A COMPREHENSIVE STUDY OF BROAD ABSORPTION LINE QUASARS. I. PREVALENCE OF He 1* ABSORPTION LINE MULTIPLETS IN LOW-IONIZATION OBJECTS

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ABSTRACT

Neutral helium multiplets, He $i^* \lambda \lambda 3189$, 3889, 10830, are very useful diagnostics for the geometry and physical conditions of the absorbing gas in quasars. So far only a handful of He i^* detections have been reported. Using a newly developed method, we detected the He $i^*\lambda 3889$ absorption line in 101 sources of a well-defined sample of 285 Mg II broad absorption line (BAL) quasars selected from SDSS DR5. This has increased the number of He i^* BAL quasars by more than one order of magnitude. We further detected He $i^*\lambda 3189$ in 50% (52/101) of the quasars in the sample. The detection fraction of He i^* BALs in Mg II BAL quasars is ~35% as a whole, and it increases dramatically with increasing spectral signal-to-noise ratio (S/N), from ~18% at S/N \leq 10 to ~93% at S/N \geq 35. This suggests that He i^* BALs could be detected in most Mg II LoBAL quasars, provided the spectra S/N is high enough. Such a surprisingly high He i^* BAL fraction is actually predicted from photoionization calculations based on a simple BAL model. The result indicates that He i^* absorption lines can be used to search for BAL quasars at low *z*, which cannot be identified by ground-based optical spectroscopic surveys with commonly seen UV absorption lines. Using He $i^* \lambda 3889$, we discovered 19 BAL quasars at z < 0.3 from the available SDSS spectral database. The fraction of He i^* BAL quasars is similar to that of LoBAL objects.

Key words: galaxies: active – quasars: absorption lines – quasars: general

Supporting material: extended figures, machine-readable tables

1. INTRODUCTION

Broad absorption line (BAL) quasars are a small yet important population of active galactic nuclei (AGNs) that have a continuous broad absorption trough spanning a large range of velocities up to several times 10^4 km s^{-1} (Weymann et al. 1991; Trump et al. 2006; Gibson et al. 2009). The BALs are generally blueshifted with respect to the systematic redshift of their emission counterparts by up to 0.1-0.2 of light speed (e.g., Weymann et al. 1991; Korista et al. 1992, 1993; Hamann et al. 2013). Traditionally, BAL guasars are classified into three subcategories depending on which absorption features are seen. High-ionization BAL quasars (HiBALs) show absorption in $\lambda\lambda$ 1393, 1402, and $\lambda\lambda$ 1238, 1242, Sirv Νv C IV $\lambda\lambda$ 1548, 1550 and comprise about 85% of the BAL guasars. Low-ionization quasars (LoBALs) show, besides all of the HiBAL features, absorption troughs in low-ionization species like Mg II $\lambda\lambda$ 2796, 2803 and Al III $\lambda\lambda$ 1854, 1862 (hereafter N v, Si IV, C IV, Mg II, Al III) and comprise about 15% of the whole BAL population (e.g., Tolea et al. 2002; Hewett & Foltz 2003; Reichard et al. 2003a). Additionally, a rare class of LoBAL termed FeLoBAL quasars shows absorption features arising from the excited state of Fe II.

BALs are generally believed to be associated with AGN outflows from an accretion disk (e.g., Murray et al. 1995). Outflows may carry away huge amounts of material, energy, and angular momentum, and they are believed to be one of the most important feedback processes that connect AGNs and

their host galaxies (e.g., di Matteo et al. 2005; Elvis 2006; Dunn et al. 2010; Farrah et al. 2012). Regarding the origin of BALs in quasars, there are two theoretical scenarios. The first is that BAL quasars are essentially normal quasars viewed along a line of sight that penetrates the outflow gas (Elvis 2000). The second is an evolution scenario, in which BALs are associated with youthful quasars enshrouded heavily with gas and dust (e.g., Williams et al. 1999). Observationally, multiwavelength comparisons find basically no intrinsic difference between BALs and non-BALs, except that BAL quasars, particularly the LoBAL ones, typically have redder ultraviolet (UV) continua than do non-BAL quasars (Weymann et al. 1991; Lewis et al. 2003; Reichard et al. 2003a; Gallagher et al. 2007). This fact is consistent with both the orientation and evolutionary scenarios. Recently, evidence has mounted that LoBAL quasars, and FeLoBAL ones in particular, are highly reddened objects with high IR luminosities, associated with ultraluminous infrared galaxies (ULIRGs) in some way (Farrah et al. 2007, 2009; Glikman et al. 2012). This leads to the interpretation that LoBALs may be just at a transition phase of the evolutionary sequence, ranging from major mergers of galaxies to starbursting ULIRGs, dust-enshrouded BAL quasars, and finally to unobscured luminous quasars (e.g., Sanders et al. 1988; Gregg et al. 2002; Shen & Ménard 2012). Therefore, the study of BALs has important implications for understanding both the structure and emission and absorption physics of AGNs and the coevolution of AGNs and their host galaxies.

	Physical Parameters of Known He 1* BALs											
Object	z	$\log N_{\rm H}~({\rm cm}^{-2})$	$\log U$	$\log n_e$	$\log N_{\mathrm{HeI}^*}$	r(kpc)	References					
SDSS J0300+0048	0.89				≤ 14.9		1					
SDSS J0802+5513	0.664	21~21.5	-1.8	5	14.73	0.1~0.25	2					
SDSS J1106+1939	3.038	$22.1_{-0.1}^{+0.3}$	$-0.5\substack{+0.3\\-0.2}$	$4.1^{+0.14}_{-0.37}$	$14.68\substack{+0.23\\-0.02}$	$0.32\substack{+0.20\\-0.14}$	3					
FBQS J1151+3822	0.335	21.7~21.9	-1.5	5.5-8	14.9	0.0072-0.127	4, 5					
LBQS J1206+1052	0.396	21~22	>-1.5	6~8	15.01		6					
Mrk231	0.042	22.7	-0.5	3.75	14.96	~0.1	7,8					
SDSS J1512+1119 ^a	2.106	$21.9^{+0.1}_{-0.1}$	$-0.9^{+0.1}_{-0.1}$	$5.4^{+2.70}_{-0.60}$	$14.84\substack{+0.03\\-0.01}$	0.3-0.01	3, 9					
AKARI J1757+5907	0.615	>20.82	>-2.15	3.8	14.2	>3.7	10					
NVSS J2359–1241	0.868	20.556	-2.418	4.4	14.14 ± 0.3	1.3 ± 0.4	11,12,13					

 Table 1

 Physical Parameters of Known He 1* BALs

References. (1) Hall et al. (2003), (2) Ji et al. (2014), (3) Borguet et al. (2013), (4) Leighly et al. (2011), (5) Lucy et al. (2014), (6) Ji et al. (2012), (7) Rudy et al. (1985), (8) Leighly et al. (2014), (9) Borguet et al. (2012), (10) Aoki et al. (2011), (11) Arav et al. (2008), (12) Korista et al. (2008), (13) Bautista et al. (2010) ^a For SDSS J1512+1119, we show the physical properties of component 2 (C2) of the absorption trough, which is associated with He I* absorption lines (see Figure 4 in Borguet et al. 2013).

Absorption lines provide abundant information about the outflows of quasars, such as velocity, column density, and ionization state and density, and furthermore distances from the central black holes and even kinetic energy. Column densities could be determined by simply integrating over the apparent optical depth profile for unsaturated absorption lines (e.g., Savage & Sembach 1991). Two or more lines from the same lower level are very helpful in jointly determining the column density and covering factor of the outflow (e.g., Hamann 1997; Arav et al. 2005). However, the commonly seen absorption lines, such as C IV and Mg II, are easily saturated when the ion column densities are high. Furthermore, the wavelength separations of the C iv and Mg II doublets are less than 10 Å, so blending is a serious problem for BALs. By contrast, the He i* absorption lines offer a number of advantages in determining the physical conditions of outflow gas. The metastable 2s state in the helium triplet, He I*, which is populated via recombination of He⁺ ions, is photoionized by photons with energies of $h\nu \ge 24.56$ eV. He i* has multiple upward transitions in a wide wavelength span from the UV to the near-infrared (NIR), which are easy to observe. The strongest three transitions are 10,830, 3,889, and 3,189 Å from the metastable state to the 2p, 3p, and 4p states, respectively. Because these transitions are widely separated, there is no blending problem. Compared to CIV and MgII ions, the He 1* atoms have much smaller abundance, and the optical depth, $\tau \propto \lambda f_{ik} N_{ion}$, is much smaller than those of C iv and Mg II ions. Therefore, the He I* may remain optically thin even when C iv and Mg II lines are saturated (Leighly et al. 2011). The He I* absorption lines are also sensitive to the ionization state of the outflow gas, and thus they can, combined with other lines, set a tight constraint on the outflow (e.g., Arav et al. 2001; Ji et al. 2014). Because the wavelength coverage of the He I* lines is between the NUV and NIR, it is convenient to search for more low-redshift BAL AGNs via the He 1* absorption lines, which can be potentially used to study the host-galaxy properties of BAL quasars.

However, the valuable He I* absorption lines have received little attention for a long time. Known He I* BAL quasars are very rare to date, with only 11 being reported in the literature: Mrk 231 (e.g., Rudy et al. 1985; Leighly et al. 2014), FBQS J1151+3822 (Leighly et al. 2011; Lucy et al. 2014), NGC 4151 (e.g., Anderson 1974; Storchi-Bergmann et al. 2009), NVSS J2359–1241 (Arav et al. 2001; Brotherton et al. 2001; Arav et al. 2008; Korista et al. 2008; Bautista et al. 2010), AKARI J1757+5907 (Aoki et al. 2011), LBQS 1206+1052 (Ji et al. 2012), IRAS 14026+4341 (Jiang et al. 2013), SDSS J080248.18+551328.9 (Ji et al. 2014), SDSS J030000.56+004828.0 (Hall et al. 2002, 2003), SDSS J151249.29+111929.36 (Borguet et al. 2012, 2013), and SDSS J110645.05+193929.1 (Borguet et al. 2013), which are summarized in Table 1. Having investigated these wellstudied objects, we noticed with surprise that all of these show the Mg II absorption troughs at the corresponding velocities of He i*. This suggests that the He i* and Mg II absorption lines may have some physical connection. Given the aforementioned merits of He I* absorption, it is important to find more He 1* BAL quasars, but we do not even know whether He 1* BAL quasars are intrinsically rare or not. In light of these considerations, as a first step, we carry out a systematic search campaign for the He $1^*\lambda$ 3889 absorption line among Mg II LoBAL quasars.

This paper is arranged as follows. In Section 2, a parent sample of Mg II LoBAL quasars is constructed, and the pairmatching method is introduced. We then adopt this method to compile a He i* λ 3889 sample. In Section 3, we present a discussion on the fraction of the HeI* absorption line in Mg II BALs, which is found to be strongly dependent on the signal-to-noise ratio (S/N) of the spectra. In Section 4, we calculate a series of photoionization models to investigate the physical conditions of the He I* absorption gas and give a physical explanation for the high fraction of the HeI* in Mg II BALs. We show one example of determining the physical condition of the outflow gas by jointly using He i* $\lambda\lambda$ 10830, 3889, 3189 lines. We also compile a sample of 19 low-z (z < 0.3) BAL candidates selected by detecting the He I* λ 3889 absorption line. The summary and future works are given in Section 5. The details of supportive NIR observations and other results are described in the appendices. Throughout this work we use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. SAMPLE OF He I* λ 3889 BAL QUASARS

2.1. Existing Samples of Mg II LoBAL Quasars

We start with existing samples in the literature of Mg II BAL quasars at $0.4 \le z \le 1.35$. The redshift cutoffs are chosen such that both He I* λ 3889 and Mg II fall in the wavelength coverage of the SDSS spectrograph (3,800–9,200 Å), which enables us to use Mg II BALs as a reference in this first systematic search for He $1^*\lambda$ 3889 BALs.

There have been more studies on C IV BAL than on Mg II BAL. Among the existing BAL samples, Trump et al. (2006, hereafter T06), Gibson et al. (2009, hereafter G09), and Zhang et al. (2010, hereafter Z10) have conducted systematic searches for Mg II BALs in the Sloan Digital Sky Survey (SDSS) data set. T06 identified 4,784 BAL quasars in the SDSS DR3 quasar catalog, and G09 identified 5,039 from the SDSS DR5 in C IV or Mg II. Specifically aimed at Mg II BALs, Z10 compiled 68 Mg II BAL guasars in the SDSS DR5 at $0.4 \leq z \leq 0.8$. Those samples were compiled by using different spectral fitting procedures and somewhat different BAL definitions (see Appendix A.1 for details). We find considerable discrepancies among the three samples: 32% of the objects in T06, 19.5% of G09, and 11.4% of Z10, respectively, are not included in the other two samples, reflecting to what extent the incompleteness of the samples could be caused by their different selection procedures and criteria. We combined these samples into a merged Mg II BAL quasar sample, from which we build the parent sample of this work. Selection biases in the individual samples, which are partially complementary to one another, are also reduced to some extent in the combined sample.

The main uncertainty caused by the selection procedure lies in determining the unabsorbed spectrum (the intrinsic quasar continuum or emission lines). There are basically two schemes in the literature. One scheme is to use some kind of quasar composite spectra to model the unabsorbed spectrum (e.g., Reichard et al. 2003b, T06) in light of the striking global similarity of UV/optical spectra of most quasars (e.g., Richards et al. 2001; Vanden Berk et al. 2001). With the advantages of simplicity and fast speed, the disadvantage of this scheme is also obvious: on the wavelength scale, as far as the BAL features are concerned, there are considerable object-to-object variations in the quasar continuum shape, broad emission line profile, iron emission multiplets (pseudocontinuum), Balmer continuum shape, and so on, which cannot be incorporated into a single composite spectrum. The other scheme is to recover the unabsorbed continuum and emission lines via χ^2 -minimization fitting with (analytic) models (e.g., Tolea et al. 2002, G09, Z10). In this case, the unabsorbed UV/ optical continuum is modeled with a single or a broken power law or polynomial, emission lines with Gaussian(s) or Lorentzian(s), and iron emission with tabulated or analytic templates (e.g., Boroson & Green 1992; Dong et al. 2011). The advantages are the flexibility of fitting individual spectral components and its quick speed, but there are still several disadvantages. For example, some spectral components (such as Balmer continua) are hard to constrain by fitting (see Wang et al. 2009); in particular, the Fe Π multiplet emissions are considerably diverse among quasars and are hard to fit well in many cases using the existing Fe II templates because those templates are all based on the famous NLS1, IZw1 (see a recent discussion in Dong et al. 2011). To sum up, though the two traditional schemes have an advantage of being fast in computation, the best-fit model of the unabsorbed spectrum is not necessarily the real one, and-even worse-this systematic error is not accounted for.

