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Discovery of a variable broad absorption line in the BL Lac object PKS B0138−097 *

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Abstract We report the discovery of a broad absorption line (BAL) of $\sim 10^4$ km s^{-1} in width in the previously known BL Lac object PKS 0138−097, which we tentatively identified as an Mg II BAL. This is the first detection of a BAL, which is sometimes seen in powerful quasars with high accretion rates, in a BL Lac object. The BAL was clearly detected in its spectra spanning two epochs at a high luminosity state taken in the Sloan Digital Sky Survey (SDSS), while it disappeared in three SDSS spectra taken at a low luminosity state. The BAL and its variability pattern were also found in its historical multi-epoch spectra in the literature, but have been overlooked previously. In its high resolution radio maps, PKS 0138−097 shows a core plus a one-sided parsec-scale jet. The BAL variability can be interpreted as follows: The optical emission is dominated by the core in a high state and by the jet in a low state and the BAL material is located between the core and jet so that the BAL appears only when the core is shining. Our discovery suggests that outflows may also be produced in active galactic nuclei at a low accreting state.

Key words: galaxies: active — galaxies: absorption lines — BL Lacertae objects: individual (PKS 0138−097)

1 INTRODUCTION

Evidence accumulated in the past decade points to the phenomenon that feedback from active galactic nuclei (AGNs) plays a crucial role in galaxy formation and evolution. The accretion onto Super-Massive Black Holes (SMBHs) can release a large amount of radiative and kinetic energy to their surroundings. This may heat and expel the interstellar and intergalactic gas, which serves as the common reservoir for both SMBH growth and star formation and thus regulates the co-evolution of SMBHs and their host galaxies (see Antonuccio-Delogu & Silk 2010 for a recent review). It is suggested that the kinetic energy output through jets and outflows is at least as important as the radiative output in most AGNs (Begelman 2004 and references therein).

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The most energetic outflows in AGNs are broad absorption line (BAL) systems, with width $\gtrsim 2000\ \mathrm{km\ s^{-1}}$ by definition. They appear in the spectra of $\sim 15\%$ of optically selected quasars and are often observed as absorption by ions of C IV, Si IV, Al III and Mg II (Tolea et al. 2002; Hewett & Foltz 2003; Reichard et al. 2003; Trump et al. 2006; Gibson et al. 2009; Zhang et al. 2010). The velocity of BAL outflows is typically a few thousand $\mathrm{km\ s^{-1}}$ and, in the extreme case, can reach values as large as $v \sim 0.2c$ (Foltz et al. 1983). It is now commonly accepted that BAL and non-BAL quasars are physically the same and a BAL region (BALR) is present in all quasars but with a small covering factor (CF). The dichotomy of BAL and non-BAL quasars is attributed to an orientation effect: BALs are observed in those quasars only when our line-of-sight passes through the BALR. Such orientation models require a rather large inclination angle for BAL quasars with the BALR suggested to be an equatorial wind driven from the accretion disk (e.g., Hines & Wills 1995; Cohen et al. 1995; Goodrich & Miller 1995; Murray & Chiang 1995). Evidence for the orientation models includes: the similarity of the emission line spectra (Weymann et al. 1991) and the spectral energy distribution (SED; e.g., Willott et al. 2003; Gallagher et al. 2007) between BAL and non-BAL quasars; a small BALR CF inferred from the emission line profiles (Korista et al. 1993) and spectropolarimetric observations (e.g., Goodrich & Miller 1995; Cohen et al. 1995; Hines & Wills 1995; Ogle et al. 1999; Schmidt & Hines 1999). However, it has been shown that BAL quasars have on average higher accretion rates than non-BAL quasars (Ganguly et al. 2007; Zhang et al. 2010). This is difficult to understand in the context of the simple inclination models. In order to avoid the well-known inverse Compton catastrophe, Zhou et al. (2006) constrained the inclination angles of the outflows to be $\lesssim 20^\circ$ in six BAL quasars (see also Ghosh & Punsly 2007 for more examples), consistent with previous radio morphology studies (Jiang & Wang 2003; Brotherton et al. 2006). Follow-up XMM-Newton observations indicate that some of the polar BAL quasars are transparent in the X-ray, contrary to what is observed in "normal" BAL quasars (Wang et al. 2008). The nature of these mysterious polar BAL outflows is unclear, as is their relation with the relativistic jets.

