THE DEPENDENCE OF C IV BROAD ABSORPTION LINE PROPERTIES ON ACCOMPANYING SI IV AND AL III ABSORPTION: RELATING QUASAR-WIND IONIZATION LEVELS, KINEMATICS, AND COLUMN DENSITIES

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ABSTRACT

We consider how the profile and multi-year variability properties of a large sample of C IV Broad Absorption Line (BAL) troughs change when BALs from Si IV and/or Al III are present at corresponding velocities, indicating that the line of sight intercepts at least some lower ionization gas. We derive a number of observational results for C IV BALs separated according to the presence or absence of accompanying lower ionization transitions, including measurements of composite profile shapes, equivalent width (EW), characteristic velocities, composite variation profiles, and EW variability. We also measure the correlations between EW and fractional-EW variability for C IV, Si IV, and Al III. Our measurements reveal the basic correlated changes between ionization level, kinematics, and column density expected in accretion-disk wind models; e.g., lines of sight including lower ionization material generally show deeper and broader C IV troughs that have smaller minimum velocities and that are less variable. Many C IV BALs with no accompanying Si IV or Al III BALs may have only mild or no saturation.

Key word: quasars: absorption lines

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Broad absorption lines (BALs) in quasar spectra are seen as a result of high-velocity outflows. The most commonly used empirical definition of BALs requires an absorption feature to have at least a 2000 km s⁻¹ width at 10% under the continuum level (e.g., Weymann et al. 1991). BAL quasars exhibit such broad absorption troughs in a wide variety of species in their rest-frame ultraviolet spectra, such as P v λλ1118, 1128 Å, Ly α λ1216 Å, N v λλ1239, 1243 Å, Si iv λλ1394, 1403 Å, C iv λλ1548, 1551 Å, Al ii λ1671 Å, Al iii λλ1855, 1863 Å, and Mg ii λλ2797, 2804 Å.

BAL quasars are classified into three groups based on the observed transitions in their spectra. The majority of BAL quasars exhibit absorption from only high-ionization transitions such as N v, Si iv, and C iv (HiBALs, e.g., Weymann et al. 1991). Approximately 10% of BAL quasars in optically selected samples also exhibit absorption from low-ionization transitions such as Al ii, Al iii, and Mg ii (LoBALs, e.g., Voit et al. 1993; Gibson et al. 2009). Only ≈1% of BAL quasars show absorption from excited states of Fe ii and/or Fe iii in addition to the high and low-ionization transitions listed above (FeLoBALs; e.g., Becker et al. 2000; Hall et al. 2002). The existence of these groups indicates that quasar outflows can have a wide range of ionization states. It has been argued that the presence of the low-ionization lines is not the only difference between these groups (e.g., Boroson & Meyers 1992; Turnshek et al. 1994; Zhang et al. 2010). The generally weak [O iii] emission and strong reddening of LoBALs suggest that LoBALs tend to be surrounded by dust and gas that has a larger global covering factor compared to HiBALs.

The details of the structure and geometry of quasar outflows remain unclear. A commonly adopted and well-developed model suggests that many BALs are formed in an equatorial wind that is launched from the accretion disk at 10¹⁶–10¹⁷ cm from the central supermassive black hole (SMBH) for black-hole masses of 10⁸–10¹⁰ M☉ and is driven by radiation pressure (e.g., Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2013). This disk-wind model successfully explains several important observational facts about BAL quasars, such as the presence of absorption from both high- and low-ionization transitions despite the luminous ionizing radiation from the central source, and the large range of outflow velocities that reach from the systemic velocity up to 0.1c. Numerical hydrodynamical simulations of the disk-wind model provide detailed predictions of the structure and dynamics of quasar outflows (e.g., Proga et al. 2000).

Previous studies have shown that some BAL troughs are much more optically thick than they appear and that the depths of such troughs only mildly depend on column density. Several pieces
of evidence for this line-saturation interpretation have been presented, such as P\textsc{iv} BALs, depth differences in unblended doublet lines, and “flat-bottom” BAL profiles (e.g., Arav 1997; Hamann 1998; Arav et al. 1999a, 1999b, 2001; Leighly et al. 2009; Borguet et al. 2012). For instance, Hamann (1998) studied spectra of the BAL quasar PG 1254+047 which possesses relatively strong P\textsc{iv} absorption at velocities corresponding to non-black strong C\textsc{iv} and S\textsc{iv} BAL troughs. The existence of P\textsc{iv} absorption was taken as evidence for saturated C\textsc{iv} absorption since phosphor is expected to be ∼ 1000 times less abundant than carbon (based on solar abundances). As another example, Arav et al. (1999a) argued that the depth differences between the unblended S\textsc{iv} doublet lines of the quasar FIRST J1603+3002 arise as a result of velocity-dependent partial coverage. Calculating the optical depths, they found that the C\textsc{iv} and S\textsc{iv} absorption lines are saturated. Such studies have suggested that the nonblack nature of these saturated lines arises due to partial coverage of the emission source along the line of sight; BAL troughs do not reach zero intensity due to photons from the emission source that are not absorbed and/or are scattered into the observer’s line of sight. Supporting this argument, spectropolarimetric observations of BAL quasars have shown that the fractional contribution from scattered emission often increases at the wavelengths where BAL troughs are found, indicating an excess of scattered light relative to direct light (e.g., Ogle et al. 1999). These lines of observational evidence indicate that some BAL quasars have highly saturated BAL troughs and that the depths of such troughs are largely set by the line of sight covering factor rather than column density. However, detailed studies of line saturation are only available for a limited number of objects and have often focused on deep C\textsc{iv} BALs. It is possible that some BALs might be weak simply because the column density along the line of sight is small.

Recent sample-based investigations of BAL variability have brought new insights about the structure, dynamics, and evolution of quasar outflows showing that variability is common for most BAL troughs on multi-year timescales (e.g., Lundgren et al. 2007; Gibson et al. 2008, 2010; Capellupo et al. 2011, 2012; Filiz Ak et al. 2012, 2013; Vivek et al. 2012; Wildy et al. 2013). These studies have revealed that the fractional variation of BAL troughs in lower ionization transitions (such as S\textsc{iv}) is generally stronger than that in C\textsc{iv} (e.g., Capellupo et al. 2012; Vivek et al. 2012; Filiz Ak et al. 2013). A recent study by Filiz Ak et al. (2013) presented a detailed investigation of the variability of C\textsc{iv} and S\textsc{iv} BALs on multi-year timescales in a large quasar sample assessing variation characteristics and the lifetimes of BAL troughs. This study found coordinated trough variability for BAL quasars showing multiple C\textsc{iv} troughs; they suggested that global changes in ionization level are the most straightforward mechanism for explaining such coordinated variability of multiple C\textsc{iv} troughs at different velocities. This mechanism would require at least some BAL troughs not to be highly saturated, as highly saturated troughs should not be responsive to the expected changes in ionization level.

