C IV absorption line variability in X-ray bright BALQSOs

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ABSTRACT

We report kinematic shift and strength variability of C IV broad absorption line (BAL) trough in two high-ionization X-ray bright QSOs SDSS J085551+375752 (at \(z_{\text{em}} \sim 1.936\)) and SDSS J091127+055054 (at \(z_{\text{em}} \sim 2.793\)). Both these QSOs have shown combination of profile shift, appearance and disappearance of absorption components belonging to a single BAL trough, which we argue that they can be explained by combination of transverse and curved path motion of many small clouds. Our results supports the BAL outflow models involving many small self shielded clouds with low volume filling factor rather than a conventional single homogeneous continuous radial outflows. We found an average deceleration of \(-0.69 \pm 0.09\) cm s\(^{-2}\), \(-1.96 \pm 0.09\) cm s\(^{-2}\) over a rest-frame time-span of 3.11 yr and 2.34 yr for SDSS J085551+375752 and SDSS J091127+055054, respectively. To our knowledge, these are largest kinematic shifts exceeding by factor 2.8, 7.8 than the highest deceleration reported in the literature; making both of them as a potential candidate to investigate outflows using multi-wavelength monitoring for their line and continuum variability.

Key words: galaxies: active - quasars: absorption lines - quasars: general quasars: individual: J085551+375752, J091127+055054.

1 INTRODUCTION

About 10–20 per cent of the QSO population shows strong blueshifted broad absorption lines (BALs), with velocity widths greater than 2000 km s\(^{-1}\) and typical outflow velocities of 1000–30,000 km s\(^{-1}\) (e.g., Weymann et al. 1991). This has been interpreted as a signature of outflows from the accretion disc. Outflows play an important role on controlling the growth of the central massive black hole, the evolution of the host galaxy and the chemical enrichment of the inter-galactic medium (e.g., Ostriker et al. 2010). However, the basic physical conditions, acceleration mechanism(s), location and three dimensional structure of QSO outflows are poorly understood. Line variability study is one of the powerful methods which can provide useful insights into structure and dynamics of the outflowing gas. In case of BAL QSOs such line variability are commonly reported as changes in absorption strength (e.g. Hamann et al. 1997; Srianand & Petitjean 2001; Misawa et al. 2005; Lundgren et al. 2007; Hall et al. 2011; Capellupo et al. 2012a,b, 2013; Filiz Ak et al. 2013); and/or appearance, disappearance of absorption trough (e.g., Hamann et al. 2008; Rodríguez Hidalgo et al. 2011; Vivek et al. 2012a,b; Hamann et al. 2013). However, the kinematic shift in BAL profiles have also been seen in very few cases (e.g., Vilkoviskij & Irwin 2001; Gabel et al. 2003; Hall et al. 2007). The observed behavior of appearance or disappearance of BAL trough, their absorption strength variation and the kinematic shift in absorption profile are most readily understood as a result of (i) changes in the ionization state as a function of velocity in a fixed outflow; (ii) changes in the acceleration profile and/or geometry of the outflow due to change in the driving force or mass-loss rate; (iii) by actual line of sight acceleration of a shell of material from an continual flow; and, (iv) due to transverse motion of the absorbing cloud(s) relative to the line of sight (Gabel et al. 2003; Hall et al. 2007; Lundgren et al. 2007; Capellupo et al. 2011; Vivek et al. 2012a).

In a general scenario, BAL outflows are believed to arise from QSO’s accretion disc and driven by the radiation pressure (Arav & Li 1994; Murray et al. 1995; Proga & Kallman 2004). However, the required radiation to push the outflow at high relativistic speed may also over-ionize the gas and hence make it transparent to the radiation that drives the flow. This problem is resolved by proposing the ra-
diative shield only to be close to the base of the outflow (Murray et al. 1995). This has also been used to explain the X-ray weakness of BAL QSOs compared to normal QSOs by attributing the X-ray weakness to the absorption due to high $N_H$ column densities in the range of $10^{22} - 10^{24}$ cm$^{-2}$, due to a radiative shield closer to the disc plane (e.g., Gallagher et al. 2006; Stalin et al. 2011). However, origin of X-ray weakness in BAL QSOs is a matter of debate till now.

