Deceleration of CIV and SiIV Broad Absorption Lines in X-Ray Bright Quasar SDSS-J092345+512710

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Abstract

We report a synchronized kinematic shift of CIV and SiIV broad absorption lines (BAL) in a high-ionization, radio-loud, and X-ray bright quasar SDSS-J092345+512710 (at \(z_{\text{em}} \sim 2.1627\)). This quasar shows two broad absorption components (blue component at \(v \sim 14,000\) km s\(^{-1}\), and red component at \(v \sim 4000\) km s\(^{-1}\) with respect to the quasar's systemic redshift). The absorption profiles of CIV and SiIV BAL of the blue component show a decrease in outflow velocity with an average deceleration rate of \(\sim 1.62^{+0.04}_{-0.05}\) cm s\(^{-2}\) and \(\sim 1.14^{+0.21}_{-0.22}\) cm s\(^{-2}\) over a rest-frame time span of 4.15 yr. We do not see any acceleration-like signature in the red component. This is consistent with dramatic variations usually seen at high velocities. During our monitoring period the quasar has shown no strong continuum variability. We suggest the observed variability could be related to the time dependent changes in disk wind parameters such as launching radius, initial flow velocity, or mass outflow rate.

Key words: galaxies: active – quasars: absorption lines – quasars: general – quasars: individual (J092345+512710)

1. Introduction

Outflows are ubiquitous and appear to be the main source of active galactic nucleus (AGN) feedback, which regulates black hole growth and host galaxy evolution as well as enrich the intergalactic and circumgalactic medium around galaxies (see Ostriker et al. 2010; Kormendy & Ho 2013). These feedback processes most likely drive the well-known observed correlation between the supermassive black hole (SMBH) mass and physical properties of the host galaxy, along with the steep decline in the number density of galaxies at high masses (Ferrarese & Merritt 2000; Hopkins et al. 2005; Ostriker et al. 2010). The signatures of strong outflows are directly observed in roughly 20% of quasar population via broad ultraviolet-resonance absorption lines (BAL; Weymann et al. 1991; Trump et al. 2006; Gibson et al. 2009), spanning a large range of outflow velocities from 1000 km s\(^{-1}\) up to several 10,000 km s\(^{-1}\) (e.g., Weymann et al. 1991; Hamann et al. 1997; Rodríguez Hidalgo et al. 2011; Rogerson et al. 2016). Nonetheless, many aspects of quasar outflows remain poorly understood, including the gas geometry, acceleration mechanism(s), and their influence on the host galaxy and its environments.

BAL variability study is a promising technique for constraining the structure and location of the associated wind. In recent systematic studies of BAL variability, BAL troughs are commonly observed to show variability in absorption strength (Barlow 1994; Lundgren et al. 2007; Gibson et al. 2008; Capelluto et al. 2011, 2012, 2013; Filiz Ak et al. 2013; Vivek et al. 2014; Grier et al. 2015; McGraw et al. 2018) and/or profile, also known as “transient BALs” showing emergence or disappearance of BAL features (e.g., Hamann et al. 2008; Hall et al. 2011; Rodríguez Hidalgo et al. 2011; Filiz Ak et al. 2012; Vivek et al. 2016; McGraw et al. 2017), over a broad range of rest-frame timescales, ranging from months to years. However, the signature of acceleration (e.g., kinematic shift of absorption profile) are more scarce, reported only a few times (e.g., Vilkoviskij & Irwin 2001; Rupke et al. 2002; Gabel et al. 2003; Hall et al. 2007; Joshi et al. 2014; Grier et al. 2016). Mechanisms proposed to understand the observed BAL variability invoke changes in ionization state and/or the movement of individual clouds or substructures in the outflow.

Also not all velocity components seen in absorption show correlated variations. This hints toward mechanisms other than photoionization induced variations. However, a unified understanding of BAL variations is an ongoing endeavor.