The available analytic calculations and numerical simulations of quasar disk winds predict the ionization level, kinematics, and column density of the outflowing gas along possible lines-of-sight to the relevant emission region (e.g., Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2013). These three quantities are expected generally to show correlated changes as the line of sight is varied. Thus, we expect correlated object-to-object changes of resulting observable phenomena such as the BAL transitions present, BAL-profile shapes, and BAL variability. In this paper, we aim to investigate systematically and quantify such correlated object-to-object changes for a large sample of BAL quasars with uniform high-quality measurements from the Sloan Digital Sky Survey (SDSS; York et al. 2000). Utilization of a large sample is important to overcome object-to-object scatter associated with, e.g., time-variable wind inhomogeneities.

To probe correlated object-to-object changes of ionization level, kinematics, and column density, we require a basic means of identifying lines of sight with different average ionization levels. We accomplish this using the strong BAL transitions of C\textsc{iv}, S\textsc{iv}, and Al\textsc{iii}. These three transitions span a significant range of ionization potential (with creation ionization potentials of 47.9, 33.5 and 18.8 eV, respectively; e.g., Hall et al. 2002), and their BAL regions can all be measured simultaneously in SDSS spectra of quasars with redshift 1.9 < z < 3.9. Another practical advantage of using these three transitions is that their local continuum emission can be modeled more reliably than that for, e.g., Mg\textsc{ii}. Lines of sight with C\textsc{iv} BALs but not S\textsc{iv} or Al\textsc{iii} BALs intercept only relatively highly ionized gas. Lines of sight with C\textsc{iv} and S\textsc{iv} (but not Al\textsc{iii}) BALs intercept at least some less ionized gas. Finally, lines of sight with BALs from all three ions intercept at least some even less ionized gas. In the numerical simulations of Proga et al. (2000), these three lines of sight lie at progressively larger inclinations relative to the rotational axis of the accretion disk.

In this study, utilizing multi-epoch observations from the SDSS (Section 2), we classify C\textsc{iv} BAL troughs into three groups considering the corresponding BAL regions of S\textsc{iv} and Al\textsc{iii} (Section 3). We present the observational results of our investigation in Section 4. In Section 5, we present a summary of our results and a discussion of their implications for disk-wind models.

Throughout this study, timescales and EWs are given in the rest frame of the quasar unless stated otherwise. Negative signs for velocities indicate that a BAL trough is blueshifted with respect to the systemic velocity. We adapt a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega\Lambda = 0.7$ (e.g., Spergel et al. 2003).

2. OBSERVATIONS, SAMPLE SELECTION, AND DATA PREPARATION

We utilize spectroscopic observations from the Sloan Digital Sky Survey-I/II (hereafter SDSS, York et al. 2000) and the Baryon Oscillation Spectroscopic Survey of SDSS-III (hereafter BOSS; Eisenstein et al. 2011; Dawson et al. 2013). SDSS is a large multi-filter imaging and spectroscopic survey using a dedicated 2.5 m optical telescope (Gunn et al. 1998, 2006) at Apache Point Observatory in New Mexico. During its first phase of operations, 2000–2005, the SDSS imaged more than 2000 deg$^2$ of the sky in five optical bandpasses, and it obtained spectra of galaxies and quasars. The SDSS spectral coverage was continuous from 3800 Å to 9200 Å at a resolution of 1800–2200 (e.g., York et al. 2000). In 2005, the survey entered a new phase, the SDSS-II, expanding its spectroscopic samples to over 800,000 galaxies and 100,000 quasars. The BOSS, part of the third phase of SDSS operations, is acquiring spectra for approximately 1.5 million luminous galaxies and 160,000 quasars (e.g., Anderson et al. 2012; Ross et al. 2012). The BOSS survey started operating in mid-2008 and is planned to continue observations until the end of 2014 June. The BOSS quasar survey provides an outstanding opportunity for investigating
intrinsic UV absorption in quasars, owing to their focus on selection at \( z > 2.1 \), which shifts the important \( \text{C} \, \text{iv} \) and \( \text{Si} \, \text{iv} \) transitions well into its spectral coverage (Smee et al. 2013). The BOSS spectral coverage is continuous from 3600 Å to 10,000 Å at a resolution of 1300–3000 (e.g., Dawson et al. 2013).

An ancillary BOSS project aims to investigate the dynamics of quasar winds over multi-year timescales utilizing second-epoch spectra for 2005 BAL quasars originally identified in the SDSS-1/II spectroscopy by Gibson et al. (2009). These 2005 quasars were initially selected following \( i < 19.3, 0.48 < z < 4.65, \) \( \text{SN}_{1700} > 6, \) and \( \text{Bi}_{6} > 100 \) km s\(^{-1}\) criteria. Here, \( \text{SN}_{1700} \) is the average signal-to-noise ratio in a 4 Å resolution element within 1650–1750 Å, and \( \text{Bi}_{6} \) is the modified “balnicity” index defined in Section 2 of Gibson et al. (2009). The details of the project and the target selection are described in Filiz Ak et al. (2012, 2013).

We select a sample of quasars for this study from these 2005 targets that were observed by SDSS between MJD 51,602 (2000 February 28) and 54,557 (2008 January 4) and by BOSS between MJD 55,176 (2009 December 11) and 56,455 (2013 June 12). Observation start dates correspond to completion of hardware commissioning for both SDSS and BOSS; post-commissioning observation start dates are described in Filiz Ak et al. (2012, 2013). The spectra following Section 3.1 of Filiz Ak et al. (2012) and select our “main sample” for this study considering the following criteria:

1. We select quasars with \( 1.9 < z < 3.9 \) to ensure spectral coverage of both the \( \text{Si} \, \text{iv} \) 1394, 1403 Å and \( \text{Al} \, \text{iii} \) 1855, 1863 Å absorption regions (out to 20,000 km s\(^{-1}\)), where blueshifted absorption features are often found.
2. We select quasars that have a \( \text{C} \, \text{iv} \) balnicity index between \( -3000 \) and \( -20,000 \) km s\(^{-1}\), \( \text{Bi}_{20}^{\text{a}} \), greater than 0 for both the SDSS and BOSS spectra; implementing this requirement for both SDSS and BOSS spectra avoids biases that could arise from non-uniform SDSS versus BOSS BAL-identification thresholds. Thus, the quasars with disappearing BAL troughs in Filiz Ak et al. (2012) are not included in this study. We define \( \text{Bi}_{20}^{\text{a}} \) using \( a = 3 \) and \( b = 20 \) for the generalized BI definition, \( \text{Bi}_{a}^{b} \).