Relativistic jets are believed to exist in radio-loud objects, accounting for about 10% of AGNs. The extreme objects are BL Lac objects, which are characterized by weak emission lines, rapid variability, high polarization and a compact radio structure (e.g., Stocke et al. 2000). BL Lac objects are extreme low-accretion ($\lesssim 10^{-2}$ of the Eddington ratio) AGNs with the relativistic jet pointing toward the observer (e.g., Blandford & Rees 1978; Urry & Padovani 1995). Low accretion rates may lead the accretion flows to be advection-dominated (Narayan & Yi 1995), thus the accretion models in most BL Lac objects might be an advection-dominated accretion flow (ADAF) or an ADAF in the inner region plus a standard thin disk (SD) in the outer region, i.e. the ADAF+SD scenario (Cao 2003).

In this paper, we report the discovery of a BAL in the classical low-frequency-peaked BL Lac object, PKS 0138$-$097, from the 1 Jy sample (Stickel et al. 1991). This is the first detection of a BAL in a BL Lac object, which provides a unique opportunity to study the possible relation between BAL outflows and jets. This BL Lac object is multi-waveband variable (e.g., Stickel et al. 1993; Stocke & Rector 1997; Rector & Stocke 2001; Barvainis et al. 2005) and highly polarized (P=6%–29%, Mead et al. 1990) and its host galaxy has remained unresolved in the optical (e.g., Stickel et al. 1993; Heidt et al. 1996; O'Dowd & Urry 2005) and in the NIR (Cheung et al. 2003). The BAL shows dramatic variability in its spectra from the Sloan Digital Sky Survey (SDSS; York et al. 2000) taken at five epochs, as well as from the previous spectra in the literature. We present a detailed spectral analysis in Section 2. The results are discussed in Section 3, together with future prospectives. Throughout this paper, we assume a cosmology with $H_0 = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\Omega_\mathrm{M} = 0.3$ and $\Omega_\Lambda = 0.7$.

2 BROAD ABSORPTION LINE AND VARIABILITY

The journals of the five SDSS spectroscopy observations are summarized in Table 1, together with those of three historical spectroscopy observations collected in the literature. The SDSS spectra are

Table 1 Journals of the Spectroscopic Observations and Measured Spectral Parameters of PKS B0138−097

Spec.	Date-Obs.	$F_{5000\text{Å}}$	$\mathrm{EW^B}$	$\mathrm{EW^N}$	Reference
LS86	1986/10	101	$\sim 3^a$	$1.23^{\,b}$	S93
KP95	1995/11/19,21	22		$\sim 1.1^c$	RS01
MMT96	1996/08/15	12		$\sim 1.1^c$	SR97
MJD 52174	2001/09/22	120	1.91 ± 0.31	1.29 ± 0.16	
MJD 53612	2005/08/30	16	$<0.56^d$	1.09 ± 0.08^e	
MJD 53729	2005/12/25	70	6.35 ± 0.35	1.36 ± 0.14	
MJD 54400	2007/10/24	23	$<0.56^d$	1.09 ± 0.08^e	
MJD 54461	2007/12/27	38	$<0.56^d$	1.32 ± 0.22	

$\mathrm{EW^B}$ and $\mathrm{EW^N}$: the observed-frame equivalent widths of the broad and narrow absorption lines in units of Å.

$F_{5000\text{Å}}$: continuum levels in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1}.

[a] $\mathrm{EW^B}$ is obtained by subtracting the average value of Mg II NAL equivalent widths from the total absorption equivalent width estimated from figure 2 in S93.

[b] the average value of Mg II NAL equivalent widths obtained from SDSS spectra.