Further, the observations of narrow absorption line outflows ($\sim$ 2000 km s$^{-1}$, some times refer to as “mini-BALs”) have extended the above canonical picture by assigning these mini-BAL outflows to the sight lines at higher latitudes that perhaps skim the edge of main BAL flows farther above the disc (Ganguly et al. 2001; Hamann et al. 2008). This was also supported by the observed weak X-ray absorption in mini-BALs, if the X-ray absorbers resides primarily near the accretion disc as proposed above. Additional complication arises when we consider that mini-BALs also posses the very high speed and moderate ionization as normal BALs, even without the protection of a radiative shield (Hamann et al. 2013). This might suggest that shield may not be a critical feature of the wind, and hence, perhaps the models involving continuous flow with radiative shield may need replacement with the models involving many small self shielded clouds with low volume filling factor and driven out by radiative force while being confined by magnetic pressure (de Kool & Begelman 1995; Rees 1987). Such clouds with magnetic confinement are also shown to have super thermal velocity dispersion and therefore only few of them can explain the observed broad and smooth BAL profiles (e.g., see Bottorff & Ferland 2000; Hamann et al. 2013). In such mechanism one would expect mixing of line shift and line strength variability introduced by small multiple clouds in contrast to smooth variability in models of homogeneous outflows. The observational signatures for such scenarios are still awaited, for which study of BAL QSOs having broad absorption trough (like normal BALs) as well as being X-ray bright in nature (like mini-BALs) will be ideal candidates. Interestingly, such new population of X-ray bright BAL QSOs have been discovered in recent X-ray surveys (e.g., Giustini et al. 2008; Gibson et al. 2009; Streblyanska et al. 2010; Stalin et al. 2011). The line-variability study of these sources may provide some useful hints towards understanding of above issues of outflow kinematics including the key question of BAL QSOs being overall X-ray weak (i.e., intrinsic or absorbed).

Recently, we have started a pilot project for the spectral variability monitoring of 10 high-ionization BAL QSOs detected in X-rays from the compilation of Giustini et al. (2008), Gibson et al. (2009) and Streblyanska et al. (2010). This sample has been constructed with the BAL QSOs having (i) optical to X-ray spectral index, $\alpha_{ox}^1$, greater than -1.8; (ii) the SDSS $g_{mag} < 19.0$, to achieve a good signal to noise ratio with 2-m class telescopes, in a reasonable time-limit; and (iii) the redshift range of approximately 1.6 < $z$ < 3.6, in order to cover the C iv BAL trough in spectral range of 3800 – 6840 Å found most suitable in our observational plan (see below). Among our full sample we found two interesting cases of C iv BAL trough variation, here we present a detailed analysis of these systems. The detail results based on our full sample will be presented elsewhere.

This paper is organized as follows. Section 2 describes our analysis including observations, data reduction and spectral analysis. In Section 3, we present the results of our analysis, followed by a discussion and conclusion in Section 4.

2 ANALYSIS

2.1 Observation and Data Reduction

The observations were carried out using the IFOSC mounted on the 2 meter telescope in IUCAA Girawali Observatory (IGO). We have taken a long-slit spectra covering the wavelength range 3800–6840 Å using Grism$^2$ #7 of IFOSC with a resolution R ~ 1140, to cover the C iv and Si iv lines, respectively. A slit width of either 1.0 or 1.5 is used. Typical seeing during our observations were around 1.5–2.0”.

The raw CCD frames were cleaned using standard IRAF$^3$ procedures. The Halogen flats were used for the flat fielding the frames. We then extracted the one dimensional spectrum from individual frames using the IRAF task “apall”. Wavelength calibration of the spectra was performed using Helium-Neon lamp. The spectrophotometric flux calibration was done using standard stars and assuming a mean extinction for the IGO site. In cases of multiple exposures we coadded the flux with 1/$\sigma_i^2$ weightage, where $\sigma_i$ is the error on the individual pixel. The error spectrum was computed taking into account proper error propagation during the combining process. The spectrum was corrected to vacuum helio-centric frame.

The reduced one-dimensional spectra of QSOs for the comparison were downloaded from the SDSS and SDSS-BOSS Data Archive Server$^4$. Details about the SDSS spectral information can be found in York et al. (2000). Briefly, these SDSS spectra cover a spectral range from 3800 to 9200 Å, with a resolution $(\lambda/\Delta\lambda)$ of about 2000 (i.e. 150 km s$^{-1}$). The BOSS spectra have wavelength coverage between 3600 – 10000 Å at a resolution of 1300 – 3000 (see Dawson et al. 2013), as listed in column 5 of Table 1.