\[
\text{Bi}_{a}^{b} = \int_{-1000 \times a}^{-1000 \times b} \left( 1 - \frac{f(v)}{0.9} \right) C dv. \tag{1}
\]

Similar to the original BI definition (Weymann et al. 1991), in this equation \( f(v) \) is the normalized flux density as a function of velocity, \( v. \) \( C \) is a constant which is equal to 1.0 only when a trough is wider than 2000 km s\(^{-1}\); it is otherwise 0.0. Following the original BI definition, the minimum red-edge velocity limit is chosen to minimize confusion between \( \text{C} \, \text{iv} \) BALs and the \( \text{C} \, \text{iv} \) emission line. In this paper we use \( \text{Bi}_{20}^{20} \), rather than \( \text{Bi}_{3}^{30} \) used in Filiz Ak et al. (2013).

3. We select only radio-quiet quasars by requiring the radio-loudness parameter, \( R, \) to be less than 10; we utilize \( R \) parameters from Shen et al. (2011). Considering that radio-loud quasars are a minority part of the quasar population and may have different BAL properties than radio-quiet quasars (e.g., Becker et al. 1995, 2000; Brotherton et al. 1998), implementing this criterion avoids possible confusion associated with the presence of an additional radio-loud population.

Differing from the original BI definition of Weymann et al. (1991), our adapted \( \text{Bi}_{a}^{b} \) definition for this study (see Equation (1)) limits the maximum blue-edge velocity of a BAL-trough region at 20,000 km s\(^{-1}\), where it is 25,000 km s\(^{-1}\) in the original definition. Given that this study is focused on the characteristics of and differences between \( \text{C} \, \text{iv} \) BAL troughs that are accompanied by \( \text{Si} \, \text{iv} \) and/or \( \text{Al} \, \text{iii} \) BALs in corresponding velocity ranges, we adjust the maximum blue-edge velocity limit of the \( \text{C} \, \text{iv} \) BAL-trough region considering the \( \text{Si} \, \text{iv} \) (1394, 1403 Å) and \( \text{Al} \, \text{iii} \) (1855, 1863 Å) BAL-trough regions. Both the \( \text{Si} \, \text{iv} \) and \( \text{Al} \, \text{iii} \) BAL-trough regions are occasionally contaminated by the emission lines of \( \text{O} \, \text{i} \) 1302 Å (at \( \approx -21,800 \) km s\(^{-1}\) from \( \text{Si} \, \text{iv} \) emission), \( \text{Si} \, \text{ii} \) 1304 Å (at \( \approx -21,300 \) km s\(^{-1}\) from \( \text{Si} \, \text{iv} \) emission), \( \text{C} \, \text{iii} \) 1334 Å (at \( \approx -14,500 \) km s\(^{-1}\) from \( \text{Si} \, \text{iv} \) emission), \( \text{Ni} \, \text{ii} \) 1741 and 1751 Å (at \( \approx -20,200 \) and \( -18,400 \) km s\(^{-1}\) from \( \text{Al} \, \text{iii} \) emission), and \( \text{Fe} \, \text{ii} \) 1787 Å (at \( \approx -12,500 \) km s\(^{-1}\) from \( \text{Al} \, \text{iii} \) emission). Although these emission lines are usually weak, a visual inspection showed that in some cases these features may bring an end to shallow BAL troughs. Moreover, low-velocity absorption from these other line species may lead to confusion in the detection of \( \text{Si} \, \text{iv} \) or \( \text{Al} \, \text{iii} \) absorption. Thus, we consider a BAL-trough region between \( -3000 \) and \( -20,000 \) km s\(^{-1}\) as a suitable balance between uncontaminated spectral regions and useful sample size. Both \( \text{C} \, \text{ii} \) and \( \text{Fe} \, \text{ii} \) have low ionization potentials (24.4 eV and 16.2 eV, respectively) and are rarely found in quasar spectra (e.g., Hall et al. 2002). From the initial set of 2005 BAL quasars, the above criteria select 714 quasars that are observed by both the SDSS and BOSS (the main sample will be reduced to 671 quasars below via further considerations). The median \( \text{SN}_{1700} \) is 10.7 for SDSS and 17.4 for BOSS observations. In order to compare multi-epoch observations of our main sample, for each spectrum, we follow the basic spectral preparation procedures given in Section 3.1 of Filiz Ak et al. (2012). These procedures include Galactic extinction correction using the \( A_{V} \) values from Schlegel et al. (1998), transforming from the observed frame to the rest frame using the redshift values from Hewett & Wild (2010), and removing pixels that are flagged by the SDSS and BOSS data-reduction pipelines (Bolton et al. 2012). As in Gibson et al. (2008, 2010) and Filiz Ak et al. (2012, 2013), we define relatively line-free (RLF) windows to reconstruct the underlying continuum. We fit the RLF windows of each spectrum with an intrinsically reddened power-law using a Small Magellanic Cloud type reddening model (e.g., Pei 1992). This fit is performed by running an iterative sigma-clipping algorithm where in each iteration we perform a nonlinear least-squares fit. We calculate the uncertainties on the continuum model using \( \Delta y^{2} \) confidence-region estimation as described in Filiz Ak et al. (2012). We do not model the emission lines. We follow the procedures of Filiz Ak et al. (2012, 2013) for error propagation of continuum uncertainties into the subsequent measurements.