[c] the absorption equivalent widths estimated from figure 3 in SR97 and figure 1 in RS01.

[d] $\mathrm{EW^B}$ is the 3σ upper-limit estimated from a spectrum fit for the low-state composite spectrum (MJD 53612, 54400 and 54461) using the broad absorption trough observed at MJD 53729.

[e] $\mathrm{EW^N}$ is measured from the composite spectrum of two low-state spectra (MJD 53612 and 54400).

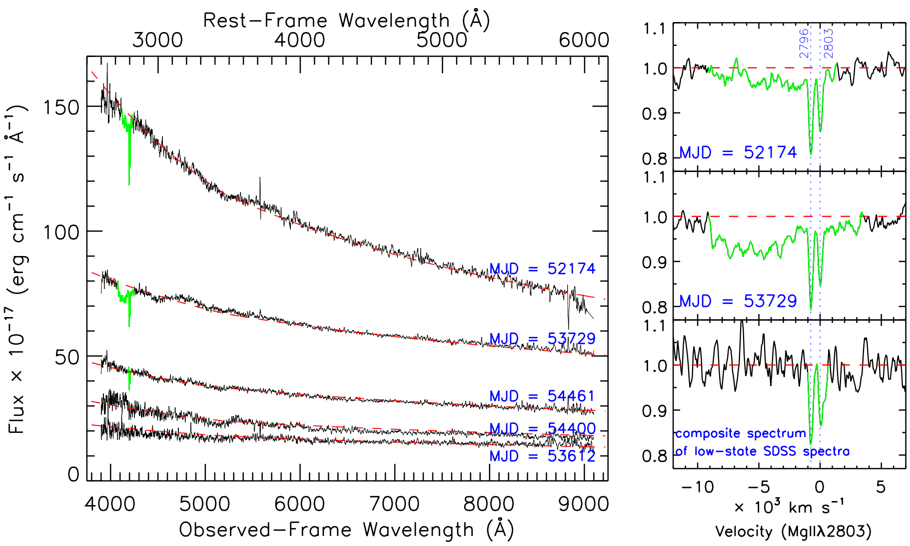

Fig. 1 *Left*: The five SDSS optical spectra of PKS B0138−097. The observed spectra from the SDSS are in black, we plot the broken power-law continuum in red and the absorption wavelength range in green. The rest-frame wavelength is transformed from the observed-frame wavelength using the absorption redshift $z_{\mathrm{abs}} = 0.5$. *Right*: The normalized spectra obtained by dividing the optical spectra by the broken power-law model continuum vs. velocity (relative to Mg IIλ2803Å), the absorption structure in green and the positions of Mg II$\lambda\lambda$2796,2803 by blue dotted lines. The red dashed lines mean the value equals 1.

displayed in the left panel of Figure 1, which are corrected for the Galactic reddening of $E(B-V) = 0.029$ mag (Schlegel et al. 1998). A prominent feature is a BAL, superimposed with a well-resolved Mg II$\lambda\lambda$2796.35,2803.53 doublet of narrow absorption lines (NALs) at a redshift of $z_{\rm a} = 0.5006 \pm 0.0001$. The Mg II doublet NALs are obvious in MJD 52174, 53729 and 54461, but can only be marginally detected in MJD 54400 and 53612 due to their low signal-to-noise ratio (S/N)[1]. The BAL shows a dramatic variability. It is detected in the earliest spectrum at the highest state, MJD 52174, but it disappeared in MJD 53612 at the lowest state; then it appeared again only about 100 days later in MJD 53729 at the second highest state with an enhanced strength; finally it disappeared when the continuum weakened in MJD 54400 and 54461.