2.2 Continuum Fitting

In order to have accurate measurements of variability in absorption lines, one needs to carefully take into account the continuum as well as the emission line flux. This is necessary because of uncertainties in the flux calibration and possible real changes in the QSO emission lines. To model the continuum over the spectrum comprising of the broad C iv

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1 Ratio between the monochromatic luminosities $L_\nu$ at 2 keV and $L_\nu$ at 2500 Å as, $\alpha_{ox} \equiv 0.3838 \log \left( \frac{L_\nu (2 \text{ keV})}{L_\nu (2500 \text{ Å})} \right)$

2 http://www.iucaa.ernet.in/∼iptp/etc/ETC/help.html#grism

3 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4 http://data.sdss3.org/bulkSpectra
absorption line region in the rest wavelength range between 1270 and 1800 Å, first we have used a single power law, i.e., $a\lambda^{-\alpha}$, along with a lower (e.g., second) order polynomial, constrained by the measured flux in emission and absorption free regions namely 1323 – 1338 Å, 1440 – 1450 Å (except for J085551+375752 having absorption) and 1680 – 1800 Å in QSOs rest-frame. We use the emission redshift, $z_{em}$, from Hewett & Wild (2010), who have refined the SDSS emission redshift values by reducing the net systematic errors by almost a factor of 20, attaining an accuracy of up to 30 km s$^{-1}$.

Since, we aim to measure the absorption line variability, it is imperative to take into account any emission line flux variation as well. For this we also carry out simultaneous fit$^{5}$ of emission lines with multiple Gaussian profiles without associating any physical meaning to them. However, fitting the C iv emission line profile over the spectra already normalized with our power law fit (see above). All other emission features in the spectrum, such as (i) the iron emission blend (marked as B BO in the SDSS spectrum) apart from the above absorption features in the emission line region which makes the estimation of QSO continua highly uncertain. Therefore, first we masked the wavelength regions having absorption signature and then used between one to three Gaussian to define the C iv line profile over the spectra already normalized with our power law fit (see above). All other emission features in the spectrum, such as (i) the iron emission blend redward of the C iv emission line, especially in the range 1500 – 3500 Å (e.g., Vanden Berk et al. 2001); (ii) the Si iv emission line and any other feature similar to the emission line profile are modelled with a single Gaussian. Lower panels in Fig. 1, 2, respectively show our fit for J085551+375752 and J091127+055054, of the final continuum fit (the dashed line) comprising of a power law, a lower order polynomial and the multi-Gaussian components.

To estimate the spectral variability, the highest signal-to-noise ($S/N$) ratio BOSS spectra, is selected as a reference spectra for comparison with SDSS and IGO spectra. Both the SDSS and BOSS data have similar spectral resolution, however, while comparing two spectra with different resolution such as SDSS/BOSS spectra (i.e., FWHM $\sim$ 2.5 Å) with IGO (i.e., FWHM $\sim$ 4.4 Å) we have degraded the higher resolution spectra to the lower one.

### Table 1. Log of observations and other basic parameters of the spectra

| QSO          | Instrument | Date (MJD) | Exposure Time (min) | Resolution (km s$^{-1}$) | S/N |
|--------------|------------|------------|---------------------|--------------------------|-----|
| J0855+3757   | IGO/IFOSC  | 55606      | 45 $\times$ 2       | 310                      | 15  |
| J085551+3757 | IGO/IFOSC  | 55606      | 45 $\times$ 2       | 310                      | 15  |
| J091127+0550 | IGO/IFOSC  | 55930      | 45 $\times$ 10$^c$  | 310                      | 48  |

$^a$ Signal-to-noise ratio over the wavelength range 5800–6200 Å.

$b$ Wavelength Coverage of 3800–6840 Å.

$c$ Among them 5 exposures belongs to observation taken after two days i.e., on MJD 55932.