3. IDENTIFICATION OF BAL TROUGHS AND MEASUREMENTS

3.1. Identification of BAL Troughs

We identify \( \text{C} \, \text{iv} \) BAL troughs in the spectra of the 714 quasars that satisfy our quasar selection criteria (see Section 2 using the definition in Equation (1) and following the BAL-trough identification algorithm for multi-epoch observations defined in Section 3.2 of Filiz Ak et al. 2013). By construction, each quasar in our main sample has at least one SDSS and at least one BOSS observation. However, \( \approx 25\% \) of the main-sample

\[\text{SN}_{1700} \approx 3600 \text{ Å to } 10,000 \text{ Å at a resolution of 1300–3000} \text{(e.g., Dawson et al. 2013). The BOSS spectral coverage is continuous from 3600 Å to 10,000 Å at a resolution of 1300–3000} \text{(e.g., Dawson et al. 2013).} \]

[We have verified that only a small percentage of quasars (≈10%) have \( \text{Bi}_{6} > 100 \) km s\(^{-1}\) but \( \text{Bi}_{20}^{20} = 0 \).]
quasars have multiple SDSS and/or BOSS observations. These repeat observations sample similar timescales (considering just the multi-year timescales of primary interest here) and could cause some of our objects to be given inordinate weight by allowing the repeat examination of BAL troughs. In order to avoid such multi-counting biases in our analyses, we use only two-epoch spectra for each quasar in our main sample. We select connecting a given BAL trough to a given line of sight; e.g., disk wind models, practically they introduce complexity in existence of such objects is entirely expected within accretion-disk wind models, practically they introduce complexity in connecting a given BAL trough to a given line of sight; e.g., BAL troughs accompanied by a Si iv BAL detected at corresponding 0A); lower

We identify 43 quasars showing multiple C iv BAL troughs that are classed in different C iv groups (38 with C iv0 and C ivS0 troughs, and 5 with C ivS0 and C ivSA troughs). While the existence of such objects is entirely expected within accretion-disk wind models, practically they introduce complexity in connecting a given BAL trough to a given line of sight; e.g., C iv0 troughs in quasars that also show C ivS0 troughs likely sample a different part of the outflow from C iv0 troughs in quasars with no other BALs (see Section 5 for further discussion). To reduce complexity and avoid potentially mixing troughs in the same C iv group that sample different parts of the outflow, we exclude from our main sample these 43 quasars. We have performed all analyses below also including such quasars, and the results do not change materially. After excluding these 43 quasars, there are 671 quasars in our main sample (see Table 1). We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL troughs in our main sample. We present our BI20α measurements and uncertainties on B3, σB3, both for SDSS and BOSS observations of BAL trou...
### Table 2

#### C iv Troughs

| Quasar ID | C iv Trough ID | $v_{\text{max}}$ (km s$^{-1}$) | $v_{\text{min}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $v_{\text{cen}}[1]$ (km s$^{-1}$) | $v_{\text{cen}}[2]$ (km s$^{-1}$) | $d_{\text{ BAL}}[1]$ | $\sigma_{d_{\text{ BAL}}}[1]$ |
|-----------|----------------|------------------------------|------------------------------|--------------------------|-------------------------------|-------------------------------|----------------|----------------|
| Q29       | C00-1          | −10957.2                     | −8528.4                      | 2428.8                   | −9712.9                      | −9676.2                      | 0.200          | 0.022          |
| Q29       | C00-2          | −7593.0                      | −4868.9                      | 2906.1                   | −6046.1                      | −6072.0                      | 0.339          | 0.024          |
| Q34       | C00-3          | −20000.0                     | −17884.3                     | 2115.7                   | −18802.9                     | −18901.7                     | 0.124          | 0.009          |
| Q34       | C00-4          | −17862.3                     | −12780.2                     | 5082.1                   | −15274.8                     | −15295.9                     | 0.130          | 0.009          |
| Q40       | C00-5          | −15763.9                     | −9381.9                      | 6382.0                   | −12610.5                     | −12497.6                     | 0.307          | 0.017          |
| Q41       | C00-6          | −20000.0                     | −16100.5                     | 3899.5                   | −17974.4                     | −17956.4                     | 0.348          | 0.020          |
| Q47       | C00-7          | −19397.8                     | −11712.7                     | 7685.1                   | −15810.3                     | −15687.3                     | 0.368          | 0.015          |
| Q47       | C00-8          | −11537.6                     | −8089.2                      | 3448.4                   | −9811.0                      | −9823.4                      | 0.329          | 0.023          |
| Q51       | C00-9          | −9963.7                      | −7962.3                      | 2001.5                   | −8946.8                      | −8954.2                      | 0.144          | 0.021          |
| Q57       | C00-10         | −20000.0                     | −4959.0                      | 15041.0                  | −12291.8                     | −12402.4                     | 0.189          | 0.006          |

#### Notes
Throughout this table, [1] indicates the first-epoch spectra and [2] indicates the second-epoch spectra.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 3

#### Si iv Troughs

| Quasar ID | Si iv Trough ID | $v_{\text{max}}$ (km s$^{-1}$) | $v_{\text{min}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $v_{\text{cen}}[1]$ (km s$^{-1}$) | $v_{\text{cen}}[2]$ (km s$^{-1}$) | $d_{\text{ BAL}}[1]$ | $\sigma_{d_{\text{ BAL}}}[1]$ |
|-----------|----------------|------------------------------|------------------------------|--------------------------|-------------------------------|-------------------------------|----------------|----------------|
| Q3        | S0-1           | −10477.0                     | −5841.4                      | 4635.7                   | −8427.4                      | −8285.0                      | 0.491          | 0.032          |
| Q4        | S0-2           | −12444.7                     | −4858.5                      | 7586.2                   | −9558.5                      | −9262.8                      | 0.697          | 0.025          |
| Q10       | S0-3           | −15491.2                     | −3000.0                      | 12491.2                  | −10869.6                     | −10629.1                     | 0.531          | 0.024          |
| Q11       | S0-4           | −11596.2                     | −5638.0                      | 5958.2                   | −8516.9                      | −8806.4                      | 0.217          | 0.010          |
| Q12       | S0-5           | −10921.6                     | −3000.0                      | 7921.6                   | −8088.0                      | −8031.0                      | 0.648          | 0.023          |

#### Notes
Throughout this table, [1] indicates the first-epoch spectra and [2] indicates the second-epoch spectra.

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Given this relatively narrow range, we do not have a reason to be concerned about luminosity effects. Moreover, using two-sample Anderson-Darling (AD) tests (see Press et al. 2007), we found that the $M_i$ distributions for the C IV$_{S0}$, C IV$_{S0}$, and C IV$_{S0}$ groups are consistent, indicating that luminosity effects should not be causing confusion in group intercomparisons.

Table 4, C IV$_{Sa}$ Troughs

Table 5, C IV$_{Sa}$ troughs in Table 6, and C IV$_{Sa}$ troughs in Table 7. We do not include these troughs in any of the groups defined above to consider only strong intrinsic absorption of the given transition; this approach should give the strongest distinction between groups.