It should be pointed out that the BAL detected in PKS B0138−097 does not strictly fulfill the conventional definitions, which require that the absorption trough must fall at least 10% below the model of continuum plus emission lines. Such a conservative criterion was first suggested by Weymann et al. (1991; see also Zhang et al. 2010 for a summary of BAL definitions) to ensure the flux deficit is not caused by improper modeling of the continuum and emission lines and/or low S/N. We note that as a BL Lac object, the spectra of PKS B0138−097 are nearly featureless except in the absorption line regime, which greatly simplifies the recovery of the absorption-free spectra. Besides, the high state SDSS spectra are of rather high quality with a median S/N$\sim 50\ {\rm pixel}^{-1}$. This enables us to measure the BAL with much improved significance than in the earlier quasar spectra. To further make sure that the BAL is real, we extracted the raw 1-d spectra of all the individual exposures of MJD 52174 and 53729, without flux calibration and with rejection of the deviant pixels. The feature persists in all of the individual spectra. This ensures that the BAL is not a false feature introduced by the SDSS spectroscopic pipeline. We examined the spectra of adjacent fibers; none of them shows a similar feature. Moreover, MJD 52174 and 53729 were observed using different plates. This excludes the possibility that the BAL was induced by either a CCD defect or improper CCD reduction. We also searched for spectroscopic data in the literature and found that three historical spectra are available (see Table 1). The BAL clearly shows itself in the spectrum observed at a high state by Stickel et al. (1993; their fig. 2, hereafter the reference is referred to as S93 and the spectrum as LS86). The BAL vanished in the spectra at a low state by Stocke & Rector (1997; their fig. 3, hereafter the reference is referred to as SR97 and the spectrum as MMT96) and Rector & Stocke (2001; their fig. 1, hereafter the reference as RS01 and the spectrum as KP95).

The BAL and its variability pattern can be seen clearly in the right panels of Figure 1, where the normalized SDSS spectra around the BAL feature are plotted against velocity relative to the Mg II NALs. The continuum level is estimated by fitting the spectra with a broken power law with the BAL masked. We plot the two high state spectra individually and combine the three spectra at the low states to increase the S/N. We calculated the observed frame equivalent width (EW) of the Mg II NALs and the BAL and listed them in Table 1. The strength of the Mg II NALs remains constant within the measurement errors in the five SDSS spectra, but the strength of the BAL changed dramatically from EW$= 6.35\pm0.35$ Å in MJD 53729 to EW$= 1.91\pm0.31$ Å in MJD 52174. Though the BAL strength trebled from MJD 52174 to 53729, the velocity structure largely remained the same, starting from $-v_{\rm min} \approx -3\times10^3\ {\rm km\ s^{-1}}$ to a maximum velocity of $-v_{\rm max} \approx 10^4\ {\rm km\ s^{-1}}$. We also estimated the BAL strength in LS86 and found EW≈ 3 Å, which is between that in MJD 52174 and 53729. Since there is no significant BAL in MJD 54461, 54400 or 53612 at a low state, we derived an upper limit of EW$\lesssim 0.56$ Å ($3\,\sigma$). Moreover, the total observed frame EWs estimated in KP95 and MMT96 are $\sim$1.1 Å, consistent with the average EW of Mg II NAL. This suggests that there is no BAL in the spectra of KP95 or MMT96, both of which have a continuum level similar to the two epoch SDSS spectra at the lowest state, MJD 53612 and 54400.

The identification of the BAL is not clear and neither is the redshift of the BL Lac object. The often quoted redshift of $z = 0.733$ is probably mis-estimated and is based on detection of weak

[1] We will denote the SDSS spectra using their Modified Julian Date of observations, MJD=JD–2400000.

