2               | this paper         | BAL        |

**Notes.**

- $^a$ The blue and red component of the absorption profile.
- $^b$ Negative value means redshift.
- $^b$ The parameter estimation comes from X.-H. Shi et al. (2015, in preparation).
SDSS J1523+3914. SDSS J1523+3914 has the strongest Balmer BAL troughs discovered to date and exhibits simultaneously the BALs of He\(\text{I}\) \(\lambda 10830\) and both ground- and excited-state Fe\(\text{II}\). However, these absorption lines have extremely broad velocity structures and heavily overlap each other, which cannot be trivially separated.

4.2. Physical Properties of the Absorber

Since the absorption lines are blended, it is not trivial to obtain the geometry and physical conditions of outflow winds via the combination of the absorption-line diagnostics. The large-scale synthesis code CLOUDY (c10.00; Ferland et al. 1998) is employed to evaluate the absorption lines of these atoms/ions in the extensive parameter space. The geometry is assumed as a slab-shaped absorbing medium exposed to the ionizing continuum from the central engine with uniform density, metallicity, and abundance pattern. The full 371-level Fe\(\text{II}\) model is used to reproduce the Fe\(\text{II}\) absorption, and solar elemental abundance is adopted and the gas is assumed free of dust. In addition, a typical AGN multicomponent continuum is set as the incident ionizing radiation, where the “Big Bump” component peaks at \(\approx 1\) Ryd and is parameterized by \(T = 1.5 \times 10^5\) K. The X-ray-to-UV ratio is \(\alpha_{\text{ex}} \approx -1.4\), and the low-energy slope of the Big Bump continuum is \(\alpha_{\text{UV}} = -0.6818\), which is measured in Section 3.3. The slope of the X-ray component is set to the default \(\alpha_{\text{ex}} = -1\) (see details in Hazy, a brief introduction to CLOUDY C10; http://www.nublado.org). We calculated a series of photoionization models with different ionization parameters, electron densities, and hydrogen column densities. The ranges of parameters are \(-3 \leq \log_{10} U \leq 0, 5 \leq \log_{10} n_e (\text{cm}^{-3}) \leq 11, \) and \(21 \leq \log_{10} N_{\text{H}} (\text{cm}^{-2}) \leq 24,\) with a step of 0.5 dex.

Synthetic model spectra are constructed to compare the simulations with observations. The underlying assumption is that other absorptions such as He I and Fe II have the same profile as Balmer lines, which means that for any ion the fraction of column density at a given radial velocity to the integrated ionic column density is the same, and the covering factor as a function of radial velocity is the same. Therefore, in constructing the model spectra, for a given absorption line, the ionic column density predicted by CLOUDY on the lower level of the transition is distributed to different outflow velocities following the fractional column density distribution versus \(v\) from Balmer series, evaluating the optical depth \(\tau\) as a function of \(v\). Then consider the effect of partial covering as \(f_{\text{model}} = C_f e^{-\tau} f_0 + (1 - C_f) f_0\) to get the model absorption profile, where \(f_0\) is the template for the unabsorbed background radiation field. When comparing the model spectrum \(f_{\text{model}}\) with the observed one, the spectra from 4000 to 7000 Å covering the three Balmer BALs are employed in the fitting process. \(f_0\) is actually the unabsorbed intrinsic spectrum, for example, the red curves shown in the top panels of Figure 3 for Balmer lines. For each set of parameters \((U, n_e,\) and \(N_{\text{H}})\), we calculated all possible combinations of individual models and selected the one with minimized \(\chi^2\), which is plotted in panels (a) and (b) of Figure 5 (green curves). We derived physical parameters \(\log_{10} U = -1.0, \log_{10} n_e (\text{cm}^{-3}) = 9,\) and \(\log_{10} N_{\text{H}} (\text{cm}^{-2}) = 23.5\) for Balmer BALs. The green curves represent the model profiles of H\(\beta\) and H\(\alpha\) absorption that match well to the observed spectra. Meanwhile, we also plotted the model absorption trough of He I\(\lambda 10830\) in panel (c) of Figure 5. The model absorption trough of He I\(\lambda 10830\) BAL is consistent with observations. Note that \(f_0\) in the He I\(\lambda 10830\) region is the blue curve shown in panel (a) of Figure 4, and the modeled \(f_{\text{model}}\) should be added with the blackbody emission component (orange dashed line in Figure 4) in the comparison of the model spectrum with observation.