We have cross-matched our 671 main-sample quasars with the SDSS DR7 quasar properties catalog of Shen et al. (2011) to obtain absolute i-band magnitudes, $M_i$ (see Table 1). We found that the majority of our main-sample quasars lie within 2.5 mag in $M_i$, corresponding to a factor of $\approx 10$ range in i-band luminosity. Given this relatively narrow range, we do not have any immediate reason to be concerned about luminosity effects.

Moreover, using two-sample Anderson-Darling (AD) tests (see Press et al. 2007), we found that the $M_i$ distributions for the C IV$_{S0}$, C IV$_{S0}$, and C IV$_{S0}$ groups are consistent, indicating that luminosity effects should not be causing confusion in group intercomparisons.

Figures 1–3 show two-epoch observations for representative examples of C IV$_{S0}$, C IV$_{S0}$, and C IV$_{S0}$ BAL troughs, respectively. We smoothed each spectrum for display purposes using a Savitzky–Golay algorithm (see Press et al. 2007) that performs a local linear regression for three consecutive points.
### Table 5

| Quasar ID | C iv Trough ID | \( v_{\text{max}} \) (km s\(^{-1}\)) | \( v_{\text{min}} \) (km s\(^{-1}\)) | \( \Delta v \) (km s\(^{-1}\)) | \( v_{\text{cen}}[1] \) (km s\(^{-1}\)) | \( v_{\text{cen}}[2] \) (km s\(^{-1}\)) | \( \delta_{\text{BAL}}[1] \) (km s\(^{-1}\)) | \( \sigma_{\delta_{\text{BAL}}}[1] \) |
|-----------|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Q6        | Cs0-1          | -19685.5                   | -17001.8                    | 2683.6                      | -18364.8                    | -18301.9                    | 0.271                       | 0.022                       |
| Q7        | Cs0-2          | -8706.6                    | -4632.3                     | 4074.4                      | -7007.8                     | -6966.5                     | 0.644                       | 0.036                       |
| Q9        | Cs0-3          | -11106.9                   | -8037.0                     | 3070.0                      | -9649.7                     | -9649.8                     | 0.386                       | 0.033                       |
| Q11       | Cs0-4          | -20000.0                   | -12762.0                    | 7238.0                      | -16286.1                    | -16213.2                    | 0.231                       | 0.008                       |
| Q14       | Cs0-5          | -7718.3                    | -4045.6                     | 3627.2                      | -5927.5                     | -6022.1                     | 0.419                       | 0.023                       |
| Q15       | Cs0-6          | -20000.0                   | -16994.0                    | 3006.0                      | -18419.0                    | -18327.8                    | 0.277                       | 0.018                       |
| Q16       | Cs0-7          | -18275.7                   | -15476.7                    | 2799.0                      | -16788.8                    | -16843.7                    | 0.357                       | 0.035                       |
| Q17       | Cs0-8          | -7513.5                    | -4592.3                     | 2921.1                      | -5896.5                     | -5936.5                     | 0.640                       | 0.040                       |
| Q18       | Cs0-9          | -20000.0                   | -16264.3                    | 3735.7                      | -18157.3                    | -17888.5                    | 0.368                       | 0.024                       |
| Q24       | Cs0-10         | -20000.0                   | -13729.8                    | 6270.2                      | -16870.4                    | -16856.6                    | 0.275                       | 0.012                       |

\[
\begin{align*}
\delta_{\text{BAL}}[2] & \sigma_{\delta_{\text{BAL}}}[2] \\
EW[1] & \sigma_{EW}[1] \\
EW[2] & \sigma_{EW}[2] \\
\Delta EW & \sigma_{\Delta EW} \\
\frac{\Delta EW}{EW_{\text{cen}}[1]} & \sigma_{\frac{\Delta EW}{EW_{\text{cen}}[1]}}
\end{align*}
\]

Notes. Throughout this table, [1] indicates the first-epoch spectra and [2] indicates the second-epoch spectra.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 6

| Quasar ID | C iv Trough ID | \( v_{\text{max}} \) (km s\(^{-1}\)) | \( v_{\text{min}} \) (km s\(^{-1}\)) | \( \Delta v \) (km s\(^{-1}\)) | \( v_{\text{cen}}[1] \) (km s\(^{-1}\)) | \( v_{\text{cen}}[2] \) (km s\(^{-1}\)) | \( \delta_{\text{BAL}}[1] \) (km s\(^{-1}\)) | \( \sigma_{\delta_{\text{BAL}}}[1] \) |
|-----------|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Q68       | Cs0-1          | -16520.3                   | -7967.2                     | 8553.2                      | -12538.7                    | -12413.4                    | 0.470                       | 0.019                       |
| Q74       | Cs0-2          | -12104.4                   | -5549.0                     | 6555.4                      | -8424.5                     | -8381.3                     | 0.542                       | 0.025                       |
| Q92       | Cs0-3          | -15812.8                   | -7274.5                     | 8538.3                      | -11143.4                    | -11523.5                    | 0.307                       | 0.018                       |
| Q95       | Cs0-4          | -20000.0                   | -7477.7                     | 12522.3                     | -14343.8                    | -13767.6                    | 0.408                       | 0.015                       |
| Q102      | Cs0-5          | -15573.0                   | -9850.9                     | 5722.1                      | -12641.0                    | -12533.8                    | 0.327                       | 0.017                       |
| Q122      | Cs0-6          | -16532.5                   | -7118.1                     | 9414.4                      | -11798.3                    | -11969.2                    | 0.335                       | 0.016                       |
| Q123      | Cs0-7          | -12716.2                   | -4706.0                     | 8010.1                      | -8953.3                     | -9023.5                     | 0.310                       | 0.017                       |
| Q192      | Cs0-8          | -16109.3                   | -11388.8                    | 4720.5                      | -13675.9                    | -13745.2                    | 0.098                       | 0.009                       |
| Q217      | Cs0-9          | -6388.4                    | -4238.7                     | 2149.7                      | -5038.8                     | -5092.9                     | 0.711                       | 0.053                       |
| Q240      | Cs0-10         | -11158.8                   | -7751.6                     | 3407.3                      | -9243.6                     | -9357.1                     | 0.415                       | 0.036                       |

\[
\begin{align*}
\delta_{\text{BAL}}[2] & \sigma_{\delta_{\text{BAL}}}[2] \\
EW[1] & \sigma_{EW}[1] \\
EW[2] & \sigma_{EW}[2] \\
\Delta EW & \sigma_{\Delta EW} \\
\frac{\Delta EW}{EW_{\text{cen}}[1]} & \sigma_{\frac{\Delta EW}{EW_{\text{cen}}[1]}}
\end{align*}
\]