A better method is required, and actually some attempts have been made. Leighly et al. (2011) used about a dozen quasar NIR spectra as templates to measure the He $I^*\lambda 10830$ Å BAL of the quasar FBQS J1151+3822. They deemed the bestmatched template spectrum as the intrinsic spectrum underlying the He^{1*} BAL and the variation in the best fits with those different templates as the systematic uncertainty. We have developed a pair-matching method to select C IV BALs (Zhang et al. 2014), which is similar to those used in the studies of extinction curves in the literature (e.g., Wang et al. 2012). The postulate of the pair-matching method is the similarity of continua and emission line profiles between BAL and non-BAL quasars, except for the (possible) dust reddening effect (see, e.g., Weymann et al. 1991; Ganguly et al. 2007). Therefore, we can always find one or more non-BAL quasars whose spectra resemble the spectral features surrounding the BAL of a given BAL quasar, provided the library of the non-BAL quasar spectra is large enough. In order to investigate the He 1* λ 3889 BALs, which are much weaker than the usually studied BALs in C IV and Mg II, we improve the pair-matching method in two aspects. First, we refine carefully the matching procedure to suit the case of He $i^*\lambda 3889$ absorption; second, we implement its merit of being able to quantify the systematic error.

Combining all of the Mg II BAL quasars detected by T06, G09, and Z10, regardless of their own selection criteria, we obtain a large sample of 351 distinct Mg II BAL quasars.⁷ In the following subsection, we will first apply the pair-matching method to the Mg II BAL quasars and obtain measurements of the BAL properties uniformly by this method; the method will also be described in detail. Then, based on our own measurements, we will build the parent Mg II BAL sample, which comprises 285 objects (see below).

2.2. Mg II BAL Measurements by the Pair-matching Method

First of all, we apply the pair-matching method to the 351 objects compiled above to measure the Mg II BALs. Our purpose is two-fold: (1) to test our pair-matching method (including the BAL selection procedure and criteria) with Mg II BALs, which is much stronger and easier to measure than He I* λ 3889; (2) to measure Mg II BAL parameters uniformly and in the same way as we will do with the He I* λ 3889 BAL in Section 2.3. The SDSS spectra⁸ are corrected for the Galactic extinction using the extinction map of Schlegel et al. (1998) and the reddening curve of Fitzpatrick (1999) and transformed into the rest frame using the redshifts provided by Schneider et al. (2010). Our automated procedure consists of the following steps.

1. Build up the library of unabsorbed quasar spectra as templates. The unabsorbed quasar spectra for the template library are all selected from the SDSS DR7 quasar catalog (Schneider et al. 2010). Only quasars at $0.4 \le z \le 2.2$ are considered to ensure that Mg II lies in the spectral coverage. We use only spectra with median S/N >25 pixel⁻¹ in the 2,400–3,000 Å region and exclude any

⁷ The published Mg II BALs in Z10 are only at $0.4 \le z \le 0.8$, so we use the same pipeline of Z10 to enlarge this sample to 175 Mg II BALs at $0.4 \le z \le 1.35$ in the SDSS DR5.

⁸ This parent sample is compiled from the SDSS DR5, but here we use the spectral data reduced by the improved SDSS pipeline, version *rerun 26*, as released since the SDSS DR7 (downloadable at http://das.sdss.org/spectro/ss_tar_26/), instead of the data reductions archived in the SDSS DR5 (version *rerun 23*).

possible BAL quasars in previous BAL catalogs. Finally, a library of 1,343 quasar spectra are selected as templates, which are visually examined to have no Mg II absorption features.

2. Loop over the templates for target BAL quasars. For each of the target BAL quasars, we fit the continuum and emission lines with each template in a looping way. We picked up acceptable fits with reduced $\chi^2 < 1.5$. To fit the spectrum of a target quasar $(f_{obj}(\lambda))$, the template spectrum $(f_t(\lambda))$ is multiplied by a second-order polynomial, accounting for possible reddening and flux calibration problem, and finally yields a best-matched spectrum $f_{t'}(\lambda)$. This can be expressed analytically as

$$f_{\rm obj}(\lambda) = f_{t'}(\lambda) = f_t(\lambda) \cdot \left(a + b\lambda + c\lambda^2\right), \tag{1}$$

where a, b, and c are free variables in the fitting.

In searching for Mg II BALs, only the spectral region in the range of 2,400-3,200 Å is used. Bad pixels identified by the SDSS reduction pipeline and absorption troughs are masked out. Initially, the wavelength range of 2,613–2,809 Å is masked out as a possible absorptionaffected region; a refined absorption-masking region, as described below, will be obtained according to the best-fit unabsorbed spectrum, and the fitting is then redone in iteration. Generally for an object spectrum there are more than 20 acceptable fittings with reduced $\chi^2 \leq 1.5$. However, in some spectra with iron absorption or a peculiar Fe II emission surrounding Mg II, the number of acceptable fittings is less than 20. For such objects, we carefully mask out those features until we get about 20 acceptable fittings. Then we make a mean model spectrum $(f_{\text{model}}(\lambda))$ of all of the acceptable fits $(f_{t'}(\lambda))$) and normalize the object spectrum with it:

$$I(\lambda) = \frac{f_{\rm obj}(\lambda)}{f_{\rm model}(\lambda)}.$$
(2)

In order to determine the region of a possible absorption trough, we smooth $I(\lambda)$ to reduce noise and unresolved absorption features. The smoothing is performed with a five-point-wide Savitsky–Golay filter of degree two. The absorption trough region, as defined by the minimum velocity (v_{min}) and maximum velocity (v_{max}) ,⁹ is determined as pixels with flux densities lower than unity by twice the rms fluctuation; i.e., $I(\lambda) < 1-2$ rms, where the rms is calculated in the 2,400–2,600 and 2,900–3,000 Å regions of $I(\lambda)$. The absorption width, W_{abs} , is defined as $|v_{max} - v_{min}|$. Likewise, the absorption depth (d_{abs}) , defined as the maximum depth in the trough,¹⁰ is calculated.

As described above, the thus-calculated absorption region serves as part of the masking regions to feed the

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fitting routine for a better iterated fit. The convergence criterion is set such that both W_{abs} and d_{abs} change less than 10% between iterations. Normally, two iterations are enough to get convergent results.

We note that in previous studies on C IV and Mg II BALs the BAL region is usually set to be the continual pixels deeper than 10% of the normalized continuum (e.g., Weymann et al. 1991). However, it is not proper for weak absorption troughs based on our following tests (e.g., in the case of He I* λ 3889 generally), so we adopt the above criterion that is set by trial and error and by which the contrast (significance) of the absorption is with respect to the spectral quality instead of to the continuum strength. Anyway, the previous treatment (10% of the continuum strength) is just used for ease of handling, though it is not physically or statistically meaningful.

3. *Identify and measure BALs*. For each of the targets, there are $\gtrsim 20$ best-fit models of the unabsorbed spectrum. In practice, we deem all of those models equally possible (in terms of their reduced χ^2 being ≤ 1.5).¹¹

For each accepted model $f_{t',i}(\lambda)$, the absorber rest-frame equivalent width (EW) of the possibly existing BAL can be calculated as follows:

$$\mathrm{EW}_{i} = \int_{\lambda_{l}}^{\lambda_{u}} \left[1 - I_{i}(\lambda) \right] d\lambda, \qquad (3)$$

where λ_u and λ_l are the wavelengths corresponding to the v_{max} and v_{min} , as described above in the rest wavelength frame, and $I_i(\lambda) = f_{\text{obj}}(\lambda)/f_{t',i}(\lambda)$.

Then the mean of all of the EW_i values, $\overline{\text{EW}}$, is a good estimate of the true value (EW), and the standard deviation indicates the systematic error of this pair-matching method (σ_{sys}) , as discussed in Section 2.1 (see also Leighly et al. 2011). On the other hand, we can estimate the purely statistical error $(\sigma_{n,i}; \text{ i.e., caused by random noises})$ for every EW_i. We follow the same method of T06 to calculate $\sigma_{n, i}$, accounting for both the error in the fit of the unabsorbed spectrum and the measurement error in every pixel comprising the absorption trough. Then we take the mean of the $\sigma_{n,i}$ values as the final random error (σ_n) . The total measurement error of the BAL EW is thus estimated as

$$\sigma_{\text{total}} = \sqrt{\sigma_{\text{sys}}^2 + \sigma_n^2} \,. \tag{4}$$

Based on the above calculated quantities, we set the criteria of bona fide BALs as follows:

i. EW $\ge 2 \sigma_{\text{total}}$ (the intensity criterion), and

ii. $|v_{\text{max}} - v_{\text{min}}| \ge 1600 \text{ km s}^{-1}$ (the width criterion).

The whole fitting and identification procedures are summarized in Figure 1. Six Mg π BALs are chosen as examples to

 $^{^9}$ Zero velocity is defined by using the improved redshifts for SDSS quasars provided by Hewett & Wild (2010), with 2,798.75 Å for Mg II and 3,889.74 Å for He I* (vacuum wavelength).

¹⁰ Note that here for convenience we define d_{abs} to be the deepest point as measured from the smoothed spectra and use it throughout the paper. We would caution that this d_{abs} is easily affected by smoothing, noisy pixels, and spectral resolution. In this work, because the noisy pixels are masked and smoothed out and the absorption trough is broad enough to be insensitive to the smoothing and the spectral resolution, this d_{abs} is robust; otherwise, the absorption-averaged depth of the trough is a better definition for the depth of the trough.

¹¹ According to our experiment, the fit of the unabsorbed spectrum predicted from the unabsorbed regions with minimum reduced χ^2 is not necessarily the real one underlying the absorption region. This is because there is essentially no ideal, well-defined relationship of quasar spectra between different wavelength regions to a very precise degree; this is even true for the local AGN continuum usually modeled with a power law. According to our trial and error (Appendix A.2), the best-fit models with reduced $\chi^2 \lesssim 1.5$ are basically indistinguishable.



Figure 1. Flowchart of the procedure to select broad absorption lines using the pair-matching method (see Section 2.2 for details). The blue solid line is the absorption line smoothed with a five-point-wide Savitsky–Golay filter of degree two, and the absorption depth (d_{abs}) is determined as the maximum depth of this.

show the fitted continua in the Mg II and He I* regions in Figure 2. The acceptable fits for each source are shown by green dotted lines, and the composite spectrum built from these fits is shown by the red solid line. The standard deviation of the acceptable fits is thus the systematic error of this method. Among the 351 sources in the combined sample, 53 sources are rejected according to our criteria, 285 Mg II BAL quasars are culled as our parent sample, and the remaining 13 sources cannot be categorized because their intrinsic spectra are unusual and difficult to fit well by the template quasars. Those 13 objects, some of which have been studied by Hall et al. (2002), are listed in Table A1 (see Appendix A.3) and are not included in our parent Mg II BAL sample.

Figure 3 is the direct comparison of the measurements of EWs (AIs), v_{max} , W_{abs} , and d_{abs} among T06, G09, Z10, and our sample. Basically, our parameter measurements are consistent with those of T06, G09, and Z10, especially for the BAL quasars that were detected by all three samples (red dots). The apparent discrepancies are mostly shown in the maximum velocities and widths of FeLoBALs (blue dots), for which the boundaries of the Mg II absorption lines are easily contaminated by Fe II absorption lines. Four FeLoBAL quasars are shown in Figure 2 (J074554.74+18187.0; J080248.18+551328.8; J084044.41+363327.8; J104459.60+365605.1), which are also marked in Figure 3 by green pentagrams.

Before applying the pair-matching method to the detection of He $i^*\lambda$ 3889, we perform a series of tests to evaluate the pair-



Figure 2. Example SDSS spectra of six He 1 λ 3889 BAL quasars. For every object, the fittings in the Mg II region (upper panel) and in the He 1* λ 3889 region (bottom panel) are shown. The acceptable fits of the unabsorbed spectrum in every panel are denoted as green dotted lines, and the mean of these acceptable fits is denoted as the red solid line. Note that J0745+1818, J0802+5513, J0840+3633, and J1044+3656 are FeLoBAL quasars.

matching method (see Appendix A.2) for both Mg II and He I*. The tests show that spectral S/N and absorption depth (d_{abs}) are the primary factors that affect absorption detection. Figure 4 shows the contour plots of the relative error of the absorption EW and recovered detected fraction in the S/N and d_{abs} space. From this figure, with increasing S/N and d_{abs} , the relative error decreases and the detection fraction increases. This figure shows that the relative error decreases and the detection fraction increases. An important implication is that we can estimate the accuracy (relative error of the absorption EW) and efficiency (detection fraction of the BAL) of the pair-matching method as long as we know the spectral S/N and d_{abs} of a given absorption line. The detection by the pair-matching method is almost complete for absorption

troughs with high S/N (\geq 35) or large absorption depth ($d_{abs} \geq 0.5$). For absorption troughs with either a low S/N (~10) or a small depth (~0.15), which is common for He I* λ 3889, the detection rate can still be as high as ~60%.

2.3. The He $i^*\lambda$ 3889 BAL Sample

Now we use the pair-matching method to search for He I* λ 3889 absorption troughs in the parent sample of 285 Mg II BAL quasars. The procedure to identify He I* λ 3889 absorption is essentially the same as described in Section 2.2 for Mg II BALs. Because He I* λ 3889 absorption is much weaker than Mg II, we make a few minor adjustments suitable for detecting weak absorption troughs (e.g., the templates of



Figure 3. Left: comparison of Mg II BAL parameters between our measurements and those by T06, G09, and Z10. Red dots are sources common in the three samples; green pentagrams are the six sources shown in Figure 2; blue circles are FeLoBAL quasars for which the Mg II absorption region is difficult to determine, and thus the measurements are the most divergent in the plots. Right: histograms of the BAL parameters measured by these different groups.

unabsorbed quasars, the masking regions, and a loosening of the width criterion). The details are as follows.

A template library of 316 unabsorbed quasar spectra at 0.4 $\leq z \leq 1.35$ is compiled from the SDSS DR7 quasar catalog; the spectra are selected to have a median $S/N > 25 \text{ pixel}^{-1}$ in the 3,500–4,000 Å region and have no absorption features.¹² Each of the Mg II BAL quasar spectra is fitted with the 316 templates. Only the line-free continuum region in the spectral range of 3,500–4,000 Å is used. Bad pixels are masked out according to the tags by the SDSS pipeline. We carefully mask the regions contaminated by the $[O II]\lambda 3727$ and $[Ne III]\lambda 3869$ emission lines to make sure that the placement of the AGN continuum around He $1^*\lambda$ 3889 will not be affected by those nearby narrow emission lines. Initially the possible He 1* absorption region is masked out according to the measured Mg II absorption region, and later on in the iterated fittings it is masked out according to the calculated v_{\min} and v_{\max} . Other absorption lines such as Ca II $\lambda\lambda$ 3949, 3969 and high-order Balmer absorption lines, if

present, are also masked. Following the procedure described in Section 2.2 (see also Figure 1), fittings with reduced χ^2 smaller than 1.5 for each candidate are picked up as acceptable, and the v_{\min} , v_{\max} , d_{abs} , EW, and σ_{total} are calculated for the (possible) He 1* λ 3889 absorption. Then the intensity criterion is applied to select bona fide He 1* BALs. The width criterion is not applied to He 1* λ 3889 because, under the typical ionization parameter (*U*) and hydrogen column density (*N*_H) conditions, the optical depth of He 1* λ 3889 is much smaller than that of Mg II (see Leighly et al. 2011, their Figure 15). Although the observed widths of He 1* λ 3889 absorption troughs are narrower than the conventional definition of BAL, we still refer to them as He 1* BALs in this paper, given that they are most likely physically associated with the BAL outflows, as shown in this work.