We further explored the various Fe II absorption and Mg II doublets in the SDSS spectrum. Here the comparison spectrum of SDSS J082806.18+063608.3 was used to represent the unabsorbed intrinsic spectrum. The observed spectrum (black curve) and modeled spectrum with absorption (green curve) for SDSS J1523+3914 are plotted in panel (a) of Figure 6. It can be seen that the modeled spectrum with absorption is in good agreement with the observed one at the red wing of Mg II and the longer wavelengths. The normalized fluxes at wavelength longer than 2800 Å are around 1. That means that the absorption multiplets of Fe II opt.6,7 and opt.8 observed in SDSS J1523+3914 can be largely recovered using the above modeled absorption. However, the match of Fe II opt.6,7 and opt.8 between model and observation is still fluky. SDSS J1523+3914 is observed to decrease in flux on the timescale of 8.99 yr from the FBQS to the SDSS, but the absorption of Fe II opt.6,7 and opt.8 changes weakly, and the dramatic absorption variabilities are Fe II UV 1, UV 62, and Mg II. A photoionization model with lower density \((\log_{10} n_e (\text{cm}^{-3}) = 7)\) and ionization parameter \((\log_{10} U = -2.0)\) than the above can approximatively match the absorption variations (see Figure 2 of Zhang et al. 2015b).

For the SDSS blue-side spectrum, there seems to be other absorption components for Fe II UV 1, UV 62, and Mg II, corresponding to outflow materials with low density. Indeed, the comparison of SDSS J1523+3914 and the two templates in panel (b) of Figure 2 suggests the existence of the other absorption components. Fe II opt.6,7 and opt.8 have similar absorption depth as the Balmer absorption troughs, while the troughs of Fe II UV 1 are nearly twice as deep as Fe II opt.6,7 and opt.8 troughs. Moreover, the residual fluxes of Fe II UV 62 and Mg II BAL troughs are even only one-third of Fe II opt.6,7 and opt.8 multiplets. The residual absorption components for Fe II UV 1 are nearly twice as deep as Fe II opt.6,7 and opt.8 troughs. We broadened a low-density model \((\log_{10} U = -1.0, \log_{10} n_e (\text{cm}^{-3}) = 5,\) and \(\log_{10} N_{\text{H}} (\text{cm}^{-2}) = 23.5)\) with a single-Gaussian profile and blueshifted it to approximately match the residual component shown in panel (b) of Figure 6. The FWHM of the Gaussian profile is 3000 km s\(^{-1}\), and the blueshifted velocity is 14,000 km s\(^{-1}\). If we use a uniform covering factor for this component, \(C_f\) is found to be \(\approx 45\%\). We also noticed that the residual absorption spectrum indicates stronger absorption of Fe II UV144–149 and UV158–164 multiplets (around 2400 Å) than the optical model (Panel (b) of Figure 2), which most likely suggests a higher density or some microturbulence in the outflow winds (X.-H. Shi et al. 2015, in preparation).

4.3. Black Hole Mass Estimate and Location of the Absorber

From the spectral fittings in Section 3.1, we can obtain the continuum and emission-line parameters and derive the quasar fundamental parameters. The measured monochromatic luminosity at 5100 Å in the rest frame is \(L_{5100} = 9.29 \times 10^{44} \text{erg s}^{-1}\). The bolometric luminosity \(L_{\text{bol}}\) is estimated from the luminosity
width of Hβ emission (Vestergaard & Peterson 2006):

$$
\log M_{BH} = \log \left( \frac{\text{FWHM} \times 1000 \, \text{km s}^{-1}}{10^{44} \, \text{erg s}^{-1}} \right)^{0.5} + (6.91 \pm 0.02).
$$