Notes. Throughout this table, [1] indicates the first-epoch spectra and [2] indicates the second-epoch spectra.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Table 7

| Quasar ID | C IV SA Trough ID | $v_{\text{max}}$ (km s$^{-1}$) | $v_{\text{min}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $v_{\text{cen}}[1]$ (km s$^{-1}$) | $v_{\text{cen}}[2]$ (km s$^{-1}$) | $d_{\text{BAL}}[1]$ | $\sigma_{d_{\text{BAL}}}[1]$ |
|-----------|-------------------|-------------------------------|-------------------------------|--------------------------|-----------------------------|-----------------------------|------------------|---------------------|
| Q2        | CSA-1             | -20000.0                      | -7997.7                      | 12002.3                  | -14588.0                    | -14972.5                    | 0.499            | 0.018               |
| Q19       | CSA-2             | -9532.0                       | -3000.0                      | 6552.0                   | -7219.7                     | -7519.0                     | 0.537            | 0.026               |
| Q21       | CSA-3             | -20000.0                      | -7452.5                      | 12547.5                  | -14198.9                    | -14177.9                    | 0.698            | 0.015               |
| Q33       | CSA-4             | -20000.0                      | -6346.1                      | 13653.9                  | -14370.2                    | -14044.3                    | 0.498            | 0.020               |
| Q39       | CSA-5             | -10772.3                      | -3000.0                      | 7772.3                   | -8305.6                     | -8191.4                     | 0.592            | 0.026               |
| Q43       | CSA-6             | -20000.0                      | -7389.2                      | 12610.8                  | -15426.7                    | -15715.8                    | 0.548            | 0.021               |
| Q45       | CSA-7             | -5099.9                       | -3000.0                      | 2099.9                   | -4180.0                     | -4273.3                     | 0.473            | 0.032               |
| Q46       | CSA-8             | -10647.4                      | -4855.0                      | 5792.4                   | -8520.5                     | -8436.7                     | 0.791            | 0.028               |
| Q49       | CSA-9             | -12874.5                      | -7052.6                      | 5821.9                   | -9976.5                     | -10007.5                    | 0.404            | 0.022               |
| Q50       | CSA-10            | -6340.5                       | -3018.0                      | 3322.5                   | -4813.8                     | -5072.8                     | 0.705            | 0.039               |

Notes. Throughout this table, [1] indicates the first-epoch spectra and [2] indicates the second-epoch spectra.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

(see Filiz Ak et al. 2012). In these figures, we indicate C IV BAL troughs and their corresponding velocity ranges in the Si IV and Al III absorption regions. The SDSS identification, redshift, and timescale between the two epochs are given in each panel.

In this study, we generally focus on the C IV, Si IV, and Al III BAL regions. We do not analyze in detail the BAL regions of the other transitions listed in Section 1 for several reasons: (1) due to the limited wavelength coverage of the observed spectra (3800–9200 Å for SDSS, and 3600–10000 Å for BOSS), only a small number of quasars have suitable wavelength coverage to investigate all of these transitions. (2) The strong Lyα and N v lines blend with each other and their blueshifted absorption lines blend with Lyα forest, where numerous absorption features from intervening gas are found. (3) A proper investigation of Mg II BALs would require modeling and subtraction of broad Fe II emission in addition to underlying continuum estimation. Moreover, only a small fraction of our targeted quasars have the wavelength coverage to investigate simultaneously C IV, Si IV, and Mg II BAL troughs.

### 3.2. Measurements of BAL Troughs

We measure the rest-frame timescales, $\Delta t$, for our main sample; $\Delta t$ is between 0.85 and 4.13 yr with a mean of 2.55 yr. Given the established connection between BAL-variation strength and timescale (e.g., Gibson et al. 2010; Filiz Ak et al. 2013), we compared the $\Delta t$ distributions for C IV$_{00}$, C IV$_{50}$, and C IV$_{SA}$ troughs. In Figure 4, we show the $\Delta t$ distributions for all C IV troughs in our main sample and for C IV$_{00}$, C IV$_{50}$, and C IV$_{SA}$ troughs. Given their definition, the sum of the total number of C IV$_{00}$, C IV$_{50}$, and C IV$_{SA}$ troughs is not equal to the total number of C IV troughs in our sample. We compared these $\Delta t$ distributions using two-sample AD tests. The test results show no significant differences between the distributions.

Considering that BAL troughs are sometimes isolated and occasionally appear in complexes in which single troughs may split or adjacent troughs may merge over time, we define minimum and maximum velocities for each BAL trough following the BAL-trough identification algorithm for multi-epoch observations described in Section 3.2 of Filiz Ak et al. (2013). We set $v_{\text{min}}$ to be the minimum red-edge velocity and $v_{\text{max}}$ to be the maximum blue-edge velocity of the associated absorption complex in all available epochs. For BAL troughs that reach beyond our adopted velocity limits (see Equation (1)), we simply truncate the BAL trough $v_{\text{max}}$ to be $-20,000$ km s$^{-1}$ and $v_{\text{min}}$ to be $-30,000$ km s$^{-1}$.

We measure the rest-frame EW of each BAL trough in each epoch. To calculate uncertainties on EWs, we propagate observational errors for each contributing pixel and continuum-estimation errors (see Filiz Ak et al. 2012, 2013) using Equations (1) and (2) of Kaspi et al. (2002). We calculate EW variations, $\Delta EW$, fractional EW variations, $\Delta EW/\langle EW \rangle$, and uncertainties on these quantities, $\sigma_{\Delta EW}$ and $\sigma_{\Delta EW/\langle EW \rangle}$, following Equations (3) and (4) of Filiz Ak et al. (2013), respectively. In this study, positive values of $\Delta EW$ and $\Delta EW/\langle EW \rangle$ indicate strengthening troughs and negative values indicate weakening troughs. In addition, we measure the average depth, $d_{\text{BAL}}$, for each trough by calculating the mean distance of each contributing data point from the normalized continuum level. We calculate a BAL-trough velocity width, $\Delta v$, and a weighted centroid velocity, $v_{\text{cen}}$, which is the mean velocity where each data point is weighted with its distance from the normalized continuum level. We adapt redshift values from Hewett & Wild (2010) for all velocity calculations.
3.3. Comparisons with Mg \textsc{ii}, Fe \textsc{ii}, and P \textsc{v}