As a sanity check, we visually inspect the SDSS spectra of the selected He I* BALs. The presence of He I* λ 3189 or even higher order He I* absorption lines in many objects is a strong support for the genuineness of our measured He I* λ 3889 absorption trough. A few spurious objects are excluded because they are mimicked by absorption features from H9, H10, or H11 Balmer absorption lines. Finally, we obtain 101 He I* λ 3889 BAL quasars, which are listed in Table 4.

¹² Some template spectra have strong $[O \ \textsc{ii}]\lambda 3727$ and $[Ne \ \textsc{iii}]\lambda 3869$ emission lines; we apply models of one polynomial plus one or two Gaussian profiles to fit the spectra locally and subtract these two emission lines from the template spectra.



Figure 4. Contours of the relative total error (panels a and b) and recovered detected fraction (c and d) in the spectral S/N and absorption depth plane based on our simulations (see Appendix A.2) for Mg II (left) and He 1* λ 3889 (right) BALs. The results based on simulated BAL spectra with Gaussian profiles are shown in the top panels; those with actual BAL profiles in the bottom panels. Also denoted are the observed parent sample of Mg II BAL quasars (red stars) and the He 1* λ 3889 BAL quasars (blue stars).

 Table 2

 Absorption Line Information

Ion	λ (Å) Vacuum	$f_{\rm ik}$	$E_{\rm low}$ cm ⁻¹	$E_{\rm up} \ {\rm cm}^{-1}$	$g_{\rm low}$	$g_{ m up}$
Не 1*	2764.63	0.004	159856	196027	3	9
He 1*	2829.91	0.007	159856	195193	3	9
Не 1*	2945.96	0.012	159856	193801	3	9
He 1*	3188.67	0.028	159856	191217	3	9
Не 1*	3889.75	0.064	159856	185565	3	9
He 1*	10833.1	0.539	159856	169087	3	9
Mgп	2796.35	0.608	0	35761	2	4
Mgп	2803.53	0.303	0	35669	2	4
Cīv	1548.20	0.190	0	64592	2	4
C iv	1550.77	0.095	0	64484	2	4

Notes. These data were taken from Kramida, A., Ralchenko, Yu., Reader, J., and NIST ASD Team (2014), NIST Atomic Spectra Database (ver. 5.2), available at http://physics.nist.gov/asd [2015 January 22], National Institute of Standards and Technology, Gaithersburg, MD, USA.

We further apply the pair-matching method to detect the He $I^*\lambda 3189$ absorption line, and 52 objects out of the He $I^*\lambda 3889$ BAL sample pass the intensity criterion. The measurements of the 52 He $I^*\lambda 3189$ BAL subsample are summarized in Table 5.

On the other hand, the optical depth ($\tau \propto \lambda f_{ik} N_{ion}$) of He I* $\lambda 10830$ is 23.5 times that of He I* $\lambda 3889$ (according to Table 2), so the absorption trough of He I* $\lambda 10830$ should be much stronger than that of He I* $\lambda 3889$. Thus, if we detect BALs in He I* $\lambda 10830$, the detection probability should be higher. As a check, we have made NIR spectroscopic observations for five sources in this present He I* $\lambda 3889$ BAL sample. It turns out that all of them show evident He I* $\lambda 10830$ BALs. The details of the NIR observations and data are presented in Appendix A.6. Based on our measurements of the Mg II and He I* λ 3889 absorption troughs using the same technique, we present a direct comparison of the two in Figure 5. Parameters such as EW, d_{abs} , v_{max} , and W_{abs} of He I* λ 3889 are consistently smaller than those of Mg II. Moreover, the absorption-weighted average velocity (v_{avg} , the velocity centroid) for Mg II and He I* λ 3889 agrees fairly well, with a very small scatter. These facts indicate a dynamical connection between the gases producing the two absorption lines.

3. FRACTION OF He 1* λ 3889 ABSORPTION IN Mg 11 BAL QUASARS

3.1. The Measured Fraction of He $i^*\lambda$ 3889 BALs

There are 101 (35.4%) He $I^*\lambda$ 3889 BAL quasars in the parent 285 Mg II BAL quasar sample. Such a high detection rate of He I^* BALs in Mg II BAL quasars is unexpected, particularly considering the scarceness of He I^* BALs reported so far.

According to the aforementioned tests (see Appendix A.2) using simulated spectra, the detection probability of absorption lines depends mainly on two factors: the spectral S/N and d_{abs} (Figures 4 and A3). Now we carry out a quick investigation of the effect of the spectral S/N on the measured fraction of He I* BALs in the Mg II BAL sample, f (He I*|Mg II). We divide the Mg II BAL sample into four S/N bins with a roughly equal number of objects in each bin (S/N < 10, 10 < S/N < 20, 20 < S/N < 30, and 30 < S/N < 50), and we then calculate the f (He I*|Mg II) of each bin. Here the S/N refers to the median spectral S/N per pixel around the He I* line (3,700–4,000 Å), and we take the mean S/N of each bin as the fiducial one. The measurement uncertainty of the faction values is estimated using a bootstrap technique. For each bin, we randomly extract a considerable number of objects from it and

	The Patent Sample of Mg II BAL Quasars in the SDSS DKS										
SDSS Name ^a	z	Spectrum ^b	Mg п ^c EW (Å)	Mg II ^d AI (km s ⁻¹)	Mg п ^е d _{abs}	$Mg \mathrm{II}^{\mathrm{f}}$ $v_{\mathrm{max}} (\mathrm{km} \mathrm{s}^{-1})$	$Mg \ \pi^{g}$ $\nu_{min} \ (km \ s^{-1})$	$Mg \ \pi^h \\ \nu_{avg} \ (km \ s^{-1})$	Mg п ⁱ S/N	References	
J000009.26+151754.5	1.197	52251-0751-354	$\begin{array}{c} 10.15 \pm 0.86 \\ 24.81 \pm 1.71 \end{array}$	1282	0.80	-4104	-126	-1457	9.1	T06, Z10	
J002623.78+135523.5	1.319	52233-0753-002		2547	0.45	-17685	-6550	-11943	14.0	T06, G09, Z10	
J004610.17+000449.7	0.826	52199–0691-494	$\begin{array}{c} 4.92 \pm 1.20 \\ 3.75 \pm 0.66 \\ 5.34 \pm 0.44 \end{array}$	391	0.33	-1846	567	-699	10.3	Z10	
J005722.48+010101.8	1.146	51783–0395-417		420	0.40	-5249	-3001	-4204	11.3	T06, Z10	
J010352.46+003739.7	0.705	51816–0396-471		556	0.28	-11571	-8433	-10071	23.7	T06, G09, Z10	

 Table 3

 The Parent Sample of Mg µ BAL Quasars in the SDSS DR5

Notes.

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^a The SDSS designation, hhmmss.ss+ddmmss.s (J2000). Sources with the same designation but suffixed with a/b/c denote sources with multiple Mg II absorption components.

^b The SDSS spectra are designated as mjd-plate-fiberid.

^c The total error σ_{total} as defined in Section 2.2.

^d Absorption index (AI) measured according to the definition of Zhang et al. (2010).

^e Maximum depth of Mg II absorption troughs.

^f Maximum velocity of Mg II absorption troughs from the zero velocity.

^g Minimum velocity of Mg II absorption troughs from the zero velocity.

^h Weighted-average velocity of Mg II BAL troughs.

ⁱ Median signal-to-noise ratio (S/N) in the range 2,400–3,000 Å.

(This table is available in its entirety in machine-readable form.)

	The He 1* λ 3889 BAL Quasars											
SDSS Source ^a	z	Spectrum ^b	Нет	He I ^c	He I ^d	He I ^e	He I ^f	He 1 ^g				
			EW (Å)	$d_{\rm abs}$	$v_{\rm max}~({\rm km~s}^{-1})$	$v_{\rm min}~({\rm km~s}^{-1})$	$v_{\rm avg}~({\rm km~s}^{-1})$	S/N				
000009.26+151754.5	1.197	52251-0751-354	2.57 ± 1.13	0.35	-1821	-445	-1024	4.7				
010352.46+003739.7	0.705	51816-0396-471	0.67 ± 0.29	0.07	-10548	-9614	-10089	30.3				
011117.34+142653.6	1.155	51821-0423-310	2.35 ± 0.54	0.17	-1598	-290	-1088	16.9				
013816.16+140431.6	0.877	51882-0426-494	3.01 ± 1.33	0.23	-4734	-2687	-3733	7.4				
013853.94–101125.7	1.305	52145-0663-217	2.61 ± 1.08	0.25	-7988	-6707	-7281	5.4				

Table 4 The He I* λ3889 BAL Ouasars

Notes.

^a The SDSS designation, hhmmss.ss+ddmmss.s (J2000). Sources with the same designation but suffixed with a/b correspond to that of Mg II in Table 3.

^b The SDSS spectrum is designated by its mjd-plate-fiber.

^c Maximum depth of He 1 λ 3889 absorption trough.

^d Maximum velocity of He 1 λ 3889 absorption trough from the zero velocity (3,889.74 Å).

 e Minimum velocity of He 1 $\lambda 3889$ absorption trough from the zero velocity (3,889.74 Å).

 $^{\rm f}$ Weighted-average velocity of the He I $\lambda 3889$ BAL troughs.

^g Median signal-to-noise ratio (S/N) of $3,500 \sim 4,000$ Å.

(This table is available in its entirety in machine-readable form.)

Table 5 He $1^*\lambda 3189$ BAL Quasars

SDSS Name ^a	z	Spectrum ^b	Не 1 λ3189	He 1 λ3189 ^c	He 1 λ3189 ^d	He 1 λ3189 ^e	He I $\lambda 3189^{\text{f}}$	He 1 λ3189 ^g
			EW (Å)	$d_{\rm abs}$	$v_{\rm max}~({\rm km~s^{-1}})$	$v_{min}~(km~s^{-1})$	$v_{\rm avg}~({\rm km~s^{-1}})$	S/N
J000009.26+151754.5	1.197	52251-0751-354	1.65 ± 0.68	0.24	-1539	-437	-894	10.6
J020105.14+000617.9	1.205	51871-0403-593	0.76 ± 0.34	0.07	-2968	-1666	-2335	25.0
J023102.49-083141.2	0.587	51908-0454-582	1.20 ± 0.59	0.10	-3339	-2107	-2714	14.1
J023153.64-093333.6	0.555	51908-0454-017	1.15 ± 0.50	0.15	-1343	-241	-766	9.4
J023445.76-085908.5	1.275	51909-0455-238	1.41 ± 0.64	0.16	-7937	-6724	-7380	10.5

(This table is available in its entirety in machine-readable form.)

calculate the He I* BAL fraction in these extracted objects, f_i . This process is repeated 100 times, and the standard deviation of the f_i values is regarded as the 1σ error to the He I* BAL fraction of this bin. The observed f (He I*|Mg II), as a function of spectral S/N, is shown in Figure 6. We find that f (He I*|Mg II) increases monotonically from 18.1% at S/N ~ 6.5–92.9% at S/N ~ 35.5.

As a comparison, the fraction $f(\text{He I}^*|\text{Mg II})$ with respect to the spectral S/N has been predicted in our tests with simulated spectra (see Appendix A.2 and Figure 7, left panel). The steeply rising trend of the observed one (Figure 6) is quite consistent with that of the tests using both assumed Gaussian absorption profiles and actual absorption profiles. It is worth noting that the fraction in low S/N bins predicted by the tests is much higher than what is observed. This can be understood in the following way. The right panel of Figure 7 shows the detection probability of the pair-matching method for absorption troughs with different d_{abs} under different S/N bins, which are marked by different colors. For absorption troughs with d_{abs} larger than 0.5, the detections are almost complete in all of the S/N bins using the pair-matching method, whereas according to measurements for the real sample, the distribution of the He I* λ 3889 absorption troughs peaks at ~0.2, and few of them reach $d_{\rm abs} \sim 0.5$ (Figure 5). This is also proved by the photoionization models in Section 4. Under normal ionization conditions (log $U \sim -1.5$), the d_{abs} of the He I* λ 3889 trough is much weaker than that of Mg II. We infer that the essential number of the He 1* λ 3889 absorption line with large d_{abs} should be smaller than the one with small d_{abs} . Compared with the uniform distribution of d_{abs} in the simulations, it is expected that the predicted fraction is much higher than the real sample in low-S/N bins. It is also remarkable that in the bins of S/N \geq 30, the fractions of both real sample and simulation are higher than 90%. As shown in the right panel of Figure 7, the recovered percentage is very high even for $d_{abs}\sim 0.1$ in the bin of S/N \geq 25. Therefore, the distribution of d_{abs} has little effect on the fraction of He 1* λ 3889 in high-S/N bins. That is to say, in high-S/N bins, the measured fraction of the He 1* λ 3889 absorption line is very close to its intrinsic value. Our results imply that He 1* λ 3889 absorption in fact has a fairly high incidence in Mg II LoBAL quasars.

3.2. Unveiling the He $i^*\lambda$ 3889 Absorption in Low-S/N Spectra

As shown above, the detection of the He 1* λ 3889 absorption troughs in the SDSS spectra of the Mg II BAL quasars is seriously hindered by the low spectral S/N (e.g., ≤ 20). In order to test our hypothesis that most, if not all, Mg II BAL quasars have He 1* BAL features, in this subsection we examine possible He 1* λ 3889 absorption troughs that are below our detection threshold in the low-S/N SDSS spectra. For this purpose we take two approaches: one is by combining the multiple observations in the SDSS legacy survey or the SDSS-III/BOSS; the second is by stacking spectra of low S/N.