The corresponding Eddington ratio is $L_{\text{Edd}}$.

$$
\frac{L_{\text{bol}}}{L_{\text{Edd}}} = 0.85. \quad \text{The black hole mass computing formula of McLure & Dunlop (2004)} \quad \text{gives similar results,}
$$

$$
M_{BH} = 5.76 \times 10^7 \, M_\odot \quad \text{and} \quad \frac{L_{\text{bol}}}{L_{\text{Edd}}} = 1.15. \quad \text{SDSS J1523+3914 is a typical narrow-line Seyfert 1 galaxy (NLS1) with a low black hole mass but high accretion ratio.}
$$

The radius of BELRs, $R_{\text{BLR}}$, can be estimated using the formula based on the luminosity at 5100 Å,

$$
R_{\text{BLR}} = \frac{\alpha L_{5100}}{(10^{44} \, \text{erg s}^{-1})^\beta} \text{lt-days},
$$

where parameters $\alpha$ and $\beta$ are $30.2 \pm 1.4$ and $0.64 \pm 0.02$ given in Greene & Ho (2005) and $20.0^{+2.8}_{-2.4}$ and $0.67 \pm 0.07$ given in Kaspi et al. (2005), respectively. Thus, the luminosity yields $R_{\text{BLR}} \approx 0.1 \pm 0.02$ pc. The radius of the dust torus, $R_{\text{Torus}}$, can also be estimated based on the thermal equilibrium of the inner side of the torus as

$$
R_{\text{Torus}} = \left( \frac{L_{\text{bol}}}{4 \pi \sigma T^4} \right)^{1/2},
$$

where $\sigma$ is the Stefan–Boltzmann constant and $T$ (\sim 1500 K) is the temperature of the inner side of the torus. Then we get $R_{\text{Torus}} \approx 0.5$ pc.

The ionization parameter is defined as

$$
U = \int_{\nu_0}^{\infty} \frac{L_{\nu}}{4 \pi r^2 \hbar \nu n_e c} \, d\nu = \frac{Q}{4 \pi r^2 n_e c},
$$

in which $\nu_0$ is the frequency corresponding to the hydrogen edge and $Q$ is the ionization photon emission rate. Using the above ionization equation and the inferred $Q$, $U$, and $n_e$ values, one can get the distance of the absorption gas of Balmer BALs from the central ionization source, $R_{\text{BAL}} \approx 0.2$ pc. Thus, the high-density outflow gas of Balmer BALs is located at or
outside of the BELRs, and less than the distance of the dust torus. Similarly, the estimated distance of the low-density outflow gas is much farther than the outflow materials with high density, reaching several tens of parsecs.

4.4. Origin of the Outflow Winds

In Section 4.1, we compared Balmer BALs in SDSS J1523 +3914 with nonstellar Balmer absorption lines in previous literature and found that SDSS J1523+3914 presents the broadest Balmer absorption lines with the maximum blueshifted velocity. Then, a question is naturally raised: why does the object present such a unique absorption property? In Zhang et al. (2014), we know that outflow velocity strongly or moderately depends on the Eddington ratio, luminosity, and UV and NIR slopes (also see Hamann 1998; Ganguly et al. 2007; Misawa et al. 2007). The first three items represent the ionization SED and the amount of the high-energy photons, and the last item is the possible contribution of the dust to the outflow acceleration. SDSS J1523+3914 is a high-luminosity NLS1 with a near-Eddington accretion rate. Meanwhile, the NIR slope of SDSS J1523+3914 is $\beta_{\text{NIR}} \sim 0.8$, which is redder than those of most BAL quasars (see Figure 2 in Zhang et al. 2014). These statistical properties bring about the occurrence of the high-velocity outflow.