emission lines in Mg IIλ2798, [Ne V]λ3426 and [O II]λ3727 and the stellar absorption doublet Ca II$\lambda\lambda$3933,3968 in KP95 (RS01) and MMT96 (SR97). Although we also detected the suspected weak signals of Mg II and [O II] in the composite of the three epoch SDSS spectra at a low state, this emission redshift is incongruous with the existence of the BAL. The deep R- and K-band imaging and the Hubble Space Telescope (HST) images reveal four nearby non-stellar objects, including a companion object within 1.44$''$ and three more fainter objects within 5$''$ from this BL Lac object (Heidt et al. 1996; Scarpa et al. 2000). The emission lines detected by RS01 and SR97 possibly come from the companion objects. Plotkin et al. (2010) assigned a lower limit of $z \approx 0.501$ to PKS B0138$-$097 from the Mg II doublet NALs. In a recent paper, Bergeron et al. (2011) confirmed the excess of intrinsic NAL in BL Lac objects using an enlarged sample of 38 BL Lac objects, including three candidates, and further reported a marginal excess (1.5$\,\sigma$) of associated/intrinsic absorbers with a velocity relative to the BL Lacs of $\sim 0.1c$. We would be able to avoid a chance coincidence for the Mg II NALs and the unknown BAL in PKS B0138$-$097, provided that the Mg II NALs are intrinsic to the BL Lac object and the BAL is Mg II. Otherwise, if the Mg II NALs were an intervening system, the BAL should be absorption of ions other than Mg^+. Then we would have a rather small probability for the two observed absorption features to coincide in wavelength in PKS B0138$-$097. For instance, if the BAL was a C IV BAL, which is most commonly seen in quasar spectra, we would have a posterior probability of $p \lesssim 1\%$ for the Mg II NALs occurring at the onset of the BAL. We therefore argue that the Mg II NALs are intrinsic to the BL Lac object and the BAL is Mg II BAL. We adopt this assumption and a systematic redshift of $z \approx 0.5$ in the rest of this paper. Note that most of the discussion in Section 3 is not dependent on such an assumption.

3 DISCUSSION AND SUMMARY

BAL variability is sometimes seen in quasar spectra and is useful for exploring the geometrical and physical properties and evolution of the BALR (e.g., Capellupo et al. 2010). The variability is often attributed to a change in the ionization state and/or in CF of the BALR (e.g., Lundgren et al. 2007; Gibson et al. 2009). Neither of the two precesses can naturally interpret what we observed in PKS B0138$-$097. On the one hand, we would need to turn the BALR on for the three-epoch spectra at a high state and to turn it off in the five-epoch spectra at a low state for the CF change scenario. On the other hand, photoionization timescales depend on both the variability of the energy input to the BALR and the density of the BALR. There is no way to fine-tune the exterior and interior conditions to adapt well to the observed BAL variability pattern. Normal Mg II BAL quasars tend to have a high accretion rate, but BL Lac objects are believed to have an extremely low accretion rate. These two kinds of BAL AGNs may have different accretion modes and, further, different origins and acceleration mechanisms of BALR. Instead of arising from the accretion disk as is generally believed in quasars, the BAL outflow in PKS B0138$-$097 is likely induced by the relativistic jet, as we discuss in the following.

PKS B0138$-$097 has a core plus a one-sided jet of parsec scale as shown in the high resolution radio map in the left panel of Figure 2 (Fey et al. 2005). The radio intensity ratio between the core and the jet is ~ 2.68. In the standard AGN unification schemes, BL Lac objects are described as Fanaroff Riley type I Radio Galaxies (FR-I RGs) with their relativistic jets pointed toward the observer (e.g., Blandford & Rees 1978; Urry & Padovani 1995). We may use M87, the adjacent FR-I RG with a well-resolved jet in multi-wavelength, as a guide line in our discussion. The radio through optical spectral index is $\alpha_{\rm ro} \sim 0.70$ for the core and $\alpha_{\rm ro} \sim 0.69$ for the jet ($S_\nu \propto \nu^{-\alpha_{\rm ro}}$; e.g., Wang & Zhou 2009; see also Meng & Zhou 2006 for more examples). Assuming these values, we obtained a rough estimate of the optical intensity ratio of $\sim$2.22 between the core and the jet in PKS B0138$-$097. This suggests that both the core and the jet may make a significant contribution to the observed optical continuum emission. It is easier for the BALR to obscure the core than to obscure the jet, since the jet is much more extended than the core. Instead of the variability of the CF or the ionization level