In the parent Mg II BAL sample, 61 sources have repeated spectroscopic observations in the SDSS Legacy program or in the SDSS DR10 (SDSS-III/BOSS; Ahn et al. 2014) and are



Figure 5. Left: comparison of BAL parameters such as EW, depth (d_{abs}) , maximum and average velocities $(v_{max} \text{ and } v_{avg})$, and width $(W_{abs}, |v_{max} - v_{min}|)$ between Mg II and He 1* λ 3889 in the He 1* BAL sample. Right: the normalized histograms of these parameters.

summarized in Table A4. Some interesting sources with repeated observations are commented upon in Appendix A.5, including several variable sources (e.g., J14264704.7 +401250.8). Combining the multiple spectra of one source could enhance the spectral S/N. Moreover, the BOSS spectra have longer exposure times than do the SDSS ones, and therefore higher S/N generally; their S/N is typically $\sqrt{2}$ times that of the SDSS DR7 spectra. According to the analysis of their SDSS DR7 spectra (see Section 2), 34 of the 61 sources do not have detected He I* λ 3889 absorption troughs. Twentyone of the 34 objects have combined spectra with S/N >15, which is sufficient to detect the He I* λ 3889 absorption line

according to our simulation. We apply the same procedure of the pair-matched method to the 21 combined spectra. It turns out that four more sources pass the He I* λ 3889 BAL criteria, which are shown in Figure 8. Among the remaining 17 sources for which we still do not detect He I* absorption, five have a strong [Ne III] λ 3869 emission line, which hinders the detection of He I* λ 3869 absorption; four sources have a flat and shallow Mg II absorption trough, so the potential He I* λ 3889 would be too shallow to be detected (see Figure 5). For the remaining eight sources, we failed to detect the He I* λ 3889 absorption line even in the combined spectra.



Figure 6. Top: the detected fraction of He $i^* \lambda 3889$ BALs in the parent Mg II BAL sample, as a function of the spectral S/N. Also plotted are the $\pm 1 - \sigma$ errors. Bottom: histograms of the spectral S/N of the He i^* BAL sample (solid line) and the parent Mg II sample (dashed line).

Second, we stack respectively the sources with and without detection of He 1* λ 3889 absorption in every S/N bin. Because there are only two nondetection sources in the highest S/N bin (30 < S/N < 40), we coalesce that bin and the 20 < S/N < 30 one. The two kinds of stacked spectra in every bin are shown in Figure 9. We can see now that the absorption troughs emerge in the stacked spectrum of nondetections in each bin. The d_{abs} of those emerging He 1* λ 3889 troughs is around 0.05, which is too weak to detect in spectra of moderate S/N level (S/N \leq 15; Figure 4). Note that the d_{abs} decreases in the bins with increasing S/N; this is

because the higher the S/N, the higher the completeness of detection in individual sources, and thus the weaker the absorption troughs in the nondetections. These results, therefore, strongly support our conclusion that the He I* absorption line has a high incidence in Mg II LoBAL quasars.

3.3. Spectral S/N or Luminosity?

We would like to mention in passing that a similar trend, that the BAL fraction increases with increasing S/N and luminosity, has also been found for CIV and MgIIBAL quasars in the literature (e.g., G09; Z10). Ganguly et al. (2007) also suggested that the most luminous quasars are more likely to show BALs. As to our sample, there is also a dependence of the He I* BAL fraction on luminosity, which is shown in the upperleft panel of Figure 10. The He I* BAL fraction is growing slowly between 44.5 < $\text{Log}L_{\lambda}(3,000 \text{ Å})$ < 46 erg s⁻¹ and increases sharply in the highest $L_{\lambda}(3,000 \text{ Å})$ bin. As a check, the upper-right panel of Figure 10 shows the relation between spectral S/N and luminosity. A clear edge appears in the spectral S/N-luminosity plane, which indicates that each spectral S/N corresponds to a minimum luminosity. For the with the highest luminosities sources $(\text{Log }L_{\lambda})$ $(3,000 \text{ Å}) > 46 \text{ erg s}^{-1})$, their spectral S/N are all larger than 25. Because the spectral S/N and luminosities are somewhat degenerate, it is important to know which is the major factor. In order to test this, we select two subsamples from the parent Mg II BAL sample. The two subsamples are selected in a narrow bin of luminosity-spectral S/N so as to check the dependence of fraction on the other parameter. The first subsample is selected as sources in the luminosity bin of $45.4 < \text{Log } L_{\lambda}(3000 \text{ Å}) < 46 \text{ erg s}^{-1}$ (see the dotted lines), in which the spread of spectral S/N is equivalent to the parent sample. The sample size is 184, which is large enough to do the statistical analysis. For this subsample, luminosity is taken as the controlled factor, and we can see that the HeI* BAL fraction has no significant dependence on luminosity. But the He i* BAL fraction still has a strong dependence on spectral S/ N, which is similar to that of the parent sample (see Figure 6). The second subsample is selected as sources in the median spectral S/N bin of 5 < median S/N < 11 (see the dashed lines), in which the spread of luminosity covers from 10^{44} to $10^{46} \text{ erg s}^{-1}$. As the lower-right panel of Figure 10 shows,



Figure 7. Left: the recovered fraction of He I* BALs as a function of S/N based on the simulated spectra (see Figure 4 and Appendix A.2). Right: the recovered fraction of He I* BALs as a function of absorption depth, based on simulated spectra of different spectra S/N (see Appendix A.2 for details).



Figure 8. Demonstration of the four sources in the parent Mg II BAL sample, whose He $1^* \lambda 3889$ absorption lines could not be detected in their SDSS DR7 spectra but are detected in the higher S/N spectra formed by combining multiple observations in the SDSS and BOSS data set. Also shown are the modeled intrinsic spectra from the pair-matching method.

although the He I* BAL fraction is growing slowly with increasing spectral S/N in this subsample, we can almost think that the spectral S/N has a limited influence on the fraction for this subsample. We do not find any significant dependence of He I* BAL fraction on luminosity in this subsample. This test strongly suggests that the spectral S/N is the major factor in determining the He I* BAL fraction.¹³

In order to further test our hypothesis, we perform direct comparisons of the absorption-line, emission-line, and continuum properties between our He I* BAL sample and those without detection of He I* absorption in the parent Mg II BAL sample (hereinafter, dubbed as "non-He I* sample"). The fittings of optical and UV continuum and emission lines are performed with the routines as described by Dong et al. (2008) and Wang et al. (2009); the results are presented in Appendix A.4. As shown in Figure 11, the Mg II BAL properties (EW and d_{abs} , v_{max} , and W_{abs}) between the two samples display no significant difference, which is confirmed by the Kolmogorov–Smirnov (K–S) test with all of the chance probabilities $P_{\text{null}} > 0.01$ or even close to one. The chance probabilities are also denoted in each panel of this figure. We also compare the continuum and emission-line properties between the two samples. Again, there are no differences in the UV and optical continuum luminosities, widths of the broad

 $[\]overline{1^3}$ It is worth noting that the problem of the He 1* BAL fraction in Mg II BAL is very different from that of the C IVOR Mg II BAL fraction in all quasars. There is a very strong physical connection between Mg II and He 1* absorption lines, which is strongly indicated by both the observation and the photoionization models (see Section 4). In other words, the probability f(He I*| Mg II) is so high that finding the He 1* absorption line in Mg II BAL may be only a problem of detection. The C IV or Mg II BAL fraction in all quasars is a much more complex problem. Whether a quasar is classified as a BAL quasar or not depends on many factors, which includes the physical conditions for a quasar to have high-speed outflows to produce absorption lines, the chance of outflow gas in our line of sight, and whether the absorption lines are strong enough for us to detect.



Figure 9. Top: stacked spectra of three bins of spectral S/N in the He $i^* \lambda 3889$ region for the sources in the parent sample without detected He $i^* \lambda 3889$ absorption (black solid lines) and those with (gray dotted lines). Bottom: the stacked spectra in the corresponding Mg II region.

Mg II and H β emission lines, optical and UV Fe II strength, [O III] λ 5007 strength, and continuum slope, as apparent in Figure 12 and confirmed by the K–S test.

As a reference, we also show the distributions for non-BAL quasars in Figure 12. We select the non-BAL quasar sample from SDSS DR7 to match the Mg II BAL sample in redshift and spectra S/N. The distribution of luminosities of non-BALs agrees well with that of the BAL sample. Besides luminosity, non-BAL quasars have different continuum and emission-line properties from the BAL sample, which is confirmed by the K–S test. The most significant difference is the distributions of $\beta_{[3k,4k]}$, that LoBAL quasars have redder UV continua than do non-BAL quasars, as has been proved by many previous studies. Our results are in accordance with theirs.

4. INTERPRETATION OF THE OBSERVED He 1* ABSORPTION

4.1. Theoretical Modeling

We generate a series of oversimplified photoionization models using CLOUDY (c13.03; Ferland et al. 1998) to investigate the physical relationships between He $I^*\lambda$ 3889 and Mg II absorption lines. We start by considering a gas slab, illuminated by a quasar, with a density of n_e and a total column density of $N_{\rm H}$. The sources in our sample have various absorption intensities for He $I^*\lambda$ 3889 and Mg II, and some of them also show Fe II, H Balmer, Ca II, and even Na I absorption lines; these imply that the detailed physical conditions of outflow gases are very different. According to previous studies on the outflows of known He I^* BALs (see Table 1), the n_e spans the range of $10^{3.75} \sim 10^8$ cm⁻³ and the log U varies from $-2.42 \sim -0.5$. To fully cover the parameter space of our

sample, we calculated a grid of models with log n_e varying from 3 to 9 with step of 1 and log U varying from -2.5 to -0.1. We adopt optically thick models to generate a fully developed ionization front, and the stop column densities are setted as $N_{\rm H}$ $=10^{24}\ {\rm cm}^{-2}.$ All of these models assume solar abundance, which can satisfactorily reproduce the observed Nion in previous studies on individual He 1* absorbers (e.g., Arav et al. 2001; Ji et al. 2014). The spectral energy distribution (SED) incident on the outflowing gas has important consequences for the ionization and thermal structures within the outflow. The commonly used AGN SED is the one constructed by Mathews & Ferland (1987) (hereafter MF87), which is given as Table AGN in the CLOUDY package. Subsequent UV and X-ray observations have indicated that the FUV slopes of radio-quiet quasars are generally softer than in MF87 (see detailed discussion in Section 4.2 of Dunn et al. (2010)). Here we calculated a grid of models of ionized clouds using a realistic, UV-soft SED, which is a superposition of a blackbody "big bump" and power laws. This UV-soft SED is set to be the default parameter given in the Hazydocument of CLOUDY as follows: T = 150,000 K, $\alpha_{ox} = -1.4$, $\alpha_{uv} = -0.5$, $\alpha_x = -1$, and the UV bump of which peaks at around 1 Ryd, softer than the MF87 one. For comparison, we also calculated the CLOUDY models using the MF87 SED. In the case of the MF87 SED, He 12³S grows steeper before the ionization front of hydrogen, and Mg⁺ also grows steeper around the ionization front than those of the UV-soft SED. However, the differences between the two sets of models is small when we consider only the properties of He I* absorption, especially in optically thick clouds as considered in this work. In this paper, we use only the results of CLOUDY modeling with the UV-soft SED. We would like to mention in passing that the ionizing SED would



Figure 10. Top-left panel: dependence of the He 1* λ 3889 BAL fraction on the AGN luminosity in the parent Mg II BAL sample. Top-right panel: distribution in the plane of luminosity and spectral S/N. Middle panels: dependence of the He 1* λ 3889 BAL fraction on the AGN luminosity (left) and on the spectral S/N (right) for the sources in the narrow luminosity bin as denoted by the dotted lines in the top-right panel. Bottom panels: for the sources in the narrow S/N bin as denoted by the dashed lines in the top-right panel.

be more important in optically thin clouds or for jointly considering other absorption lines (Arav et al. 2001), and this needs a series of case studies.

Figure 13 shows the overview of the models. The Mg II and He I* show different behaviors near the hydrogen ionization front: $N_{\text{Mg II}}$ increases sharply around the ionization front of hydrogen, and $N_{\text{He I}^*}$ grows in front of the ionization front of hydrogen and stops growing behind it. This is consistent with the results of Arav et al. (2001, see their Figure 8) and Ji et al. (2014, see their Figure 7). Therefore, as the absorption gas grows thicker, the He I* and Mg II absorption lines will appear in order. It is also worth noting that the N_{ion} of different models are set apart from each other according to ionization parameter (U), while models with the same U but different n_e show no large divergences. This indicates that He I* and Mg II are more sensitive to ionization state, which agrees well with Ji et al. (2014).

Our goal is to compare the measurements for the observed sample with the results of calculated models. To realize this, we are going to transform the relationship between $N_{Mg II}$ and $N_{He I}$ of the models to the relationship between absorption depths. To simplify the discussion, we assume that the absorption gas fully

covers the incident continua, so the apparent column densities $(N_{\rm ion})$ can be derived from an apparent optical depth profile $\tau = -\ln(I_r)$ directly, where I_r is the normalized residual intensity of the absorption trough. That is,

$$N_{\rm ion} = \frac{m_e c}{\pi e^2 f \lambda} \int \tau(\upsilon) d\upsilon = \frac{3.7679 \times 10^{14}}{f \lambda} \\ \times \int \tau(\upsilon) d\upsilon \ \left(\rm cm^{-2} \right)$$
(5)

where λ is the transition wavelength and *f* is the oscillator strength, and where the velocity is measured in km s⁻¹. As a reference, we provide a table for the first five He I* lines and the Mg II and C IV doublets, including their wavelengths and oscillator strengths (see Table 2).

According to the measurements for the He I* sample, the v_{avg} of the He I* λ 3889 and Mg II absorption lines have a strong correlation, which indicates that the two lines are associated dynamically (Figure 5). In the sample, the measured He I* is much narrower than Mg II for most sources. This is because, on one hand, the Mg II absorption lines we measured are a blend of Mg II doublets, and on the other hand, the shape of the absorption feature of low-ionization lines is usually different



Figure 11. Comparison of the normalized distribution of the Mg II BAL parameters between the sources with He $i^* \lambda 3889$ absorption and those without in the parent sample. Also denoted are the chance probabilities from the K–S test, which indicate that the two have the same distribution.

from that of high-ionization lines for BALs. Here we roughly build up the relation of the Mg II and He I* absorption profile from the sample. Four composites for the Mg II absorption profile were constructed in four width (W_{abs}) ranges: 1600 < width < 2500, 2500 < width < 3500, 3500 < width < 4500, and width > 5000. Simultaneously, composites for the He 1* λ 3889 absorption line are also built up. The following is the procedure for the simulation. A series of Mg II absorption profiles with different d_{abs} are generated based on these composites. In each bin of $(n_{\rm H}, U, d_{\rm abs, MgII})$, we calculated $N_{Mg II}$ by integrating the Mg II absorption profile, and $N_{\text{He I}^*}$ was also obtained according to the relationship of $N_{\text{Mg II}}$ and $N_{\text{He}\,I^*}$ predicted by the models. Then the corresponding He $1^*\lambda$ 3889 absorption profile was generated, and we measured its d_{abs} . Figure 14 shows the simulated procedures for a model with parameters of BAL outflow gas: $\log n_e = 7.0$, $\log U = -1.5$. Figure 15 shows the relationship between Mg II and He $I^*\lambda$ 3889 absorption depths of the simulation. In the left panel, we can see that the results of the simulation coincide well with the measurements of our sample (gray dots). In the right panel, the d_{abs} of He 1* λ 3889 produced by outflows with different n_e only show slight differences, whereas in the middle panel, the d_{abs} of the He $1^*\lambda$ 3889 absorption line are layered according to ionization parameter (U). These again indicate that the d_{abs} of the He $I^*\lambda$ 3889 absorption line is sensitive to the ionization parameter but insensitive to n_e . Outflows with large U will

produce He $I^*\lambda 3889$ absorption troughs with depths equal to or even larger than that of Mg II.