The BAL features are widely believed to be formed in “disk winds,” launched from the surface of the accretion disk at 10–100 light days from the central SMBH (of \(\sim 10^9 M_\odot\)) mainly driven by radiative forces (Arav & Li 1994; Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2014). In radiation-driven scenarios, the wind is efficiently accelerated to high velocities by invoking the shielding gas close to the base of outflow, which prevents the UV-absorbing gas from becoming overionized by nuclear X-ray and extreme-ultraviolet (UV) photons (Murray et al. 1995; Proga et al. 2000). The above paradigm is challenged by the observed flows having high velocities and lower degree of ionization in X-ray bright mini-BAL (typical full width half maximum of 500–2000 km s\(^{-1}\)) quasars (Hamann et al. 2008, 2013). These observations favor the substructured flow, involving tiny dense clouds with a low volume filling factor, driven out by radiative forces while being confined by magnetic pressure (Rees 1987; Baskin et al. 2014; Matthews et al. 2016). It suggests that the strong radiative shielding gas may not be a universal component of quasar outflows for accelerating the gas to high speeds. This idea is also supported by the recent high-energy X-ray observations showing that a large fraction, \(~6\%–23\%\), of BAL quasars
among the general BAL quasar population are perhaps intrinsically X-ray weak in nature (Luo et al. 2013, 2014; Teng et al. 2014; Liu et al. 2018).

The emerging picture of BAL outflows suggests that the mini-BALs and BALs arise from the same quasar wind, where BALs form in the main part of the outflow near the accretion disk plane while mini-BALs form along sight lines at higher latitudes (Ganguly et al. 2001; Hamann et al. 2008, 2013). This also explains the observed X-ray bright nature of mini-BALs. Interestingly, a new population of X-ray bright BAL quasars was recently discovered in X-ray surveys (e.g., Giustini et al. 2008; Gibson et al. 2009; Streblyanska et al. 2010; Liu et al. 2018), which further possess major challenges to the models of BAL outflows. Note that if the X-ray bright BAL quasars are preferentially originated in a structured flow viewed along the sight lines of higher latitudes, then one would naively expect to see the combination of line shift and line strength variability in this subclass. Indeed, in our recent efforts to probe the variability nature of X-ray bright BAL quasars, a systematic study of this rare population of X-ray bright BAL quasars will provide important observational constrains on the BAL geometry and the physical mechanisms for launching and accelerating the quasar outflows.

Here, we report the detection of a deceleration-like signature in C IV and Si IV BAL outflows toward X-ray bright quasar J092345+512710. This source is part of our ongoing monitoring program of BAL spectral variability in rare X-ray bright BAL quasars (see, Joshi et al. 2014). Given the X-ray weak nature of the general population of BAL quasars, a systematic study of this rare population of X-ray bright BAL quasars will provide important observational constrains on the BAL geometry and the physical mechanisms for launching and accelerating the quasar outflows.

2. Observation and Data Reduction

The BAL quasar J092345+512710 ($\z_{\text{em}} = 2.1627$) was first detected in the Sloan Digital Sky Survey (Trump et al. 2006), which we have followed with 2 m telescope at IUCAA Girawali Observatory (IGO), using IUCAA Faint Object Spectrograph and Camera (IFOSC). We performed a long-slit spectroscopic observation of this target on 2011 April 1. In order to cover the C IV and Si IV BAL troughs we have used Grism7 of IFOSC, in combination with a 1.5 arcsec slit. This yielded a wavelength coverage of 3800–6840 Å at a spectral resolution $R \sim 1140$ (i.e., $\sim 310 \text{ km s}^{-1}$). We acquired two exposures of 45 minutes each. The raw CCD frames were cleaned using standard IRAF6 procedures. We carried out the bias and flat-field corrections to all the frames. The Halogen flats were used for flat-fielding the frames. We then extracted the one-dimensional spectrum from individual frames using the IRAF task “apall.” Wavelength calibration was done using the standard helium–neon lamp spectra and flux calibration was done using a standard star observed on the same night. We applied air-to-vacuum conversion and coadded the spectra, using $1/\sigma^2$ weighting in each pixel, after scaling the overall individual spectrum to a common flux level. Subsequently the quasar was observed twice again as part of the SDSS-BOSS survey. This four-epoch data forms the main resource for the analysis presented here. Details are given in Table 1.

We also used photometric light curves from publicly available Catalina Real-Time Transient Survey7 (CRTS) to judge the amount of flux variations seen in this quasar.