We have compared our adopted classification of C\textsc{iv} BAL troughs with the standard subtypes of HiBALs, LoBALs, and FeLoBALs (see Section 1). All 113 C\textsc{iv}00 and 246 C\textsc{iv}50 troughs fit into the definition of HiBALs where only BAL troughs of high-ionization transitions are present in the spectra. Standard classes of LoBALs and FeLoBALs are identified with the presence of Mg\textsc{ii} and Fe\textsc{ii} absorption, respectively. We visually investigated the Mg\textsc{ii} \(\lambda\lambda2797, 2804\) Å and Fe\textsc{ii} \(\lambda\lambda2400, 2600\) Å absorption-line regions for 95 C\textsc{iv}SA troughs to examine the correspondence to the standard LoBAL and FeLoBAL definitions. The spectra of 34 quasars with C\textsc{iv}SA troughs do not have coverage of the Mg\textsc{ii} region, and these are not utilized in our correspondence checking. We find that \(\approx74\%\) (45 out of 61) of quasars with C\textsc{iv}SA troughs exhibit Mg\textsc{ii} BAL/mini-BAL troughs at corresponding velocities; four of them also exhibit Fe\textsc{ii} BAL/mini-BAL troughs. There are 16 quasars with C\textsc{iv}SA troughs that have no Mg\textsc{ii} absorption. Due to the differences between their ionization potentials (28.4 eV for Al\textsc{iii} and 15.0 eV for Mg\textsc{ii}), Al\textsc{iii} absorption is expected to be slightly more common than Mg\textsc{ii} absorption given that higher ionization troughs are found more frequently than lower ionization troughs in BAL quasars (e.g., Hall et al. 2002).

Previous investigations of P\textsc{v} \(\lambda\lambda1118, 1128\) Å absorption lines corresponding in velocity with C\textsc{iv} and Si\textsc{iv} BAL troughs have shown that P\textsc{v} absorption lines are an important indicator of line saturation (e.g., Hamann 1998; Arav et al. 2001); note that the ionization potentials of P\textsc{v} (65.0 eV) and C\textsc{iv} (64.5 eV) are very similar. We thus visually investigate the P\textsc{v} BAL regions that align with our C\textsc{iv}00, C\textsc{iv}50, and C\textsc{iv}SA troughs. The spectral coverage is sufficient to investigate the P\textsc{v} BAL region for 40 C\textsc{iv}00 troughs, 113 C\textsc{iv}50 troughs, and 47 C\textsc{iv}SA troughs. Our visual inspection reveals that spectra of a large fraction (\(\approx88\%\)) of C\textsc{iv}SA troughs exhibit visually detectable P\textsc{v} absorption features; a majority (\(\approx70\%\)) of C\textsc{iv}SA troughs are accompanied by moderate-to-strong P\textsc{v} absorption. P\textsc{v} absorption that aligns with C\textsc{iv}50 troughs is generally weaker than that aligning with C\textsc{iv}SA troughs. Approximately half of the C\textsc{iv}50 troughs are accompanied by detectable P\textsc{v} absorption; however, only \(\approx10\%\) of those C\textsc{iv}50 troughs align with moderate-to-strong P\textsc{v} absorption. Only a small fraction (\(\approx12\%\)) of C\textsc{iv}00 troughs are accompanied by detectable P\textsc{v} absorption; we visually investigate the Mg\textsc{ii} BAL troughs with no detection of BAL or mini-BAL troughs at corresponding velocities in the Si\textsc{iv} and Al\textsc{iii} absorption regions from SDSS (red) and BOSS (black). The \(x\) axes show both the rest-frame wavelength (bottom, in Å) and the blueshift velocity from the Si\textsc{iv}, C\textsc{iv}, and Al\textsc{iii} emission lines (top, in \(10^3\) km s\(^{-1}\)). The \(y\) axes show flux densities normalized by the fitted continuum model (\(F_\lambda\)). The horizontal solid-blue bars designate C\textsc{iv} BAL troughs, and the dashed blue bars indicate corresponding velocities in the Si\textsc{iv} and Al\textsc{iii} BAL regions. The lower section of each panel shows deviations between SDSS and BOSS observations for each \(\approx4\) Å pixel in units of \(\sigma, N_\sigma\), and the dashed-red lines show \(\pm1\sigma\) levels.

(A color version of this figure is available in the online journal.)
absorption, and the strength of this P ν absorption is generally weak. These results show that quasars possessing detectable P ν absorption in their spectra are also more likely to present lower-ionization transitions; therefore their C iv troughs are likely to be C iv SA or to a smaller extent C iv S0 troughs.

4. RESULTS

In this section, we present the observational results of our investigation. Utilizing the two-epoch observations for 113 C iv00, 246 C iv50, and 95 C ivSA BAL troughs, we investigate the C iv, Si iv, and Al iii BAL profiles (Section 4.1), the C iv trough strengths (Section 4.2), the C iv trough velocities (Section 4.3), the C iv trough variation profiles (Section 4.4), the C iv trough EW variation characteristics (Section 4.5), and the C iv, Si iv, and Al iii trough EW variation correlations (Section 4.6).

4.1. BAL-trough Profiles

It is well known that BAL troughs from different transitions show different profiles; for instance, Al iii BAL troughs tend to be narrower and align with lower velocity portions of corresponding C iv BAL troughs (e.g., Weymann et al. 1991; Voit et al. 1993; Trump et al. 2006). Moreover, previous studies (e.g., Weymann et al. 1991; Reichard et al. 2003; Allen et al. 2011) have demonstrated that C iv BAL troughs tend to be stronger in quasars exhibiting Al iii and/or Mg ii BAL troughs (i.e., LoBAL quasars). To compare the typical properties of C iv00, C iv50, and C ivSA BAL troughs, we calculate composite mean profile shapes for each C iv group. Figure 5 shows the mean profile shapes for 113 C iv00, 246 C iv50, and 95 C ivSA BAL troughs as a function of outflow velocity relative to $v_{\text{min}}$. We calculate the mean profiles by defining an outflow velocity, $v_\Delta = v - v_{\text{min}}$, which is set to 0 at its $v_{\text{min}}$ and runs from 0 to $\Delta v$ (where $\Delta v$ is the trough velocity width). We fix the normalized flux density, $F_\lambda$, to 1 at velocities higher than $v_{\text{max}}$ for each C iv BAL trough. Given the BAL-trough definition, $F_\lambda$ is less than 0.9 for $0 < v_\Delta < \Delta v$. We also present mean profile shapes of Si iv and Al iii BAL troughs in overlapping velocity ranges for comparison.