Figure 16 shows the ionization structure in a cloud slab of C IV, Mg II, and He I* predicted by the photoionization models we described before. Here we adopt models with $\log n_{\rm H}$ $(cm^{-3}) = 7$ as the example. The distance from the illuminated surface of the cloud (r, thickness of the cloud) is represented by hydrogen column density $(N_{\rm H})$, that is, the total column density of hydrogen integrated from the illuminated surface to r. The column densities of other species are calculated in the same way. We can see that the column density of the respective species (and thus absorption strength) depends on ionization parameter (U) and the cloud/outflow thickness (namely the cloud's column density, $N_{\rm H}$). When the $N_{\rm H}$ of an outflow is too small to develop a hydrogen ionization front (the case of optically thin clouds), $N_{Mg II}$ decreases with increasing U; when the cloud has a sufficiently large $N_{\rm H}$ (optically thick), both high- and low-ionization absorption lines would be detected. Based on the simulation for the He $I^*\lambda$ 3889 absorption depths, we can investigate the possible $N_{\text{Mg II}}$ and $N_{\text{He I}}$ range that can be observed. Using the composites for Mg II and He I* λ 3889 that we constructed for the simulation, we calculated the ionic column densities corresponding to the absorption trough with $d_{\rm abs} \sim 0.05$, which is the minimum $d_{\rm abs}$ we can detect using the pair-matching method. Therefore, these ion column densities are the boundary of detection for each absorption line. The red, orange, and black colors in this figure represent the detection



Figure 12. Comparison of normalized distributions of continuum and emission-line properties between the He $1^* \lambda 3889$ BAL sample (solid line), the parent Mg II BAL sample (filled with tilted lines), and non-BAL quasars (gray shaded). Also denoted are the chance probabilities from the K–S test between the He 1^* BAL sample and the parent Mg II BAL sample, and those between the Mg II BAL sample and non-BAL quasars.

boundary for He 1* λ 3889, He 1* λ 10830, and Mg II, respectively. According to the figure, as an outflow is growing thick, the He 1* λ 10830 absorption line will be detected first. In the outflow with low ionization parameter (e.g., log U = -2), the Mg II absorption line will be detected before He 1* λ 3889, while in the outflows with intermediate (e.g., log U = -1.2) and high (e.g., log U = -0.5) ionization parameter, the He 1* λ 3889 absorption line will be detected before Mg II. This sequence explains why the He 1* λ 3889 absorption lines are so prevalent in Mg II BAL quasars. We may also expect that if we observe Mg II BALs in the near-infrared band, the fraction of He 1* BALs that appear in Mg II LoBALs will be much higher. According to this figure and Figure 15, there should be a kind of BAL with obvious He 1* λ 3889 or strong He 1* λ 10830

did find three such cases, SDSS J0352–0711, J1413+4400, and J0936+5331, which are shown in Appendix A.6. SDSS J0352–0711 is a BAL quasar rejected by T06, G09, and Z10 because of the weakness of the Mg II absorption. However, as Figure A10 shows, they have a significant C IV absorption line and He 1* $\lambda\lambda$ 3889, 10830 absorption lines. In the spectra of low-*z* BALs J1413+4400 and J0936+5331, we can hardly find Mg II absorption lines, but the He 1* $\lambda\lambda$ 3889, 10830 are significant, which are associated with the C IV absorption trough. In addition, the published He 1* BAL SDSS J1512+1119 (Borguet et al. 2012, 2013) is also in such a situation in this case. The strength of the He 1* λ 2946 absorption line is roughly the same as the Mg II λ 2796 absorption line (Borguet et al. 2012 Figure 3), so the He 1* λ 3889 or He 1* λ 10830 absorption lines should be much stronger.



Figure 13. Ionization structure of Mg⁺ (left) and He I^{*} (middle) and the ratio of the number of the two species (right) for a cloud slab calculated by CLOUDY. Here the distance from the illuminated surface of the cloud (*r*, *x* axis) is represented by $N_{\rm H}$, that is, the total column density integrated from the illuminated surface to *r*. The column densities of Mg II and He I^{*} (*y* axis) are calculated in the same way. Models with different hydrogen number densities ($n_{\rm H}$) are marked by different colors. Bundles from left to right in each panel denote models with different ionization parameters: log U = -2.0, -1.8, -1.5, -1.2, -1.0, -0.7, -0.5, and -0.3. Note that the ionization structure of both species is almost insensitive to $n_{\rm H}$ yet fairly sensitive to U.

4.2. Case Study: Deriving Physical Conditions of the Outflow Gas Using He 1*

The He I* absorption lines are important diagnostics of the physical conditions of the AGN outflows. The metastable state He I* has multiple upward transitions in a large wavelength span from the UV to the NIR band, and these absorption troughs are well separated. In particular, the very small abundance of the metastable state (with a number abundance of about 6×10^{-7}) makes the He I* lines hard to saturate and valuable in probing outflows of high column density. The different oscillator strengths of the He I* lines allow us to determine the real optical depth and covering factor of the He I* absorbers (e.g., Leighly et al. 2011), as well as the ionization state of the outflow gas.

Here we present an individual FeLoBAL quasar FBQS 0840 +3633 in our He i* BAL sample to exemplify the power of the He i* absorption lines to probe the physical condition of the outflows. Its UV spectrum, taken by Keck/HIRES, has been studied in detail by de Kool et al. (2002). According to their measurements, the outflow covers a range of velocities from -700 to -3,500 km s⁻¹ (negative values denoting blueshift), with two main components centered at -900 and $-2,800 \text{ km s}^{-1}$, respectively. The physical conditions of the two components are found to be significantly different, the lowvelocity gas being of lower density $(n_e < 500 \text{ cm}^{-3})$ and farther away from the active nucleus (~230 pc) than the highvelocity one. The $N_{\text{He I}^*}$ is growing fast before the ionization front, so both the detection and nondetection of He 1* absorption lines can place a strong constraint on the column density of the gas. In light of the absence of the He I* λ 2830 absorption line in the Keck/HIRES spectrum, they set an upper limit on the hydrogen column density of $N_{\rm H} \lesssim 2 \times 10^{21}$ cm^{-2} .

We detect significant He $1^*\lambda 3889$ and He $1^*\lambda 3189$ absorption lines in its SDSS spectrum. Then we obtain a NIR spectrum by the TripleSpec spectrograph on the P200 telescope on 2014 January 17 to measure the expected broad He $1^*\lambda 10830$ absorption line (see Appendix A.6). We apply the pairmatching method to measure the Mg II and He 1^* $\lambda\lambda 3189$, 3889, 10830 absorption lines. To fit He $1^*\lambda 10830$, an NIR spectral library of 76 high-S/N unabsorbed quasars from Glikman et al. (2006), Riffel et al. (2006), and Landt et al. (2008) is built up. Our measurements show that the He 1^* $\lambda 10830$ absorption covers from -1,300 to -4,400 km s⁻¹, roughly corresponding to the high-velocity gas in de Kool et al. (2002), with which the He 1* $\lambda 3889$ and He 1* $\lambda 3189$ troughs agree well. Figure 17 shows the fitting results for the Mg II and He 1* $\lambda 3189$, 3889, 10830 absorption troughs. The left panels show the best-fit local continuum (blue) for each line, and the right panels show the zoomed-in normalized absorption troughs.

We use the He I* absorption lines to explore the partialcoverage situation for the outflow gas. The optical depth $(\propto \lambda f_{ik} N_{ion})$ of He I* $\lambda 10830$ is over 23 times that of He I* $\lambda 3889$, so He I* $\lambda 10830$ should be heavily saturated given the observed depth of the He I* $\lambda 3889$ trough. The nonzero flux in the 10,830 trough implies a partial-coverage situation for the He I* absorber (see Leighly et al. 2011 for the arguments in detail). In addition, because the contribution of residual flux of the 10,830 trough to the spectrum is larger than the contribution of broad emission lines, the absorber should only cover a fraction of the accretion disk. Therefore, we should subtract the emission lines and normalize the involved part of the spectrum with respect to the AGN continuum only. The observed, normalized spectrum can be expressed as follows:

$$R = (1 - C_f(v)) + C_f(v)e^{-\tau(v)}.$$
 (6)

Here, $C_f(v)$ is the cover fraction, and the τ ratio ($\propto \lambda f_{\rm ik} N_{\rm ion}$) of He 1* $\lambda\lambda$ 10830, 3889, 3189 is 23.5:1:0.33. Following the methodology of Leighly et al. (2011), we derive the covering fraction, the optical depth and column density of He 1*, and their 1 σ uncertainties as a function of velocity (see Figure 18). The He 1* column density and its uncertainty is calculated by integrating: log $N_{\rm He 1^*} = 14.9 \pm 0.07 \,{\rm cm}^{-2}$. The velocity-averaged covering fraction is ~50%. According to the relation between the $N_{\rm He 1^*}$ and the ionization parameter obtained by Ji et al. (2014, see their Figure 8), we estimate that the ionization parameter log U is between -1.7 and -1.5. Assuming that $n_{\rm He 1^2 3S}/n_{\rm He II} \sim 6 \times 10^{-6}$ (de Kool et al. 2002), we estimate the total hydrogen column density $N_{\rm H}$ to be $\approx 1.36 \times 10^{21} \,{\rm cm}^{-2}$.

A second approach is taken to probe the physical conditions of the outflow gas, in the case of the presence in BALs of lowionization species such as Fe II. Besides the covering



Figure 14. Illustrating the procedure that generates the corresponding He 1* λ 3889 absorption lines (bottom right panel) from Mg II BALs with given absorption depths (top right panel). This example is for an absorbing cloud with the typical physical parameters: log $n_e = 7.0$ and log U = -1.5. The velocity width of the Mg II absorption line constructed from the sample is ~2,000 km s⁻¹, and the corresponding He 1* absorption line is ~1,000 km s⁻¹. From the observed Mg II BAL, the Mg⁺ column density and then the total column density can be derived according to the CLOUDY calculation (top left panel; see Figure 13), then the He 1* column density (bottom left panel). Based on these cloud parameters, the He 1* BAL can finally be generated.



Figure 15. The CLOUDY calculations reveal the relationship of absorption depth between Mg II and He 1* λ 3889 BALs. In the left panel, black dots show the relation between Mg II and He 1* λ 3889 predicted by the calculations. Gray dots are the measurements of the He 1* BAL sample, as shown in Figure 5. The next two panels are the same as the left panel, but with different colors denoting ionization parameters (log *U*) and electron density (*n_e*), respectively. Note the strong dependence of He 1* λ 3889 absorption depth on ionization parameter, yet little on electron density.

fraction, He I* and total hydrogen column densities, and ionization parameter derived by the first approach, this second approach can further constrain the electron density of the gas. The strategy, called "synthetic-spectra fitting," is as follows (see Shi et al. 2014 for details). Assuming that the absorption of low-ionization metal ions shares the same profile as He I*, we run a grid of photoionization simulations with Cloudy 13.03 to produce synthetic spectra that cover the full space of the above-mentioned parameters and match them to the observed spectrum (including the continuum, emission lines, and particularly all of the absorption lines of interest). Then from the best-matched synthetic spectrum we derived the physical



Figure 16. Ionization structure in a cloud slab of C IV (blue), Mg II (black), and He 1* (red) calculated by CLOUDY, which depends strongly on ionization parameter (log *U*). Horizontal shaded stripes represent the ion column density ranges corresponding to the absorption troughs with different widths and with a depth of 0.05, the lower limit by the pair-matching method, for He 1* λ 3889 (red), He 1* λ 10830 (orange), and Mg II (black), respectively.

parameters of the absorbing gas. We apply this approach to FBQS 0840+3633 and derive the hydrogen column density log $N_{\rm H} = 22 \,{\rm cm}^{-2}$ and ionization parameter log U = -1.7, which are consistent with those obtained by the first approach, and the electron density log $n_e = 7.5 \,{\rm cm}^{-3}$. Figure 19 displays the bestmatched synthetic spectra in the NUV region (left panel) and the NIR region (right panel), respectively.

In our He 1* λ 3889 BAL sample, more than half of the sources have He $I^*\lambda 3189$ absorption lines, and a few of them also have higher-order He I* lines. We can also obtain He I* $\lambda 10830$ with follow-up NIR spectroscopic observations. Thus we can derive important physical parameters of the outflow gas such as the covering factor (C_f) and He i^{*} column density (N_{He}) using the He i* absorption lines directly. Because He I* absorption lines are sensitive to the ionization state of clouds, the ionization parameter (U) can be determined by the He I* lines alone provided the clouds are optically thick and in a moderate range of n_e (Ji et al. 2014), or by joint use of He I* and lowly ionized absorption lines such as Mg II. The electron density (n_e) of the outflow gas can be determined by absorption lines sensitive to n_e , such as absorption lines from the excited Fe II state. With the above parameters, we can further locate the outflows from the AGN central engine, which is very important in studying the connection between supermassive black hole (SMBH) growth and host-galaxy buildup.

4.3. Searching for Low-z BAL AGNs via He $i^*\lambda$ 3889

Thus far, low-*z* BAL AGNs are still very rare because of the difficulty of carrying out UV spectroscopic observations for the absorption lines such as C Iv and Mg II, yet low-*z* BAL AGNs (particularly the high-luminosity version, quasars) are of great importance. First of all, their proximity enables us to investigate not only the properties of their host galaxies but also the spatially resolved outflows per se on the host-galaxy scale and the interplay between the outflows and the host-galaxy interstellar medium (ISM). Additionally, a number of important spectral diagnostics can be obtained easily through optical spectroscopic observations, e.g., narrow emission lines to estimate the SMBH mass.