2.1. Continuum Fitting

Following Gibson et al. (2009), we model the quasar continuum emission using a Small Magellanic Cloud-like reddened power-law function from Pei (1992). We use the emission redshift of $\z_{\text{em}} = 2.16274$ from Hewett & Wild (2010) to get the rest-frame quasar spectrum and fit only regions largely free from emission and absorption features, which are in the ranges 1280–1300 Å, 1700–1800 Å, 1950–2200 Å, 2650–2710 Å, and 2950–3700 Å. To the uncertainties over the continuum fit, we performed Monte Carlo simulations by randomizing the flux in each pixel with a random Gaussian deviate associated with uncertainty over the pixel. We fit the continuum to the new spectrum over 100 times and adopt their standard deviation as the uncertainties of the continuum fit.

In addition, to remove the emission line features, we model them using Gaussian profiles over continuum subtracted spectra, without associating any physical meaning. Note that modeling the C IV emission is nontrivial as the line profile is usually asymmetric and blanketed with multiple strong absorption features. Therefore, to model the C IV emission profile we exclude the wavelength ranges that have absorption signatures and fit the remaining C IV feature using a double Gaussian profile. We model the Si IV emission line with a single Gaussian. The final continuum fit (solid line), comprised of a power law for the line-free continuum and the multi-Gaussian components for the broad emission lines is shown in the top panel of Figure 1. The flux uncertainties from both the continuum fit and flux measurement errors were propagated to determine the final uncertainty on the normalized spectrum. Finally, we generate the continuum-normalized spectra to examine the BAL variability.

3. Analysis

J092345+512710 is a HiBAL quasar having smooth C IV and Si IV BAL profiles at a similar outflow velocity of $v \sim -9000$ to $-20,000 \text{ km s}^{-1}$ (see the top panel of Figure 1). We refer to this as the “blue” component (marked as “B” in Figure 1). We also detect N V absorption corresponding to that of the C IV BAL trough in the BOSS spectra of Epoch 3 and 4 at very blue part of the spectra having a poor signal-to-noise ratio (S/N). There is a hint of weak Ly$\alpha$ absorption at a similar velocity as the C IV BAL. In addition, we also detect associated C IV and N V absorption components with $v \sim -1000$ to $-6000 \text{ km s}^{-1}$ composed of several narrow components. We refer to this as the “red” component (marked as “R” in Figure 1). The Si IV is found to be weak in this component. We also searched for the additional BAL features in the spectrum but there are no Al III and Mg II BALs at the corresponding position of the C IV BAL trough.

In Figure 1, lower subpanels, we compare the continuum-normalized C IV and Si IV absorption line profiles (smoothed

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7 http://numku.caltech.edu/cgi-bin/getcssonedb_release_img.cgi
over 3 pixels) in the IGO spectrum obtained on MJD-55652 (Epoch 1) and SDSS spectrum from epoch MJD-52252 (Epoch 1), MJD-56607 (Epoch 3) with a reference BOSS spectrum obtained on MJD-57046 (i.e., year 2015), in velocity scale with $v = 0 \text{ km s}^{-1}$ corresponding to systemic redshift of the quasar, i.e., $z_{\text{em}} = 2.1627$. A decrease in radial velocity for both CIV and SiIV BAL troughs in the “blue” component is apparent in high S/N spectra between Epochs 1 and 4, over a rest-frame timescale of 4.15 yr. Interestingly, a clear signature of velocity shift for the C IV component is also seen in our low S/N IGO spectrum (see the left subpanels of Figure 1), over a rest-frame time span of 2.95 and 1.21 yr between Epochs 1 and 2 and Epochs 2 and 4, respectively. However, no such kinematic shift is seen between Epochs 3 and 4 over a relatively shorter rest-frame time span of $\sim 0.38$ yr. Additionally, for the “red” component that shows narrow substructures we do not find any kinematic shift, which ensures that the observed kinematic shift in the “blue” BAL trough is real. We note that our IGO (Epoch 2) spectrum is too noisy at shorter wavelengths where Si IV absorption is present, hence, we do not use it further to study the Si IV BAL variability. Unfortunately, as the N V region is not covered in the early epoch SDSS and IGO spectrum that prevents us from studying the kinematic shift of NV.