### 3 RESULTS

#### 3.1 J085551+375752

The optical spectrum of J085551+375752, plotted in Fig. 1, shows a distinct BAL trough of C iv at $z_{abs} \sim$ 1.746, with a BALnicity index (BI, Weymann et al. 1991) of 1296 km s$^{-1}$ (Streblyanska et al. 2010) and an absorption index (AI, Hall et al. 2002) of 1482 km s$^{-1}$ (Trump et al. 2006). However, the corresponding BAL troughs for other high-ionization species such as Si iv and N v are not seen in our spectrum. Its optical to X-ray spectral index, $\alpha_{ox}$, is found to be $-1.78$ which is larger than the typical value of soft X-ray weak QSOs having $\alpha_{ox} < -2$ (Giustini et al. 2008).

The pseudo-continuum normalized spectra of J085551+375752 is plotted in upper panel of Fig. 1 in velocity scale, with $v = 0$ km s$^{-1}$ corresponding to reference redshift of, $z_{em} = 1.936$. The plots show the comparisons between the SDSS, IGO and the reference BOSS spectrum over an elapse time of $\Delta t = 9.12, 1.11$ yr in observed frame, respectively. For visual clarity spectra are smoothed over 5 pixel. The plot shows that the BAL trough has varied over a velocity range from $-29521$ to $-5670$ km s$^{-1}$, with a nominal change of $17.95 \pm 1.01$ per cent in the equivalent width (EW) averaged over this entire velocity range, however, variation of individual components is very striking (see below).

As an be noted from Fig. 1 that the BAL trough seen in SDSS (MJD 52643) spectrum is composed of two narrow components at $\sim -20230$ km s$^{-1}$ (marked as N1SD and $\sim -16454$ km s$^{-1}$ (marked as N2SD) along with one broad component ranging from $-15550$ to $-8850$ km s$^{-1}$ (marked as B3SD, see Fig. 1). The corresponding components in BOSS spectrum are subscripted with ‘BO’ like ‘SD’, the subscript used to refer the SDSS spectrum. The narrow component in the SDSS spectrum N1SD has shown a redward kinematic shift of $\sim 800$ km s$^{-1}$ as marked N1BO in BOSS spectrum. However, the other narrow component N2SD is clearly visible in SDSS spectrum but barely appears in the BOSS (MJD 55973) spectrum (marked as N2BO). The broad component in the SDSS spectrum, (B3SD), has grown in the strength (marked as B3BO) between the SDSS and IGO (MJD 55568) epoch and has shown no change afterwards.

We also note that the line profile of N1SD component in the SDSS spectrum is very similar to the N1BO component in the IGO/BOSS spectrum, apart from the above constant velocity shift. This shift along with the invariance of line-profile of this component gives a hint of the outflow deceleration, which we have estimated from the position of their line centroid to be $\sim 217.64 \pm 22.19$ km s$^{-1}$ yr$^{-1}$ (i.e., $\sim -0.69 \pm 0.09$ cm s$^{-2}$), where for error we have taken a conservative value corresponding to uncertainty of one pixel. However, with the outflow speed of $\sim 20,000$ km s$^{-1}$ the absorbing cloud would have moved by a distance of $\sim 2.1 \times 10^{17}$ cm over the rest-frame time span of 3.11 yr, which is about the size of broad emission line region (BLR), $R_{BLR} \sim 6 \times 10^{17}$ cm, estimated using the size-luminosity scaling relationship for luminosity at $\lambda 1350$ Å (e.g., see...
The second narrow component $N_{2,SD}$ seen at $\sim -16454$ km s$^{-1}$ in the SDSS epoch data has disappeared at the time of our IGO observation (MJD 55568) and not appeared afterwards (both in the later BOSS and IGO observations). This can be explained by the absorbing gas tran-
sitting through our line of sight. The disappearance of this component is also consistent with the gas having transverse component of velocity as discussed above in the case of narrow component $N_{1,SD}$.

The broad component $B_{SD}$ seen in velocity range $-15550$ to $-8850$ km s$^{-1}$ in the SDSS spectrum, shows an increase in EW between the SDSS (MJD 52643) and IGO (MJD 55568) epoch and remained constant afterwards. From the publicly available Catalina Real-Time Transient Survey\(^6\) (CRTS) light-curve we find a nominal photometric variability between SDSS and BOSS spectrum. In the

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Figure 1. Lower panel: The final continuum fit (smooth curve) comprising of a power law, a lower order polynomial (dashed curve) and the multi-Gaussian components (dotted curve). Middle panel: Two-epoch absorption line variation in a continuum-normalised SDSS, BOSS and IGO spectra for SDSS J085551+375752 in velocity scale, with $v = 0$ km s$^{-1}$ corresponding to QSO emission redshift of $z_{em} = 1.936$. Upper panel: gives the ratio of absolute deviation to the total error-bars.