Here we demonstrate the power of using He $i^*\lambda 3889$ absorption troughs to select low-z BAL AGNs by the pairmatching method. We simply set the redshift cutoff to be z < 0.3 and start from all of the quasar catalogs of the SDSS-I, II, and III (Schneider et al. 2010; Pâris et al. 2014). The

selection procedure follows the method described in Section 2. Note that it is more difficult to identify He $I^*\lambda$ 3889 absorption lines without the reference of Mg II absorption. As the result of our above He I* BAL sample shows, the measured widths of He $1^*\lambda 3889$ absorption troughs are narrower than those of the corresponding Mg II BALs, so we set the width criteria to be $|V_{\text{max}} - V_{\text{min}}| > 800 \text{ km s}^{-1}$ for low-*z* He I* λ 3889 BALs. Then, we carefully examine the candidate spectra that pass the He I* BAL selection criteria. As for the He I* λ 3889 absorption of those low-z objects, the high-order Balmer absorption lines from host-galaxy starlight are the principal contamination. Once we find Balmer absorption lines in a spectrum, we omit the object from the sample. In addition, some other absorption lines located at the same velocities as the candidate He $I^*\lambda 3889$ absorption, such as He $i^*\lambda 3189$, He $i^*\lambda 2946$, and even Na D absorption in some spectra, are useful for our identification. Finally, 19 low-z He I* BALs are identified and are summarized in Table 6. Note that we only included the most secure detections of the broad He $I^*\lambda 3889$ line. The real number of He 1* BAL quasars might be much larger than this. For the typical data quality of SDSS spectra, the detection fraction of He i* BAL is about 35%. This suggests that there might be at least 54 low-z He i* BAL guasars. Thus we can roughly estimate the fraction of He I* BALs. There are 2,539 quasars with z < 0.3 in Schneider et al. (2010) for SDSS DR7 and Pâris et al. (2014) for BOSS DR10 in total. The conservative fraction of He 1* λ 3889 BAL guasars is about 2.13%. This value is similar to the Mg II LoBAL quasar fraction.¹⁴

The combination of He 1* $\lambda\lambda$ 3889, 10830 is very useful to determine the physical properties of absorption gas. We carried out NIR spectroscopic observations for five low-*z* He 1* λ 3889 BAL AGNs, namely J0752+1935, J0936+5331, J1535 +564406.5, J1634+2049, and J2220+0109, using the Triple-Spec spectrograph on the Palomar 200-inch Hale telescope. All five objects show evident He 1* λ 10830 absorption features, which confirms our detection of He 1* λ 3889. Nearly full coverage is found in four of the five absorbers. The remaining one, J0752+1935, is about 50%.

The details of the NIR observations and data are described in Appendix A.6. In addition, J0936+5331 and J1305+1819 have archival FUV and NUV spectra, taken by the Cosmic Origins Spectrograph (COS) and Space Telescope Imaging

¹⁴ The observed C IV BAL fraction in quasars has been calculated as ~15% (e.g., Hewett & Foltz 2003; Reichard et al. 2003a; G09), and LoBALs comprise ~15% of C IV BAL quasars (e.g., Weymann et al. 1991).



Figure 17. Left: demonstration of the absorption troughs in Mg II, He 1* $\lambda\lambda$ 10830, 3889, 3189 (black) of FBQS 0840+3633, and the acceptable fittings (green) and the mean spectrum (red) by the pair-matching method, as well as the intrinsic AGN continuum (blue) determined according to several line-free regions. Right: normalized versions corresponding to the left panels. The gray shades indicate the absorption-line regions. The gray dotted line in the second panel from the top shows the He 1* λ 10830 absorption profile as predicted from the He 1* λ 3889 absorption trough under the full-coverage assumption.

Spectrograph (STIS) aboard *Hubble Space Telescope (HST)*. J0936+5331 shows C IV BAL, while the Mg II absorption feature is absent in its NUV spectra; it is thus another example of a HiBAL quasar discussed in Section 4. J1305+1819 shows both C IV and Mg II BALs at the same velocities as our identified He 1* λ 3889.

5. SUMMARY AND FUTURE WORKS

The primary findings of this work are as follows.

1. We have carried out the first systematic search for He 1* BAL quasars, yielding a sample of 101 quasars with He 1* λ 3889 absorption troughs culled from the SDSS DR5 data set. This increases the number of quasars with any He 1* absorption lines—all discovered serendipitously in the literature and including those found via the He 1* λ 10830 line—by more than an order of magnitude. In addition, 52 objects of this He 1* λ 3889

BAL sample have even He $i^*\lambda 3189$ absorption detected from their SDSS spectra.

- 2. We have developed an effective pair-matching method and selection procedure, aimed at selecting uniformly weak or shallow BALs. Careful treatments are given to the definition of the absorption region (namely the maximum and minimum velocities of the absorbing outflows) and to the BAL criteria by invoking several statistical measures, particularly taking advantage of the statistical merit of being able to estimate the *systematic error* of the pair-matching method. This methodology, with minor adaption, can be applied to detect other weak spectral features that are highly blended with their complicated surrounding components.
- 3. This search for He $I^*\lambda$ 3889 BALs is based on a large parent sample of Mg II BAL quasars compiled from the literature, with the information of the Mg II absorption used as auxiliary reference to guarantee the genuineness



Figure 18. Calculation results (top panel) of the He I absorption lines of FBQS 0840+3633 under the partial-coverage model. The top panel shows the observed profiles with $\pm 1\sigma$ error bars of He I* λ 3189 (purple dots), λ 3889 (blue dots), and λ 10830 (black dots), and their models as reproduced by the model parameters. The model parameters (the optical depth, covering fraction, and column density of the outflow gas) are shown in the other three panels as functions of velocity.

of He 1* λ 3889. We find that the observed fraction of He 1* λ 3889 BAL quasars in the parent Mg II sample is 35.4%. When only the spectra with S/N >30 are considered, the fraction is 93%, which is surprisingly high. According to our simulations, we conclude that the observed overall fraction is mainly affected by spectral S/N, and we suggest that (almost) all LoBAL quasars have associated He 1* BAL lines.

4. We demonstrate the power of the He I* absorption line as a probe of the physical parameters of AGN outflows by performing a case study on FeLoBAL FBQS 0840+3633. Through detailed analysis of the He I* $\lambda\lambda$ 3189, 3889, 10830 absorption lines, we estimate the covering factor (\sim 50%), hydrogen column density $(N_{\rm H} = 1.36 \times 10^{21} \,\mathrm{cm}^{-2})$, and ionization parameter $(\log U = -1.7 \sim -1.5)$ of the outflow gas. We also run a grid of photoionization models using Cloudy 13.03 to produce synthetic spectra and match them to the observed spectrum. According to the best-matched synthetic spectrum, we derive the physical parameters log $N_{\rm H} = 22 \,{\rm cm}^{-2}$ and log U = -1.7, which are consistent with the estimation above. The electron density is determined as $\log n_e = 7.5 \text{ cm}^{-3}$ in this way.

5. As another extended application of the He I* absorption lines, we have conducted a pilot search for low-z BAL AGNs via He I* λ 3889 in all of the SDSS spectroscopic archives. Those AGNs have to be free of host-galaxy starlight (e.g., the stellar high-order Balmer absorption lines) in their SDSS spectra. Finally, we find 19 AGNs at z < 0.3 with He I* λ 3889 absorption troughs. These low-z BAL AGNs are valuable in studying the outflow launching mechanism, the interplay between the AGN outflow and the host-galaxy ISM, the properties of the host galaxies, and the AGN feedback.

There are several lines of fruitful work for the future. First of all, follow-up NIR observation of the He $I^*\lambda 10830$ absorption lines would be instructive to confirm their BAL nature. Moreover, the joint use of He $I^*\lambda\lambda 10830$, 3889 absorption lines will enable us to determine the covering factor, column density, and the ionization parameter of the outflow. In the optical band, by exploiting the huge volume of the data set of spectra with sufficient S/N and spectral resolution (e.g., the SDSS), we can further develop elaborate procedures to carefully separate stellar absorption features and identify He $I^*\lambda 3889$ BALs. This would be very useful for identifying BALs in AGNs at low redshifts whose spectra are contaminated by starlight.

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APPENDIX

A.1. Overview of Existing Mg II BAL Samples

As described in Section 2.1, we combine the Mg II BAL quasars in the T06, G09, and Z10 samples, from which a parent sample of 285 objects is built. Below we overview and compare those three samples.



Figure 19. Best-fit model for FBQS J0840+3633 by the method of synthetic-spectra fitting, with the model spectra synthesized by CLOUDY.

Table 6 Low-z BAL AGNs

SDSS Name	z	Spectrum	He ι*λ3889 EW (Å)	He 1* λ 3889 d_{abs}	He $i^*\lambda 3889$ $v_{\rm max} (\rm km \ s^{-1})$	He $t^*\lambda 3889$ $v_{\rm min}({\rm km \ s}^{-1})$	He $i^*\lambda 3889$ v_{avg} (km s ⁻¹)	He 1*λ3889 S/N
J013117.14+162535.5	0.274	55833-5137-627	2.54 ± 0.68	0.27	-1805	-291	-897	15.19
J014219.00+132746.5	0.267	51820-0429-303	3.17 ± 0.35	0.23	-621	553	-57	26.49
J075217.84+193542.2	0.117	52939-1582-612	1.78 ± 0.23	0.10	-661	444	-94	43.72
J081527.29+445937.4	0.268	51877-0439-034	3.06 ± 0.65	0.14	-3398	-515	-2180	17.89
J081542.53+063522.9	0.244	52934-1295-580	1.98 ± 0.72	0.09	-5106	-1485	-3303	21.14
J081652.88+241612.5	0.276	52962-1585-178	0.70 ± 0.25	0.06	-7291	-6278	-6790	28.11
J092247.03+512038.0	0.161	52247-0766-614	0.95 ± 0.32	0.06	-7421	-6611	-7035	26.16
J093653.84+533126.8	0.228	52281-0768-473	1.20 ± 0.22	0.11	-1404	-302	-851	34.85
J101325.43+221229.4	0.275	53739-2365-389	0.69 ± 0.36	0.07	-7524	-6647	-7099	29.39
J105311.38+261522.6	0.249	53793-2357-388	1.32 ± 0.27	0.16	-1249	-422	-826	20.85
J113804.88+400118.9	0.292	53466-1972-484	1.48 ± 0.50	0.22	-838	-218	-503	12.01
J130534.49+181932.8	0.118	54479-2603-443	1.86 ± 0.13	0.24	-1023	-196	-563	34.66
J130712.33+340622.5	0.148	53476-2006-628	2.21 ± 0.30	0.16	-1856	-66	-896	21.18
J134704.91+144137.6	0.135	53858-1776-612	1.39 ± 0.19	0.16	-7510	-6498	-6996	41.80
J140136.63+041627.2	0.164	52339-0856-010	0.84 ± 0.27	0.09	-7479	-6399	-6918	24.73
J153539.25+564406.5	0.208	52072-0617-352	2.82 ± 0.21	0.20	-1939	-425	-984	25.86
J163459.82+204936.0	0.129	53224-1659-542	4.70 ± 0.49	0.34	-4498	-2860	-3638	15.53
J215408.71-002744.4	0.218	52078-0371-106	2.75 ± 0.58	0.17	-2438	-307	-1211	17.68
J222024.58+010931.2	0.213	52140-0375-361	5.44 ± 0.36	0.42	-1672	-88	-724	31.15

(This table is available in its entirety in machine-readable form.)

The traditional definition for C ${\rm Iv}$ BAL, "balnicity index" (BI), was first introduced by Weymann et al. (1991) and is defined as

$$BI \equiv \int_{\upsilon_l=3,000}^{\upsilon_u=25,000} \left[1 - \frac{f(-\upsilon)}{0.9} \right] C \, d\upsilon, \tag{7}$$

where f(v) is the continuum-normalized spectral flux. The dimensionless factor *C* is initially set to zero, and changes to one only when an absorption trough continuously dips 10% or more below the estimated continuum over an interval of 2,000 km s⁻¹. The value BI = 0 means no BAL, while a positive BI indicates not only the presence of one or more BAL troughs but also the strength of the total absorption. Using BI-based criteria and the spectroscopic data set from the SDSS DR5, G09 identified 5,039 BAL quasars. In their work, the v_l in the BI definition was simply revised to be 0 km s⁻¹ instead of the blueshifted 3,000 km s⁻¹, to avoid omitting the BAL features at low outflow velocities.

T06 identified 4,784 quasars in the SDSS DR3 quasar catalog (Schneider et al. 2005). In their work, a different definition of BALs, termed "intrinsic absorption index" (AI),

was devised; the original definition of AI was first introduced by Hall et al. (2002) to select LoBAL quasars. AI is essentially an EW to measure all of the absorption flux within the absorption trough. The definition of T06 is as follows:

$$AI \equiv \int_{v_l=0}^{v_u=29,000} [1 - f(-v)] C' dv$$
 (8)

where f(v) is the normalized template-subtracted flux spectrum; C'(v) = 1 in continuous troughs that exceed the minimum depth (10%) and the minimum width (1,000 km s⁻¹); otherwise, C'(v) = 0.

Z10 searched specifically for Mg II BAL quasars in the SDSS DR5 data set and obtained 68 Mg II BAL quasars at $0.4 \le z \le 0.8$, with a median S/N \ge 7 pixel⁻¹ of the SDSS spectra. They used an AI-based selection criteria, setting a maximum velocity of Mg II BALs to 20,000 km s⁻¹ and a minimum velocity width of 1,600 km s⁻¹. The latter is a trade-off between the completeness and consistency with respect to the canonical definition (i.e., the velocity width of the trough being \ge 2,000 km s⁻¹). Because the published Mg II BAL quasars in Z10 are only at $0.4 \le z \le 0.8$, we use the same pipeline of Z10



Figure A1. Venn diagram displaying the relationships of the Mg II BAL quasars among the T06, G09, and original Z10 samples. The sources of the three samples used here are reselected according to the same BAL criteria based on our measurements (see Section 2.1). The numbers with a shaded box denote the number of sources in every minimum region enclosed by the arcs.

to enlarge this sample to 175 Mg II BALs at redshifts of 0.4 $\leq z \leq 1.35$ in the SDSS DR5.

For ease of comparison, we select only the sources in those samples that satisfy the following criteria: (1) from the SDSS DR3 only, which is common to the three samples; (2) with median spectral S/N > 7 pixel⁻¹; (3) with the width of the continuous Mg II absorption trough ≥ 2000 km s⁻¹, which is the strictest BAL width criterion among the three samples. The thus-culled samples have 106 (T06), 77 (G09), and 70 (Z10) sources, respectively. Forty-nine sources are common in the three samples, and the combined sample has 134 sources in total. Thirty-three percent of the objects of T06, 19.5% of G09, and 11.4% of Z10 are rejected by the other two samples, respectively (see Figure A1). This indicates the degree of incompleteness of the samples caused by different selection procedures and criteria.

A.2. Reliability of the Pair-matching Method

We perform a series of tests to evaluate the pair-matching method. The tests aim at three aspects: identify the major factors influencing the BAL measurements, assess the efficiency of our selection procedure (particularly the completeness of the selection sample), and check the accuracy of our measurements of BAL parameters (namely, assessing the total error σ_{tot} and the systematic error σ_{sys} described in Section 2.2).