To quantify the kinematic shift of the BAL trough, specifically the blue component, between two epochs’ spectra, we perform a cross-correlation function (CCF) analysis (see also Grier et al. 2016). For this, we consider the spectral region including the BAL trough in question plus 2000 km s$^{-1}$ on each side and measure the cross-correlation coefficient ($\tau$) by shifting the early epoch spectrum with 1 pixel step (i.e., 69 km s$^{-1}$) over a velocity range of $-6000$ to $+6000$ km s$^{-1}$. We measure the velocity shift as the most significant peak in the correlation coefficient and the centroid of CCF using only points around the peak (i.e., with $\tau > 0.8 \tau_{\text{peak}}$). In order to account for the measurement uncertainties, we perform the Monte Carlo simulations, randomizing the fluxes of both spectra by a random Gaussian deviate associated with uncertainty over each pixel. We generate 1000 such realizations and measure the CCF and the corresponding peak and centroid for each realization of spectra. We take the median of the cross-correlation centroid distribution (CCCD) as final velocity shift and 1$\sigma$ uncertainty as the central interval encompassing 68% of CCCD. The measured CCF and CCCD for two spectra from Epochs 1 and 4 are shown in the lower-left and lower-right panels of Figure 2. The best velocity shift and the corresponding deceleration values between different epochs for C IV and Si IV components are given in columns 4, 5, and 8, 9 of Table 2, respectively. The average deceleration for the “blue” C IV BAL component is found to be $-1.62^{+0.04}_{-0.05}$ cm s$^{-2}$ between Epochs 1 and 4, over a rest-frame timescale of 4.15 yr. However, the average measured deceleration may not be constant over time. We measure a deceleration of magnitude $-1.18^{+0.16}_{-0.04}$ cm s$^{-2}$ between Epochs 1 and 2, which increase to $-1.61^{+0.30}_{-0.25}$ cm s$^{-2}$, only at the $\sim 1.3 \sigma$ level, between Epochs 2 and 4. A similar average deceleration is also observed for the Si IV BAL component (see column 9 of Table 2). We have also given the upper limits for the cases where no significant acceleration is detected. It is worth noting that based on very few cases of BAL kinematic shift reported in the literature (Gabel et al. 2003; Grier et al. 2016) the wind acceleration is not found to be constant when multiple epochs are compared.

Next, we test the variability in strength and/or shape of the BAL profile because the highly variable optical depths may also mimic the actual deceleration (specific to our case) signatures. For this, we perform a $\chi^2$ test between different epoch spectra by applying a measured velocity shift to the later epoch spectrum (see the top panel of Figure 2). The reduced $\chi^2$ and corresponding null probability $p$ of the BAL profile, which is similar between the two epochs for C IV and Si IV BAL components, are listed in columns 6, 7, and 10, 11 of Table 2, respectively. The higher value of $p$ would imply that the C IV BAL profile is similar between Epoch 1 via-a-vis 2 and Epoch 2 via-a-vis 3 but show a significant variability between Epochs 1 and 3 and Epochs 1 and 4. Similarly, the probability of the Si IV BAL profile to be different between Epochs 1 and 3 is less than 10%, whereas, a significant difference between Epoch 1 and 4 is shown (see also Table 2). A similar trend can also be seen from the measured rest-frame C IV ($W_{1549}$) and Si IV ($W_{1400}$) equivalent width between different epochs, listed in columns 6 and 7 of Table 1. The change in $W_{1549}$ between Epochs 1 to 2 and Epochs 2 to 3 is significant at only the 2.7$\sigma$ and 2.3$\sigma$ levels, respectively. For Si IV BAL, the difference in $W_{1400}$ between Epochs 1 and 3 is marginal (at 1.0$\sigma$) but between Epochs 1 and 4 is significant at the 5.5$\sigma$ level. Note that both C IV and Si IV absorption do not show saturation, which either implies an optically thin absorption or partial coverage. Since, Si IV optical depth is smaller than C IV and both absorptions are well detached from the corresponding emission it is indicated that Si IV is optically thin even if C IV is saturated. While the overall profile shape has not changed, the equivalent width ratio of Si IV/C IV has changed by up to a factor of two (see column 8 of Table 1). Since C IV may be saturated, as a result its profile variation will be minimal.