From Table 3, we knew that only three of the literature quasars are the Balmer BALs, and others are just the Balmer NALs. Indeed, the absorption troughs of Balmer and He $^\text{II}$ series can help us to straighten out the classification of BALs. For example, there are suspected overlapping absorption features of Fe $^\text{II}$ in two objects; Hall et al. (2002) classified them into a special absorption subtype, the so-called many-narrow-trough FeLoBAL (mntFeLoBAL). However, the troughs of Balmer and He $^\text{II}$ series present the true absorption profiles with narrow widths, and these profiles are used to model Fe $^\text{II}$ absorption multiplets (X.-H. Shi et al. 2015, in preparation). The CLOUDY simulations provided the physical conditions of outflow gases for part of objects listed in Table 3. It can be seen that almost all absorption lines are constrained to come from high-density gases ($\sim 10^8$–$10^9$ cm$^{-3}$), and SDSS J1523+3914 is among the sources with the highest density, led by SDSS J112526.12+002901.3. The high density suggests that the outflow winds should survive in the inner region of the AGN. The photoionization model gave an estimation of a distance of $\sim 0.2$ pc. The outflow winds in SDSS J1523+3914 are close to the central ionizing source, which is slightly farther than that of BELRs. In the disk wind scenarios (Murray et al. 1995), most photoionized clouds emerge from the accretion disk and accelerate outward. The velocities of the clouds are assumed to be a function of the initial velocities, the terminal velocities, and the radii at which they are away from the center. The terminal velocities are approximately inversely proportional to the square root of the radius at which the streamlines rise. Thus, the innermost streamlines have the highest rotational and terminal radial velocities and highest ionization states. Balmer absorption winds in SDSS J1523+3914 are just located at the distance of $\sim 0.2$ pc from the central ionizing source. We suggest that this is the reason why Balmer BALs in this object have very large outflow velocities. Panel (c) of Figure 2 shows that the minimum velocity of the BAL troughs is $v_{\text{min}} \sim 5000$ km s$^{-1}$, which means that the absorption winds have large initial velocities when they emerge, or they have been accelerated from (inside) the BELRs. If the mass flux is continuous, the optical depths decrease as a function of the blueshifted velocity. If the outflow is gathering speed, it seems that the volumes of absorption winds expand gradually during acceleration outward. That is consistent with the existence of the excess outflow component of Fe $^\text{II}$ UV 62 and Mg $^\text{II}$ BAL troughs (Figure 6). This component shows higher blueshifted velocity ($v \sim 14000$ km s$^{-1}$), larger covering factor ($C_v \sim 45\%$), and lower density ($\log_{10} n_e$ (cm$^{-3}$) = 5) and is estimated to exist in remoter regions (several tens of parsecs).

5. CONCLUSION

In this work, we present the discovery of Balmer-series absorption lines from H$\alpha$, H$\beta$, and H$\gamma$ in SDSS J1523+3914 from the quasi-simultaneous optical and near-infrared spectroscopy. The redshift of the Balmer absorption troughs is $z_{\text{abs}} = 0.6039 \pm 0.0021$, and it is blueshifted by $v = 10353$ km s$^{-1}$ with regard to the Balmer emission lines. Balmer BALs have outflowing velocities a factor of two larger than the previously known Balmer absorption lines. We searched for the same velocity components seen in other NIR Balmer absorption lines. We found a component in the He $^\text{II} \lambda 10830$ absorption line at the same redshift. The absorption trough in He $^\text{II} \lambda 10830$ has a uniform absorption profile with the Balmer series, with the absorption width $\Delta v \sim 12000$ km s$^{-1}$. Therefore, SDSS J1523+3914 is the object with the broadest Balmer absorption lines detected so far. We measured the profiles of Balmer BELs and derived their widths of FWHM $\sim 1744$ km s$^{-1}$. The estimation of the fundamental parameters shows that SDSS J1523+3914 is a typical NLS1 with a low black hole mass but high accretion ratio. We approximately evaluate the BALs by employing CLOUDY in an extensive parameter space. The outflow winds of Balmer BALs are suggested to have an electron density of $\log_{10} n_e$ (cm$^{-3}$) = 9, an ionization parameter of $\log_{10} U = -1$, and a distance of $\sim 0.2$ pc from the central ionizing source, which is slightly farther than that of BELRs.

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