According to the BAL definitions (BI and AI; see Appendix A.1), the depth (d_{abs}) and width (W_{abs}) of the absorption troughs are the two quantities that affect the BAL measurement. Obviously, the spectral S/N is another influencing factor in any measurements, so in the following tests we focus on evaluating the three factors.

We carry out the tests using Monte Carlo simulations, first for the parent Mg II BAL sample and then for the He I* BAL sample. We generate 200 spectra for each (S/N, d_{abs} , W_{abs}) grid by randomly combining a BAL spectrum with an unabsorbed quasar spectrum. First, for simplicity, the BAL spectra are assumed to be of Gaussian profile, with the centroid values (namely the blueshifted offset relative to the emission line) following the distribution of the parent Mg II BAL sample. The distributions in every d_{abs} and W_{abs} interval also follow the observed distributions of the parent Mg II BAL sample. The first d_{abs} bin is [0.05, 0.1], and the rest range from 0.1 to 0.9 with a bin size of 0.1. The W_{abs} bins are centered at 1,600, 2,000, 4,000, 6,000, 8,000 and 10,000 km s⁻¹. The blueshift of the absorption line is fixed at -5,000 km s⁻¹ because the v_{avg} of the Mg II and He I* absorption troughs are mainly between -10,000 and 0 km s⁻¹. We will also adopt actual absorption profiles later. The unabsorbed quasar spectra are selected from the SDSS DR7 data set with decent spectral S/N. Gaussian noises may be added to the generated spectra to meet the S/N of every bin. The S/N bins are [5, 10], [15, 20], [25, 30], and [35, 40], covering the spectral S/N range of our sample.

Then we apply the pair-matching method to the simulated spectra, using the same procedure described in Section 2.2. Based on the fitting results of all of the (S/N, d_{abs} , W_{abs}) grids, we can evaluate the measurement uncertainties, the detection ability, and so on of the three influencing factors. First of all, we analyze the fitting results of the 200 spectra in every single grid. We consider the relative difference between the input absorption EW (EW_i) and the recovered one (EW_o), $\frac{EW_o - EW_i}{EW_i}$. These relative differences in every grid turn out to be normally distributed, which is illustrated in Figure A2. This figure, with the blueshift of absorption lines being fixed at $-5,000 \text{ km s}^{-1}$, shows the histograms of $\frac{EW_o - EW_i}{EW_i}$ in the two-dimensional parameter space of S/N and d_{abs} . We can see that basically it is normally distributed. The other grids are all a similar situation. The dispersion of $\frac{EW_o - x_i}{EW_i}$ is essentially the relative total error of the absorption EW, namely σ_{tot} /EW (see Section 2.2). The 90% confidence interval is taken as the measurement uncertainty of the pair-matching method, which is set by matching the actually calculated σ_{tot} for the Mg II BAL quasars (see Section 2.2 and Table 2). Such a confidence interval (namely 1.6 σ instead of the commonly used 1 σ) should be caused by the effects of other-albeit minor-factors (e.g., the profile shape of absorption troughs). The mean of the derived systematic errors (σ_{sys}) of the 200 fittings of a grid is regarded as the typical σ_{sys} of that grid. The detection probability is straightforward to define as the recovered fraction of BALs out of the 200 spectra in every grid.

The relative total error and detection probability as functions of S/N, d_{abs} , and W_{abs} are shown in Figure A3 (left panel) for Mg II BALs. We can clearly see that the relative total error decreases, and the detection probability increases, with both increasing S/N and d_{abs} , while the effect of W_{abs} is not so significant. Therefore, we can reasonably conclude that the spectral S/N and the absorption depth are the two most important factors influencing the pair-matching method. That is why we consider the S/N– d_{abs} plane only, by collapsing the $W_{\rm abs}$ dimension, in Figure 4. The detection probability of the pair-matching method is almost complete for Mg II BALs with S/N > 35 or d_{abs} > 0.5. Figure A3 shows σ_{sys} and σ_{sys} /EW as functions with S/N, d_{abs} , and W_{abs} . The value of σ_{sys} increases with W_{abs} in every grid of (S/N, W_{abs}), yet is it is less sensitive to S/N and d_{abs} . However, similar to the relative total error, σ_{sys}/EW has a positive dependence on d_{abs} , although the dependence on S/N is not so significant.

The above conclusions are based on the simulated spectra with BALs assumed to have a Gaussian profile. Now we build simulated spectra with actual absorption lines from the parent



Figure A2. Histograms of the relative difference between input and output EW of the Mg II BALs, $\frac{EW_o - x_i}{EW_i}$, in every two-dimensional grid of spectral S/N and absorption depth (d_{abs}), with the absorption blueshift being fixed to $-5,000 \text{ km s}^{-1}$. In all panels, the green dashed line denotes the mean value of the distribution, which is almost zero; the blue, orange, and gray dotted lines denote the measured 1σ (standard deviation), 2σ , and 3σ of the distribution, respectively; the red dashed line denotes the 1.6σ , which corresponds to the 90% confidence level and is regarded as the relative total measurement uncertainty (σ_{tot}/EW) of the pair-matching method. Note that, except for the panel of the shallowest width and poorest S/N, the distributions are close to Gaussian (dark-gray lines).

Mg II sample. The BAL spectra are normalized and the lines are corrected into zero velocity shift. Consistent with the above W_{abs} bins, we categorize the Mg II BAL spectra into six subsamples. Then we build an arithmetic mean composite spectrum of normalized Mg II BALs for each, using the composite spectrum method of Dong et al. (2010). The composite spectra have very high S/N and serve as the templates of Mg II BAL profiles for the six W_{abs} bins (see the upper panel of Figure A5). Following the procedure in the case of a Gaussian profile, a series of simulated spectra are generated for all of the three-dimensional grids of (S/N, d_{abs} ,

 W_{abs}), and the pair-matching method is applied to them. The results are also shown in Figures 4, A3, and A4. The general trends are almost the same as in the case of a Gaussian profile. This confirms that the most important influencing factors in the pair-matching method are S/N and d_{abs} .

We repeat the above tests for He I* λ 3889 absorption. To fully cover the measured parameter space of the He I* BALs, the grids in the tests are 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5 for d_{abs} and 500, 1,000, 1,500, 2,000, and 3,000 km s⁻¹ for W_{abs} . The centroid of the He I* absorption line is simply fixed to be the blueshifted 5,000 km s⁻¹, the typical blueshift of the



Figure A3. Relative total errors (measure of σ_{tot} /EW; the top two rows) and the recovered fraction (the bottom two rows) as functions of the spectra S/N and depth and width of the BALs for Mg II (*left*) and for He I* λ 3889 (*right*). Rows one and three from the top are for the tests with simulated BAL of Gaussian profiles; the other two rows are of actual BAL profiles. Different absorption depths are denoted with different colors.



Figure A4. Same as Figure A3, but for the systematic error (σ_{sys}) and the relative systematic errors (σ_{sys} /EW).

Mg II BALs of the parent sample. The test results are illustrated just like the tests for Mg II; both Gaussian profiles and actual profiles (Figure A5, bottom panel) for the simulated BAL spectra are tried. The test results are illustrated in Figures 4, A3, and A4, which are similar to the case for Mg II BAL quasars.

As to testing the possibility of false identification of He I* λ 3889 BALs, the most reliable way is to observe other He I* absorption troughs at corresponding velocities. In our He I* λ 3889 BAL sample, the He I* λ 3189 absorption line is detected in over half of the samples from the SDSS spectra. Moreover, in our follow-up NIR observations, five of five He I* λ 3889 BAL quasars (100%) have the expected He I* λ 10830 BALs (see also Section 2.3 and Appendix A.6). Thus the false identification rate should be very low. More NIR

observations of He $_{1}^{*}\lambda 10830$ are needed to investigate this issue.

A.3. Unusual Quasars Not Included in Our Parent Sample

Thirteen sources compiled as Mg II BAL quasars in the T06, G09, or Z10 samples show unusual spectral features. It is difficult to use our pair-matching method to recover their unabsorbed spectra. Here we list those quasars in Table A1, and their SDSS spectra are shown in Figure A6. Among them, J010540.75–003313.9, J030000.57+004828.0, and J112526.12 +002901.3 have been investigated in detail by Hall et al. (2002); for J112526.12+002901.3, we have recently studied



Figure A5. Composite normalized absorption-line spectra for Mg II (top) and He $I^*\lambda 3889$ (bottom), serving as templates of BAL profiles of different absorption widths in the tests.

the physical conditions of its outflow gas using the method mentioned in Section 4.2 (Shi et al. 2014).

A.4. UV and Optical Measurements for the Parent Sample

The analysis of the near-UV spectra is performed with the routine described in detail in Wang et al. (2009). Here the pseudocontinuum consists a local power-law continuum, an Fe II template, but also an additional component for the Balmer continuum, which is assumed to be produced in partially optically thick clouds with a uniform temperature. The Fe II emission is modeled with the semiempirical template for I Zw 1 generated by Tsuzuki et al. (2006). To match the width and possible velocity shift of the Fe II lines, the template is convolved with a Gaussian and is shifted in velocity space. Each of the lines of the Mg II doublet is modeled with two

components, one broad and the other narrow. The broad component is fit with a truncated, five-parameter Gauss–Hermite series; a single Gaussian is used for the narrow component. The fitting results for the entire Mg II BAL sample are summarized in Table A2.

For the optical spectra of the objects at z < 0.8, the fitting is performed with the routine described in detail in Dong et al. (2008). In the spectra of these BAL quasars, the starlight is negligible. The broad emission lines, particularly the Fe II multiplets, are so broad and strong that they blend in and essentially leave no line-free wavelength regions, so we fit the nuclear continuum, the Fe II multiplets, and the other emission lines simultaneously. The AGN continuum is approximated by a single power law with a free index. The optical Fe II emission is modeled with two separate sets of analytic spectral templates,

 Table A1

 Unusual Mg II BAL Quasars Not Included in the Parent Sample

SDSS NAME	z	MJD	Plate	Fiberid	He 1* Detection	Source
J010540.75-003313.9	1.179	51816	0396	156	no	T06
J030000.57+004828.0	0.900	51816	0410	621	yes	T06, G09
J080015.06+194359.6	1.252	53315	1922	474	no	G09, Z10
J100605.66+051349.0	0.968	52641	0996	243	yes	T06, G09
J112220.76+153927.8	1.109	53383	1753	404	no	G09
J112526.12+002901.3	0.863	51614	0281	427	yes	T06, G09
J120627.62+002335.4	1.114	51999	0286	499	yes	T06, G09
J123103.70+392903.6	1.004	53466	1992	529	no	G09
J125942.79+121312.6	0.752	53473	1695	075	yes	G09, Z10
J134951.93+382334.1	1.094	53460	2014	477	no	G09
J144800.15+404311.7	0.808	53119	1397	198	yes	G09
J152350.42+391405.2	0.658	52765	1293	234	no	T06, G09, Z10
J164941.87+401455.9	1.266	52050	0630	482	no	T06, G09



Figure A6. Mg II BAL quasars with unusual spectral features. These spectra are smoothed by a five- pixel boxcar.

one for the broad-line system and the other for the narrow-line system, constructed from measurements of IZw 1 by Véron-Cetty et al. (2004). Within each system, the respective set of

Fe II lines is assumed to have no relative velocity shifts and the same relative strengths as those in IZw 1. Emission lines are modeled as multiple Gaussians. Following Dong et al. (2011),

we assume that the broad Fe II lines have the same profile as the broad H β . The results of the optical fittings for the Mg II BAL quasars at z < 0.8 are summarized in Table A3.

A.5. Sources With Multiple-epoch Spectroscopic Observations in SDSS and BOSS

In our parent Mg II BAL sample, 61 sources have repeated spectroscopic observations in the SDSS Legacy program or in the SDSS DR10 (SDSS-III/BOSS). Detailed information on these sources is summarized in Table A4. We find that four of them show obvious variability in the absorption profile; they are J083525.98+435211.3, J090825.06+014227.7, J114209.01+070957.7, and J14264704.7+401250.8. The most extreme variability occurs in J14264704.7+401250.8, with both its Mg II and He I* absorption lines being evidently weakened (Figure A7). For the other three sources, as Figure A8 shows, the changes in their Mg II absorption line profile are evident. Such changes in the absorption may result from the nuclei continuum, the covering factor of the outflow, or the physical conditions of the outflow gas, which is interesting to investigate further.

A.6. He *i**λ3889 BAL Quasars With Supporting NIR and UV Spectra

We have performed follow-up NIR spectroscopic observations for sources from the He 1* λ 3889 BAL sample to check their expected He 1* λ 10830 BAL features. The NIR observations were made by the Palomar P200 telescope with the TripleSpec spectroscope on 2012 April 15–16, 2013 February 22–23, and 2014 January 17–19. All spectra were taken in an A-B-B-A dithering mode, in the primary configuration of the instrument (a spectral resolution of $R \sim 3,500$ through a 1" slit). The telluric standard stars were taken quasisimultaneously. The data were reduced with the IDL program SpexTool (Cushing et al. 2004). The flux calibration and telluric correction were performed with the IDL program that adopts the methods as described in Vacca et al. (2003).

On the other hand, some sources have UV spectra in the *HST* or *IUE* archives, where C IV BAL is present, confirming our detection of their He $I^*\lambda 3889$ absorption line.

A.6.1. Four Sources in the He $i^* \lambda 3889$ BAL Sample

J074554.74+181817.0. J0745+1818 is a FeLoBAL quasar at z = 1.054, which was first identified by G09. In its rest-frame UV spectrum, broad Mg II and Fe II absorption lines are seen. The Mg II absorption trough spans from -613 to -3,971 km s⁻¹, with a weighted-average velocity of -1,887 km s⁻¹. The associated He I* $\lambda\lambda$ 3889, 3189 absorption lines are first identified in this work, the detections of which are also confirmed by the NIR observation using TripleSpec on the Palomar P200 telescope. This NIR observation was performed on 2014 January 19, and four 240 s exposures were taken in A-B-B-A dithering mode. One telluric standard star was taken quasi-simultaneously.

J080248.18+551328.9 (Ji et al. 2014). J0802+5513 is identified as a LoBAL quasar by G09 based on the detection of Mg II absorption lines. Plenty of absorption lines are detected, including He I*, Fe II*, and Ni II*, which arise from metastable or excited levels, as well as resonant lines in Mg II, Fe II, Mn II, Ca II, and Mg I. All of these absorption lines are associated with the same profile of ~2,000 km s⁻¹ width centered at a common redshift of the quasar emission lines. Ji et al. (2014) studied this target in detail and determined that the absorber has a density of $n_e \sim 10^5 \text{ cm}^{-3}$ and a column density of $N_{\rm H} \sim 10^{21} - 10^{21.5} \text{ cm}^{-2}$ and is located at $\sim 100 - 250 \text{ pc}$ from the central SMBH. J0802+5513 is also included in our He I* λ 3889 absorption-line sample.