| Instrument | Date (Epoch,yy:mm:dd) (MJD) | Exposure Time (minutes) | Resolution (km s$^{-1}$) | S/N$^a$ | $W_{1549},b$ (Å) | $W_{1400}$ (Å) | $W_{1549}/W_{1400}$ |
|------------|-----------------------------|-------------------------|--------------------------|--------|------------------|-----------------|------------------|
| SDSS       | 52252 (#1, 2001.09.12)       | 80 × 1                  | 150                     | 11     | 14.0 ± 0.5       | 9.4 ± 0.5       | 1.5 ± 0.1        |
| IGO/IFOSC  | 55652 (#2, 2011.07.01)       | 45 × 2                  | 310                     | 4      | 17.7 ± 1.3       | 11.8 ± 1.1      | 1.5 ± 0.2        |
| SDSS-BOSS  | 56607 (#3, 2013.11.11)       | 75 × 1                  | 150                     | 14     | 20.8 ± 0.3       | 8.8 ± 0.3       | 2.5 ± 0.1        |
| SDSS-BOSS  | 57046 (#4, 2015.24.01)       | 90 × 1                  | 150                     | 11     | 19.1 ± 0.4       | 6.1 ± 0.4       | 3.1 ± 0.2        |

Notes.

$^a$ Signal-to-noise ratio per-pixel over the wavelength range of 5100–5500 Å.
$^b$ $W_{1549}$ is measured over a velocity range of $-22.576$ to $-8735$ km s$^{-1}$.
$^c$ Wavelength Coverage of 3800–6840 Å.
compare to the Si IV when there is any change in ionizing condition (either due to quasar luminosity change or cloud density or change in the distance between the absorbing gas and quasar). It is also clearly evident from Figure 1 that overall shape of the absorption profile of the C IV and Si IV BALs is quite similar over all the epochs, except for a moderate broadening of C IV BAL in Epochs 3 and 4. CRTS V-mag light curve is available between MJD 53700 and 56545, which does not show any systematic brightening/dimming of the source though short timescale fluctuations may be present. The mean V-mag is 19.22 with a σ of 0.49 mag. Thus the long timescale equivalent width variations may not be linked to quasar flux variation.

The main point to understand now is the deceleration-like signature shown by the “blue” component with a very similar profile at different epochs albeit having mild evolution in the observed rest equivalent widths. In the following section, we consider different possibilities.

4. Discussion and Conclusions

We report on the kinematic shift of C IV and Si IV BAL profiles in a radio-loud quasar SDSS-J092345+512710. This quasar belongs to a rare subclass of X-ray bright BAL quasars with a neutral hydrogen column density of $N_H < 3 \times 10^{22} \text{ cm}^{-2}$ and an optical to X-ray spectral index,
\( \Omega_{\text{ox}} \), of \(-1.59\) which is greater than the typical \( \Omega_{\text{ox}} \) measured for soft X-ray weak quasars, i.e., \( \Omega_{\text{ox}} < -2 \) (Giustini et al. 2008). In addition, the difference between observed \( \Omega_{\text{ox}} \) and expected \( \Omega_{\text{ox}} \) from the UV luminosity, i.e., \( \Delta \Omega_{\text{ox}} \), is found to be 0.04 (Giustini et al. 2008). We detect an average acceleration-like signature of \(-1.62^{\pm0.04} \pm0.08 \text{ cm s}^{-2} \) and \(-1.14^{\pm0.22} \text{ cm s}^{-2} \) in C IV and Si IV BALs trough, respectively, over a rest-frame time span of 4.15 yr (Table 2). We do not find any acceleration signature for the “red” component. Interestingly, we find that the measured deceleration for “blue” C IV BAL may not be constant over time, the rate of deceleration between Epochs 2 and 4 is more rapid, about a factor of 1.4 (significant at only the 1.3σ level) higher than Epochs 1 and 2.