\(^6\) http://numuku.cacr.caltech.edu/cgi-bin/getcssconedb_release_img.cgi
BOSS spectrum the QSO is brightened by nine per cent at \( \sim 7000 \) Å and becomes dimmer roughly by five per cent at \( \sim 4000 \) Å. A simple power law extrapolation suggests that the dimming could be as much as a factor of two at the Ly-limit during the BOSS epoch compared to that in SDSS epoch. Absence of Si \( \text{iv} \) absorption suggest that the ionization parameter range should be such that when the radiation filed decreases, the EW of C \( \text{iv} \) (or its column density) should increase (e.g., see figure 1 of Hamann et al. 1997). Based on the available observations we can not rule out the possibility that the observed variation in C \( \text{iv} \) optical depth of its broad component \( (B_{SD}) \) may be triggered by changes in the ionization state.

Further, assuming the observed variability time-scale (i.e., 3.11 yr in the QSO rest-frame) as an estimate for recombination time-scale, then the photoionization equilibrium would imply the electron number density, \( n_e \), to be \( \gtrsim 3000 \) cm\(^{-3}\). In addition, the presence of the C \( \text{iv} \) ions implies that the ionization parameter, \( U \), should be such that \( \log U > -2 \) (e.g., see Hamann et al. 1997). This in conjunction with the fact that \( \log U \propto 1/n_e r^2 \) have allowed us to estimate the distance, \( r \), of the absorbing cloud from the QSO centre to be \( \lesssim 3 \) Kpc. An alternate explanation for this enhancement in EW of broad component can also be due to transverse motion of the clouds where additional gas is added to our line of sight.

In summary, the line variability seen in J085551+375752 can be explained by the gas moving in a curved path, though photoionization induced variability of the broad component can not be ruled out.
3.2 J091127+055054

J091127+055054 is a gravitationally lensed QSO at $z_{em} = 2.793$ (Bade et al. 1997). It is also an X-ray bright radio quiet QSO having X-ray luminosity of $4 \times 10^{46}$ ergs s$^{-1}$ (Bade et al. 1997) and $\alpha_{ox}$ of $-1.58$ (Giustini et al. 2008). Chandra observation of this source on 1999-11-02 and 2000-10-29, shows that its $0.5 - 8.0$ keV flux to be invariant over the rest frame time span of about 95 days (Gilson & Brandt 2012). Its optical spectrum shows a distinct BAL trough of C iv at $z_{abs} \sim 2.549$, with a BI value of 2358 km s$^{-1}$ (Streblyanska et al. 2010) and an AI of 1149 km s$^{-1}$ (Trump et al. 2006).

A comparison between SDSS (MJD 52652), IGO (MJD 55568, 55930 and 55979) and the reference BOSS (MJD 55896) spectrum of C iv BAL trough (all smoothed over 5 pixel), over a time span of about 8.89 and 0.89 yr respectively are shown in Fig. 2 in velocity scale with $v = 0$ km s$^{-1}$ corresponding to reference redshift of $z_{em} = 2.793$.

Between the SDSS and the BOSS epoch spectra, the continuum flux at 5000 Å has decreased by a factor of about 1.7. A similar trend is also seen in our flux calibrated IGO spectrum. Large change in the ionizing radiation is also hinted by the C iv emission line that appears stronger in the BOSS spectrum than the earlier epoch SDSS spectrum. Absorption from other species such as Si iv and N v associated to the C iv BAL trough are not detected in our spectrum. As can be seen from Fig. 3 (where we reproduce the C iv BAL trough spectral portion from Fig. 2), there is a clear change in the C iv absorption profile. The C iv absorption in the SDSS epoch shows three components marked as ‘A’, ‘B’ and ‘C’. The absorption in component ‘A’ in IGO and BOSS spectrum got weakened compared to the SDSS epoch. On the other hand, the component ‘C’ which is clearly visible in SDSS spectrum has almost disappeared in IGO and BOSS spectra. The change in the absorption of components ‘A’ and ‘C’ can be thought of as a transverse bulk motion of absorbing clouds; also proposed above for the line variability seen in J085551+375752. This also seems consistent with the emergence of a new absorption component seen in the IGO/BOSS spectrum between the components ‘B’ and ‘C’, marked as ‘D’ (see Fig. 3).