J084044.41+363327.8. This FIRST Bright Quasar Survey (FBQS) quasar was first reported by Becker et al. (1997) as a radio-moderate LoBAL. A spectropolarimetry study by Brotherton et al. (1997) reveals that it is a highly polarized BAL quasar. The spectrum of this quasar in the rest-frame wavelength range is dominated by the absorption lines of Fe II, and it also contains lines of the other singly ionized iron-group elements Si II, Mg II, Al III, and Fe III. According to de Kool et al. (2002), the outflow gas of this quasar covers a range of velocity from -700 to -3,500 km s⁻¹, with two components centered at -900 and -2,800 km s⁻¹. The low-velocity gas is determined to be a low-density gas $(n_e < 500 \text{ cm}^{-3})$ and is ~ 230 pc away from the AGN. The high-velocity gas shows a high density and is $\sim 1 \text{ pc}$ away from the AGN. This distance is determined by the absence of a detectable He $I^*\lambda 2830$ absorption line. In our sample, this quasar is classified as a He $1^*\lambda$ 3889 BAL, which is also confirmed by the NIR observation for the He $1^*\lambda 10830$ absorption line. The total column density and location of the absorption gas can be better determined via the He I* lines in combination with other lines. The NIR observation was carried out on 2014 January 17 using TripleSpec at the P200 telescope, and 4×180 s exposures were taken in A-B-B-A mode.

J120924.07+103612.0. LBQS 1206+1052 is reported by Ji et al. (2012) as a rare Balmer BAL quasar, and it also displays He I* Mg II absorption lines in the SDSS spectrum taken on 2003 March 24. Joshi et al. (2011) reported the significant variations over their observational run of ~ 4 hr. We performed a series of follow-up observations for this quasar. On 2012 May 7, LBQS 1206+1052 was observed with the Yunnan Faint Object Spectrograph and Camera (YFOSC) mounted on the Lijiang GMG 2.4 m telescope in a rest wavelength range of 2,500–5,400 Å. Compared with the SDSS spectrum, the absorption troughs fade over nine years. On 2014 April 23, this quasar was observed with a double spectrograph (DBSP) at the P200 telescope in the rest wavelength ranges of 2,250–4,180 and 5,620–7,450 Å. The states of the absorption lines show little variability relative to the YFOSC observation. An NIR observation was carried out on 2013 February 22 to obtain the He $I^*\lambda 10830$ absorption line profile, which shows a narrow faded He $1^*\lambda 10830$ absorption trough. This target is studied in detail in L. Sun et al. (2015, in preparation).

A.6.2. Two Example C IV BAL Quasars with Evident He 1*\3889 Absorption yet Weak Mg 11 Absorption

J035230.55–071102.3. J0352–0711 is known as 3C094, which is a steep-spectrum radio-loud quasar. The FUV spectrum for this quasar, which was obtained with the Faint Object Spectrograph on board the *HST* by Tytler & Davis (1995) using the G270H grating, shows a broad C IV absorption line. We detected the He I* λ 3889 absorption line in the SDSS spectrum. However, this quasar is not in our parent Mg II BAL sample because of the weakness of the Mg II absorption line. We observed this quasar using TripleSpec at the P200 telescope on 2012 February 23, and 4 × 180 s exposures were

SDSS Name	Z	$\beta_{[3k-4k]}^{a}$	$\log L3000$ erg s ⁻¹	$\log F_{2500} \\ \text{ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$	$\log F(\text{UV Fe II}) \\ \text{ergs s}^{-1} \text{ cm}^{-2}$	$FWHM(Mg \ II^b)^b \\ km \ s^{-1}$	$\log F(\text{Mg II} \ ^b)^c$ ergs s ⁻¹ cm ⁻²	$\log F(\text{Mg II}^{n})^{d}$ ergs s ⁻¹ cm ⁻²	$\log {M_{ m BH}}^{ m e}$ M_{\odot}	$L/L_{\rm Ed}$
J000009.26+151754.5	1.197	-1.30	45.4	-15.93	-14.40	2435	-14.68	-15.61	8.38	0.5
J002623.78+135523.5	1.319	5.03	45.39	-15.95	-13.47	2812	-14.38	-15.92	8.50	0.4
J004610.17+000449.7	0.826	-1.65	44.96	-15.93	-14.48	7771	-14.39		9.16	0.0
J005722.48+010101.8	1.146	-1.27	45.52	-15.74	-13.91	3239	-14.36	-15.94	8.69	0.3
J010352.46+003739.7	0.705	-0.75	45.43	-15.34	-13.08	2747	-13.66	-15.77	8.50	0.3

Table A2 UV Continuum and Emission-line Parameters of the Entire Parent Sample

Notes. 30

^a Continuum slope between ~3,000 and ~4,000 Å. ^b Line widths (FWHM) of broad component of Mg II emission line. ^c Flux of broad component of Mg II emission line. ^d Flux of narrow component of Mg II emission line.

^e Mass of SMBH derived by width of Mg II emission lines, and the formula used is Equation (10) in Wang et al. (2009).

(This table is available in its entirety in machine-readable form.)

Table A3
Optical Continuum and Emission-line Parameters of the $z < 0.8$ Objects in the Parent Sample

SDSS NAME	z	$\log L5100$ erg s ⁻¹	$FWHM (H\beta^b)^a$ km s ⁻¹	$ \begin{array}{c} \log \\ F\left(\mathbf{H}\beta^{b}\right) \\ \mathrm{ergs \ s}^{-1} \\ \mathrm{cm}^{-2} \end{array} $	$\log F (H\beta^n)^c$ ergs s ⁻¹ cm ⁻²	FWHM ([О ш]) km s ⁻¹	$\log F([O III])$ ergs s ⁻¹ cm ⁻²	$\log F$ (OpticalFe II) ergs s ⁻¹ cm ⁻²	$\log M_{ m BH} d$	$L/L_{ m Edd}$
J010352.46+003739.7	0.705	44.97	4964	-13.57	-15.54	-13.91	2913	-13.66	8.63	0.15
J014534.36+143136.9	0.636	44.27	7005	-14.37	-15.81	-15.03	803	-14.60	8.45	0.05
J023102.49-083141.2	0.587	44.18	3812	-14.23	-16.36	-14.78	1058	-14.16	8.11	0.08
J023153.64-093333.6	0.555	44.13	5557	-14.27	-16.08	-15.23	707	-14.50	8.27	0.05
J024220.10-085332.7	0.800	44.43	5939	-14.08	-15.37	-14.40	354	-14.50	8.45	0.07

Notes.

^a Line widths (FWHM) of broad component of $H\beta$ emission line.

^b Flux of broad component of H β emission line.

^c Flux of narrow component of $H\beta$ emission line.

^d Mass of SMBH derived by width of H β emission lines, and the formula used is Equation (11) in Wang et al. (2009).

(This table is available in its entirety in machine-readable form.)

Duplicate Spectroscopic Observations										
Object	Z	MJD	Plate	Fiberid	Observation Date	Source	He 1* Detection ^a			
J010352.46+003739.7	0.705	51816	0396	471	2000 Sep 29	SDSS	1			
		53726	2313	384	2005 Dec 22	SDSS	0			
		55214	3736	0522	2010 Jan 18	BOSS	0			
		55475	4226	0600	2010 Oct 06	BOSS	0			
J011117.34+142653.6	1.155	51821	0423	310	2000 Oct 04	SDSS	1			
		55835	5131	0054	2011 Oct 01	BOSS	0			

Table A4

Notes.

^a Detection of He 1* λ 3889 absorption line: "1" denotes a spectrum with He 1* λ 3889 absorption line; "0" denotes a spectrum that failed to detect the He 1* λ 3889 absorption line.

(This table is available in its entirety in machine-readable form.)



Figure A7. Multiepoch spectra of SDSS J14264704.7+401250.8 in the rest frame, in the Mg II region (left) and the He I* 3889 region. Spectra are smoothed with a two-pixel boxcar. Note that both the Mg II and He I* absorption become ever weaker with time.

taken in A-B-B-A mode. The significant He $i^*\lambda 10830$ absorption trough is seen in the NIR spectrum.

J141348.33+*440014.0.* PG 1411+442 is one of the nearest HiBAL quasars ($z_{em} = 0.0896$). It shows broad Ly α , N v, Si IV, and C IV absorption features in the UV spectrum

(Malkan et al. 1987; Wang et al. 1999). It is also known as a X-ray-quiet quasar because of substantial intrinsic absorption with $N_{\rm H} > 10^{23} \,{\rm cm}^{-2}$ (e.g., Brinkmann et al. 1999). PG 1411+442 is also a luminous infrared quasar with a total infrared luminosity of $\log L_{\rm IR} = 11.6 L_{\odot}$ (Weedman



Figure A8. SDSS spectra of the three sources, displaying significant changes in their Mg II absorption line.



Figure A9. Sources in our main sample that have NIR spectra.

et al. 2012). On 2014 January 17, this quasar was observed by TripleSpec at the P200 telescope, and 4×180 s exposures were taken in A-B-B-A mode. The He 1* λ 10830 absorption trough is seen in the NIR spectrum, which shares a common blueshift with the C IV absorption line. On 2014 April 23, this quasar was observed by DBSP at the P200 telescope in the rest-wavelength ranges of 3000–5400 and 7200–9500 Å, and 2 × 300 s exposures were taken. The He 1* λ 3889 absorption trough is detected in the NUV spectrum.

A.6.3. Six Sources in the Low-z BAL Sample Identified with He 1*\3889

J075217.84+193542.2. J075217.84+193542.2 is a Seyfert I galaxy at z = 0.117, which is the nearest target in our low-z He I* sample. We observed this target using TripleSpec at the P200 telescope on 2013 February 23, and 4×120 s exposures were taken in A-B-B-A mode. The He I* λ 10830 absorption line is detected in the NIR spectrum.

J093653.81+533127.0. J0936+5331 is a Seyfert 1 galaxy at z = 0.227. It is a low-z C IV HiBAL based on the detection of







Figure A11. Low-z He 1* BALs that have UV or NIR spectra.



Figure A12. Demonstration of the spectral fitting for all 52 sources that have Mg II, He $1^*\lambda$ 3889, and He $1^*\lambda$ 3189 absorption troughs. These spectra are smoothed by a three-pixel boxcar. The acceptable fittings of the unabsorbed spectrum of an object are denoted as green dotted lines, and their mean spectrum denoted as a red solid line.

(An extended version of this figure is available.)



Figure A13. Demonstration of the spectral fitting of the 49 He $1^*\lambda 3889$ BAL quasars without a He $1^*\lambda 3189$ absorption line detected. These spectra are smoothed by a three-pixel boxcar The symbols are the same as Figure A12. (An extended version of this figure is available.)

the C ivabsorption trough and the absence of the Mg II absorption feature in UV observations by *HST*. FUV and NUV spectra for this quasar were obtained with the COS G140L grating and the STIS G430L grating on board the *HST*,

respectively, by Lusso et al. (2014). We detected the He I* $\lambda\lambda$ 3189, 3889 lines in its SDSS spectrum, which have a blueshift in common with that of C IV. The NIR observation was carried out using TripleSpec at the P200 telescope on 2013

February 23, and 4×180 s exposures were taken in A-B-B-A mode. The expected He $i^*\lambda 10830$ absorption line is seen in the NIR spectrum.

J130534.49+181932.8. J130534.49+181932.8 is a low-z (z = 0.118) quasar. We detect the He I* λ 3889 absorption line in its SDSS spectrum. This source was also observed by the COS G140L grating and the STIS G430L grating on board the HST telescope in 2011 by Lusso et al. (2014). The C iv and Mg II absorption lines are detected in the FUV and NUV spectrum, and they have a blueshift in common with the He I* λ 3889 absorption line.

J153539.25+564406.5. J1535+5644 is a Seyfert I galaxy at z = 0.208. An He i* $\lambda\lambda$ 3189, 3889 and a rare H α absorption line are detected in the SDSS spectrum. The NIR observation was carried out using TripleSpec at the P200 telescope on 2013 February 23, and 4×180 s exposures were taken in A-B-B-A mode. The expected He $i^*\lambda 10830$ absorption line is seen in the NIR spectrum.

J163459.82+204936.0. J1634+2049 is а nearby (z = 0.1295) ultraluminous infrared galaxy with a total infrared luminosity of $\sim 1 \times 10^{12} L_{\odot}$, according to the photometry of IRAS. The star-formation rate (SFR) one gets from $L_{\rm IR}$ is ~ 120 M_{\odot} , but the [O II] shows that the SFR is normal. This quasar shows a red broadband SED relative to that of a composite spectrum of quasars. The reddening calculated from the decrement for narrow lines is much larger than that for broad lines, with $E(B - V)_{\text{narrow}} = 1.13$ and $E(B - V)_{\text{broad}}$ = 0.75. These narrow lines are mainly from the H π region, according to the BPT diagram. These properties suggest that this quasar is an obscured starburst quasar. He $1^*\lambda$ 3889 is detected in the SDSS spectrum, and, interestingly, a broad Na D absorption line is also detected, which indicates a large column density for the outflow gas. The NIR observation was carried out on 2012 April 15, using TripleSpec at the P200 telescope, and 4×120 s exposures were taken in A-B-Adithering mode. The expected He $i^*\lambda 10830$ absorption line is seen in the NIR spectrum, and strong P α and P γ emission lines are also detected. We will investigate this quasar in detail in a later paper (W.-J. Liu et al. 2015, in preparation).

J222024.58+010931.2. J2220+0109 is a type I quasar in the SDSS Stripe 82, and it shows significant variability (Meusinger et al. 2011). We detected deep and broad He $i^*\lambda\lambda 3189$, 3889 and weak Balmer absorption lines in the SDSS spectrum. The NIR observation was carried out using TripleSpec at the P200 telescope on 2011 October 21, and 4×300 s exposures were taken in A-B-B-A mode. The expected He $i^*\lambda 10830$ absorption line is seen in the NIR spectrum.

A.7. Demonstration of Fitting the He $I^*\lambda$ 3889 BAL Quasars

A.7.1. Sources Also with He $I^*\lambda$ 3189 Absorption Line

Here we demonstrate the spectral fittings of 52 He $i^*\lambda$ 3889 BAL quasars that have He $i^*\lambda 3189$ absorption troughs in their SDSS spectra; see Figure A12.

A.7.2. Sources without He $i^*\lambda$ 3189 Absorption Line

Here we demonstrate the spectral fittings of 49 He $I^*\lambda$ 3889 BAL quasars that have no He $1^*\lambda$ 3189 absorption troughs detected in their spectra; see Figure A13.

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