In the handful of previous studies of the kinematic shift in individual objects Vilokovskij & Irwin (2001), Rupke et al. (2002), and Hall et al. (2007) have measured a positive kinematic shift (i.e., acceleration) of BAL with a typical acceleration rate of \(0.035 \pm 0.016 \text{ cm s}^{-2} \), \(0.08 \pm 0.03 \text{ cm s}^{-2} \), and \(~0.0154 \pm 0.025 \text{ cm s}^{-2} \) respectively. The first detection of negative kinematic shift (i.e., deceleration) was reported by Gavel et al. (2003) in the Seyfert galaxy NGC 3783. Using the multiepoch observations they have found a synchronous kinematic shift of C IV, Si IV, and N V absorption features, while preserving the absorption profile, with a varying deceleration rate that rises from \(-0.1 \pm 0.03 \text{ cm s}^{-2} \) to \(-0.25 \pm 0.05 \text{ cm s}^{-2} \) in the later interval. In addition, Joshi et al. (2014) have detected a relatively larger deceleration rate of \(-0.7 \pm 0.1 \text{ cm s}^{-2} \) and \(-2.0 \pm 0.1 \text{ cm s}^{-2} \) of C IV BAL in two X-ray bright BAL quasars over rest-frame time spans of 3.11 and 2.34 yr. Recently, Grier et al. (2016) performed the first systematic search for BAL acceleration using three epoch SDSS spectra of 140 BAL quasars over timescales of 2.5–5.5 yr and found only three cases, two acceleration and one deceleration, of monolithic velocity shift showing an overall lack of widespread BAL acceleration. They have measured an average acceleration/deceleration rate of \(0.63^{+0.14}_{-0.13} \text{ cm s}^{-2} \), \(0.54 \pm 0.04 \text{ cm s}^{-2} \) and \(-0.83^{+0.19}_{-0.24} \text{ cm s}^{-2} \) which is comparable to the present study. Using the upper limits for C IV BAL acceleration and deceleration in 76 BAL troughs, over a rest-frame timescale of 2.5–5.5 yr, they show that the majority of BALs exhibit stable mean velocities to within about 3%. Interestingly, for all three cases, they have found that the wind acceleration rate is not constant over time.

The observed kinematic shift in BAL can be produced due to several reasons, e.g., actual line-of-sight acceleration of a shell of material from an intermittent outflow, directional shift in the outflow, and changes in velocity dependent quantities such as ionization state or covering factor (Hall et al. 2002, 2007; Gavel et al. 2003). At first, we consider the simplest case of changing radiation energy, which will lead to a decrease in the injected momentum and thus will slow down the wind. As mentioned before using the CRTS light curve we find that our source shows a negligible variation, less than an order of half a magnitude, over the time spanned by our observations. In addition, we do not see any significant variation in the emission line flux that responds to the continuum. So we conclude that change in radiative energy/momentum may not be the primary source of deceleration.

Second, we consider the possibility of gravitational force for the bulk radial deceleration of the flow. Most of the accretion disk wind models predict the BAL outflow at a typical distance of 0.01 pc from the central source (Murray et al. 1995; Proga et al. 2000), whereas the observations suggest that the outflows are located at much larger distances in the range of parsecs to several kiloparsecs. Recently, using the Si IV BAL trough, Xu et al. (2018) have shown that more than 75% of BAL outflows are at >100 pc (see also Arav et al. 2018, and references therein). Given that the central black hole mass of J092345+512710 is \(3 \times 10^9 M_\odot \) (Shen et al. 2011) and assuming that the absorbing cloud is at a typical distance of 1 pc from the central ionizing source where gravity is mainly dominated by the black hole, at the SDSS Epoch 1, we find that the escape velocity is much lower (\(~5081 \text{ km s}^{-1} \) than the average outflow speed of \(15,000 \text{ km s}^{-1} \). This indicates that the observed deceleration-like signature of the outflow is very unlikely to be caused by the deceleration of continual flow due to gravitational force. Simultaneous coverage of different ions at high signal-to-noise and spectral resolution is needed to constrain the distance of the absorbing gas from the quasar.