An alternate possibility to our above complex explanation is that the new component ‘D’ seen in IGO and BOSS spectra may have appeared due to deceleration of the original component ‘A’ and ‘B’ by shifting to ‘A1’ and ‘B1’, respectively (see Fig. 3). Such constant average shift for all components can be computed using cross-correlation technique by minimizing $\chi^2$ (e.g. see, Hall et al. 2007, and inset in Fig. 4). Using this technique a best-fitting average shift of $21 \pm 1$ pixel (i.e., $\sim 5$ Å in QSO rest frame) has been found between SDSS and BOSS spectrum (i.e., separating ‘A1’ from ‘A’ and ‘B1’ from ‘B’; see, Fig. 3). It corresponds to a deceleration of $a = -1.96 \pm 0.09$ cm s$^{-2}$, over a rest-frame time span of 2.34 year. Note however even in this deceleration scenario we need the absorption strength to decrease in the BOSS epoch.

We also note that this outflow velocity of the absorber relative to the QSO (i.e., $\sim 20,000$ km s$^{-1}$) is very large as compared to the typical escape velocity needed in the vicinity of BLR ($\sim 500 - 1000$ km s$^{-1}$; Greene et al. 2011). As discussed before, it seems that the dominance of the gravity may not be responsible for the above inferred deceleration. But it can be attributed to the absorbing cloud moving along a curved path outside the BLR region. Other possibility is that such a slowdown may also occur due to the interaction of gas with the confining medium. However, this appears to be unlikely because any such interaction with such moving clouds at high speed will give rise to the shock, which could completely ionize the gas.

We also note here, from Fig 4, that the overall velocity spread of C iv absorption remains same between two epochs, however, the overall absorption has weakened. This allows one to suggest a possible photoionization induced variability mechanism as well, which is also expected based on the continuum flux variation noted above. Now, assuming the observed variability time-scale (i.e., 2.34 yr here), as an estimate for recombination time-scale, we have computed the electron number density and the distance of an absorbing cloud from the J091127.6+055054 centre to be $> 4000$ cm$^{-3}$ and $\leq 5$ Kpc, respectively, using the approach adopted above in the case of J085551+375752 (see Section 3.1). However, this is most likely because based on the absence of other species we expect the ionization parameter range to be such that when radiation filed decreases the absorption line strength should increase. This is contrary to what we see in this case. Therfore, even in this case we favor the variability introduced by gas moving in transverse direction.

4 DISCUSSION AND CONCLUSIONS

In view of the fact that BAL trough variability can be a powerful tool to probe the physical condition in the vicinity of the QSO, there has been many systematic efforts to detect the EW and the absorption centroid variations (Filiz Ak et al. 2013, and references therein). How-
ever, till now very few cases of variability in the absorption kinematics of BAL troughs have been reported (e.g., Vlkoviskij & Irwin 2001; Rupke et al. 2002; Gabel et al. 2003; Hall et al. 2007). A first detection of a change in radial velocity in an outflow associated with a narrow absorption system in a Seyfert 1 galaxy, NGC 3783, is discovered by Gabel et al. (2003), where, they found a radial shift in C IV, N V, and Si IV lines. In addition, they also determined a deceleration values of $\alpha = -0.25 \pm 0.05$ and $-0.10 \pm 0.03$ cm s$^{-2}$ over the rest frame time span of 0.75 and 1.1 yr respectively. Similarly, Hall et al. (2007) have reported the largest BAL trough acceleration in SDSS J024221.87+004912.6, at $\alpha = 0.154 \pm 0.025$ cm s$^{-2}$, over a rest frame time span of 1.39 yr.

Our investigation is related to the BAL variability of less explored X-ray bright BAL QSOs, where we have monitored 10 well selected high-ionization X-ray bright BAL QSOs (see Section 1). Here, we have reported the detection of C IV BAL variability for two members in our sample, namely J085551+375752 and J091127+055054.