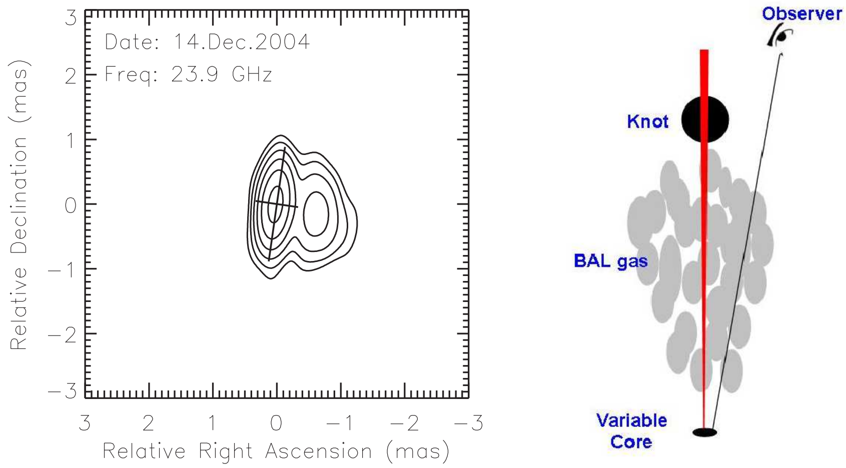

Fig. 2 *Left*: The VLBA radio map at 23.9 GHz of PKS B0138−097. Peak flux = 0.211 Jy beam^{-1}, rms_noise = 1.3 mJy beam^{-1} and the levels = 5, 10, 20, 40, 80 and 161 mJy beam^{-1}. *Right*: The edge-on viewing diagram of the jet and BAL winds. The gray clouds of the BAL winds are the gases entrained by the powerful jet. Nested inside is a relativistic jet in red. The core and knot of the jet are shown by black clouds.

of the BALR, the unusual BAL variability pattern observed in PKS B0138−097 likely results from the variable ratio between the emission components from the core and the jet. We create a diagram in Figure 2 to illustrate this simple scenario. The right panel shows the edge-on viewing of the jet and BAL winds. The BAL material is located somewhere between the core and the knot. When the optical emission is dominated by the core, the BAL feature appears, otherwise the BAL disappears.

It has been suggested that jet-cloud interaction is a common phenomenon in blazars at both small and large scales (Jones 1996; Yuan et al. 2000; Gómez et al. 2006; Araudo et al. 2009; Reynolds et al. 2009; Bergeron et al. 2011). This process may serve as a natural mechanism to accelerate gas to high velocity. That is possibly the reason for the BAL occurrence in BL Lac objects with extremely low accretion rates. The frequency of the BAL occurrence in BL Lac objects and its dependence on the BL Lac properties is unclear. We examine the optical and near-IR spectra of 20 objects with emission or absorption redshift $\min\{[z_{\rm emi}, z_{\rm abs}]\} \geq 0.4$ in all the 34 BL Lac objects in the well defined 1 Jy sample, but we do not find any other BL Lac objects showing BAL. The fraction of BAL occurrence in BL Lac objects is $\sim 5\%$ in the 1 Jy sample. Considering the non-detection of BAL because of the low spectrum S/N and strong BAL variability, such as PKS B0138−097, the true fraction of BAL BL Lacs is likely to be higher.

In this paper, we report the first detection of a BAL in a BL Lac object. The concurrence of Mg II NALs and the BAL suggested that the intrinsic redshift of this object is $z \sim 0.5$ and the BAL is Mg II BAL. However, these results are tentative and further confirmation is needed. The Mg II BAL appeared with a similar velocity structure in the two epoch optical spectra at a high state and disappeared in all the three low state spectra. The BAL material is suggested to possibly be located somewhere between the core and the knot and is accelerated when the jet propagates through it. The BAL variability is likely caused by the varying relative contribution of the continuum emission from the core and the jet. This scenario can be confirmed by detection of the expected correlation between the core emission and the BAL strength via high resolution radio mapping and optical spectrophotometric monitoring, respectively.

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