Alternatively, if we consider the absorbing clouds to be at larger distances, it is quite plausible that the outflowing gas may interact with the ambient material in the host galaxy which in turn may cause the deceleration of BAL winds (see Leighly et al. 2014). In such a scenario, the interaction will also change the ionization and thermal state of the gas, thereby introducing profile variation. This is not evident from the observed BAL profiles. In view of the fact that the majority of BALs are stable within 3% of their mean velocity, Grier et al. (2016) argue that the BAL cloud may not have traveled sufficiently far to interact with the ambient medium. However, more such examples of BAL deceleration will be crucial to test this scenario.
In disk wind models, the BAL profiles are not only produced in a steady smooth wind (Murray et al. 1995), but also in unsteady clumpy flows (Proga et al. 2000; Proga & Kallman 2004) and magnetically confined disk wind (Arav & Li 1994; de Kool & Begelman 1995). In a case of steady wind for which the density and velocity as a function of radius is governed by force equation (balance between radiative acceleration and gravity) and mass and momentum conservation at all radial distances \( r \), it is known that parameters such as the initial injection position and velocity of the wind and mass outflow rate will alter velocity and density at a radial distance from the quasar (for example, see the basic set of equations given in Section 2.4.2 of Borguet & Hutsemékers 2010). Therefore, even if the quasar luminosity does not change, any time variation in the initial condition of the wind (launch radius, initial velocity, and mass outflow rate) can lead to acceleration or deceleration signatures (see Section 4.1 of Grier et al. 2016). It may be noted that absorption profile change introduced by the radial velocity profile change and the associated density profile change due to the continuity equation will also produce ionization change effects (even when the radiation field remains constant). Therefore, while producing velocity shift, one will have independent constraints from the equivalent width and equivalent width ratio variations.

Proga et al. (2000) have shown that the outflowing disk wind is self-shielded and unsteady, and it is radially accelerated to relatively high velocities by the UV radiation. In addition, such a wind can be spatially inhomogeneous having velocity and time dependent partial coverage (see also Dyda & Proga 2018a, 2018b, for 3D axisymmetric disk wind simulations). This variable covering factor may also lead to the apparent profile shape variations (Proga et al. 2012). Interestingly, Waters & Proga (2016) have shown that the acceleration by the radiation pressure is very efficient when flux is time dependent, it can lead to a large change of about a factor two in the net acceleration for a small flux variation of \( \sim 20\% \). Given the fact that the optical flux is not a perfect tracer of the line-driving flux and that quasars may show a higher amplitude variability in UV (Welsh et al. 2011), it is possible that observed deceleration-like signature can also be produced in the time dependent disk winds.

Alternatively, the disk wind may involve many small self-shielded clouds with low volume filling factor, driven out by radiative force, while being confined by magnetic pressure (de Kool & Begelman 1995). Not only can the magnetically confined clouds maintain a roughly constant density and ionization across the acceleration region (de Kool 1997), but they also have superthermal velocity dispersion and therefore only a few of them can explain the observed broad and smooth BAL profiles (Bottorff & Ferland 2000). In view of the X-ray bright nature of J092345+512710, the BAL troughs may favor the small clouds scenario instead of the homogeneous radial outflows, producing the observed velocity shift due to acceleration or change in covering factor and/or optical depth. Therefore, disentangling these effects would further require variability follow-ups. Also, high signal-to-noise spectra at higher spectral resolution will be important to further constrain the outflow models.

In our BAL variability studies of X-ray bright BALQSOs until now we have found significant profile shift in three cases. Joshi et al. (2014) reported two cases of deceleration-like signatures. Unlike in the present case the deceleration is also accompanied by profile shape variation in the other two cases. However, there are few common trends we notice in all three cases: (i) The decelerating components typically have large ejection velocities (i.e., > 10,000 km s\(^{-1}\)), (ii) There is associate absorption at low velocities without showing any signatures of acceleration. (iii) The optical quasar continuum has not varied appreciably. Additionally, it is intriguing that we have not yet seen acceleration signatures in X-ray BALs combined with the fact of high frequency of occurrence of deceleration-like signatures in them compared to the X-ray weak typical BALs. Confirmation of this trend in a large sample will be interesting for understanding the physical origin of X-ray loudness (or weakness) of BAL quasars.

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