In J085551+375752, we see a BAL trough having two main narrow and one broad components. The first narrow component (N$_{1SD}$ in Fig. 3) has shown a shift of about 800 km s$^{-1}$ beside preserving the line profile over a time span of about 3.11 yr (in QSO rest-frame). This has resulted as an evidence of outflow deceleration of about $-0.69 \pm 0.09$ cm s$^{-2}$. As noted above, the highest deceleration value reported till now is $\alpha = -0.25 \pm 0.05$ cm s$^{-2}$ by Gabel et al. (2003) for NGC 3783 is much smaller than as we found here for this component. Such kinematic shift in absorption profile are attributed to either change in acceleration profile and/or due to the transverse motion of absorbing cloud relative to our line of sight. As discussed in Section 3.1, the outflow speed of this component suggests that the noted deceleration, if true, is more likely related to the non-gravitational forces such as flow along curved path, generally found where flow is confined by magnetic fields. In contrast to the deceleration of first component the second component (N$_{2SD}$ in Fig. 3) has disappeared after 3.11 yr, possibly due to its transverse motion. On the hand, the broader component (B$_{SD}$ in Fig. 3) showing increase in EW suggests that more gas has moved in to our line of sight in contrast to component N$_{2SD}$ where gas has moved out of our line of sight. Taking all these three together, it appears that the variability of J085551+375752 showing kinematic shift, appearance and disappearance of absorption components is probably due to the motion of many individual clouds in transverse and curved path relative to our line of sight.

For our second source J091127+055054, we also found the appearance and disappearance of BAL components, as discussed in detail in Section 3.2. For this source it is clear that overall absorption after 2.34 yr has got weakened and shifted redwards (e.g., see Fig. 3). We discussed the two scenario (i) with its original two components getting weakened and a new redward component appeared and (ii) the possibility that this new component instead is the result of deceleration of the original two components. For the former scenario, we consider the photoionization induced variability mechanism by assuming recombination time-scale similar to the observed variability time-scale, and estimated the absorber distance from the center to be 5 Kpc. However, for the more likely later scenario, we propose the bulk motion of gas along the curved path decreasing its radial velocity component. This results in an average deceleration of about $\alpha = -1.96 \pm 0.09$ cm s$^{-2}$, which is about factor 7.8 larger than the highest value reported by Gabel et al. (2003) for NGC 3783 and factor $\sim 2.8$ larger than the value we found for our above first source J085551+375752 (i.e., about $-0.69 \pm 0.09$ cm s$^{-2}$). Like in the case of J085551+375752, multiple streaming flows possibly in the curved path with appreciable transverse velocity can explain the observed variability. Other possibilities such as gas interaction with the confining medium seems to be unlikely as it can produce shock causing complete ionization of gas, and will also produce change in the line optical depth; both of which are not supported by our observations.

Summarising the line variability results found above for our two X-ray BAL QSOs, which shows combination of profile shift, appearance and disappearance of absorption components belonging to a single BAL trough; suggests that the cause of variability may be due to combination of motion in transverse and curved path of many small clouds probably confined by magnetic fields rather than a single homogeneous continuous radial outflow. The former appear also consistent with their X-ray brightness due to small covering fraction of many small individual clouds in contrast to heavy absorption of X-rays in the case of homogeneous radiation driven outflow models. Hence, our results supports the BAL outflow models involving many small self shielded clouds with low volume filling factor rather than a conventional single homogeneous continuous radial outflows. Given its important implications for kinematics of QSO outflows, we conclude that J085551+375752 and J091127+055054 are potential candidates to investigate outflow by monitoring them both in optical as well as in X-rays for their line and/or continuum variability.

Figure 4. Overplot of SDSS and BOSS epoch spectra for BAL QSO J091127.6+055054 after applying best-fitting pixel shift of 21 pixel on BOSS spectra for BAL QSO; the inset displays the $\chi^2$ versus pixel shift curve.
A systematic search for such kinematic shift and change in BAL absorption trough in large spectroscopic surveys like SDSS/BOSS will certainly help to increase such cases. Further, a dense sampling of time-variability over larger wavelength coverage of such candidates already showing signature of BAL shift and/or strength variability will be helpful to improve our understanding of the kinematics of QSO outflows.

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