A comparison of the resulting composite profiles in Figure 5 indicates that C iv00 troughs tend to be shallower and narrower than both C iv50 and C ivSA troughs. The C iv50 and C ivSA trough depths change in a characteristic manner as a function of velocity within the trough: troughs are generally deeper at lower velocities. Consistent with previous studies, the composite profile shapes show that C iv BALs are usually deepest when there is an Al iii BAL at corresponding velocities. Similarly, a
We find qualitatively consistent results when computing median composites instead of mean composites. This indicates that outliers are not strongly affecting our composites.

4.2. CIV BAL-trough Strengths

For a more quantitative comparison between the CIV$_{00}$, CIV$_{S0}$, and CIV$_{SA}$ groups, we assess differences between measured CIV BAL-trough properties in this subsection and the next. Figure 6 shows the distributions of average EW from two-epoch observations. (EW), for CIV$_{00}$, CIV$_{S0}$, and CIV$_{SA}$ BAL troughs. Considering that the total number of BAL troughs increases with decreasing (EW), the fraction of BAL troughs with given (EW) is also displayed in Figure 6. We calculate the fractions as the ratio of the number of CIV$_{00}$, CIV$_{S0}$, and CIV$_{SA}$ BAL troughs to all 852 main-sample CIV troughs; they therefore need not sum to unity in a given bin.

The mean (EW) is $15.46 \pm 0.42$ Å for all 852 CIV BAL troughs in our main sample, whereas it is $4.76 \pm 0.25$ Å for CIV$_{00}$, $19.29 \pm 0.62$ Å for CIV$_{S0}$, and $32.38 \pm 1.35$ Å for CIV$_{SA}$ troughs as given in Table 8. Uncertainties on the mean are calculated using the standard $\sigma/\sqrt{N}$ formula. The median (EW) is $11.51$ Å for all CIV, $4.44$ Å for CIV$_{00}$, 17.58 Å for CIV$_{S0}$, and 31.14 Å for CIV$_{SA}$ BAL troughs. These results confirm and quantify the increase of CIV BAL-trough strength with the existence of absorption lines from lower ionization-level transitions.
In order to determine the contributions of the depth and width components of BAL EWs, we assess average depth from two-epoch observations, \( \langle d_{\text{BAL}} \rangle \), and velocity width, \( \Delta v \), distributions for C\text{IV}_00, C\text{IV}_0S0, and C\text{IV}_SA troughs (see Figure 7). Table 8 presents the mean \( \langle d_{\text{BAL}} \rangle \) and \( \Delta v \) values for all three C\text{IV} BAL-trough groups. We compare these distributions using an AD test and find that both the \( \langle d_{\text{BAL}} \rangle \) and \( \Delta v \) distributions for C\text{IV}_00, C\text{IV}_0S0, and C\text{IV}_SA BAL troughs are significantly different (at a confidence level of >99.9\%) from each other. Our findings indicate that C\text{IV}_SA BAL troughs tend to be the deepest and widest BAL troughs, while C\text{IV}_00 troughs tend to be the shallowest and narrowest. The ranges of the \( \langle d_{\text{BAL}} \rangle \) and \( \Delta v \) values for C\text{IV}_00, C\text{IV}_0S0, and C\text{IV}_SA BAL troughs demonstrate that the contributions of the depth and the width to the differences between BAL-trough EWs are comparable; the \( \langle d_{\text{BAL}} \rangle \) values change by a factor of \( \approx 2.3 \) and the \( \Delta v \) values change by a factor of \( \approx 3 \) between the C\text{IV}_00 and C\text{IV}_SA samples.

Note that for BAL troughs extending beyond our adopted BAL-trough definition velocity limits, the \( v_{\text{min}} \) and \( v_{\text{max}} \) values are truncated at \(-3000\) and \(-20,000\) km s\(^{-1}\), respectively. Due to this truncation process, the measured \( \Delta v \) values are only lower limits for such BAL troughs. However, the results discussed in Section 4.3 indicate that such truncation does not have a strong effect on our main conclusions.

As can be seen in Figures 5, the strength of Si\text{iv} BAL troughs is also larger when Al\text{iii} BAL troughs are present. The mean (EW) is \( 7.35 \pm 0.49 \) Å for Si\text{iv} BAL troughs in the C\text{IV}_0S0 sample and \( 20.84 \pm 1.02 \) Å for Si\text{iv} BAL troughs in the C\text{IV}_SA sample. The mean (EW) values change by a factor of \( \approx 2.8 \), which is even stronger than the corresponding change for C\text{IV} of \( \approx 1.7 \).
4.3. \textit{CIV} BAL-trough Velocities

To assess differences in BAL-trough velocities, we investigate minimum velocity, \( v_{\text{min}} \), maximum velocity, \( v_{\text{max}} \), and average centroid velocity from two-epoch observations, \( \langle v_{\text{cent}} \rangle = 1/2 (v_{\text{cent}} + v_{\text{cent}}) \), for \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) BAL troughs. We present these distributions in Figure 8.

Given our adopted BAL-trough definition, \( v_{\text{min}} \) and \( v_{\text{max}} \) values are truncated at \(-3000\) and \(-20,000\) \( \text{km s}^{-1} \), respectively, for BAL troughs exceeding these limits. It is apparent from Figure 8 that this effect is present for the \( v_{\text{max}} \) and less severely for the \( v_{\text{min}} \) distributions for \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) BAL troughs. We thus compare \( v_{\text{min}} \) and \( v_{\text{max}} \) distributions using a two-sample Peto-Prentice test (PP; e.g., Latta 1981), implemented in the Astronomy Survival Analysis (ASURV; e.g., Lavalle et al. 1992) package, which considers such censoring effects in the samples. The PP test results show that all three \( v_{\text{min}} \) distributions are significantly different (at a level of \( >99.9\% \)) from each other and all three \( v_{\text{max}} \) distributions do not show highly significant differences (\( P \) is 30.0\% for the \textit{CIV}\(_{00}\) versus \textit{CIV}\(_{S0}\) samples, 35.2\% for the \textit{CIV}\(_{S0}\) versus \textit{CIV}\(_{SA}\) samples, and 75.8\% for the \textit{CIV}\(_{00}\) versus \textit{CIV}\(_{SA}\) samples). We also compare \( v_{\text{min}} \) and \( v_{\text{max}} \) distributions for the three \textit{CIV} groups and find similar results; the consistency of both the PP and AD tests suggests that the truncation of \( v_{\text{min}} \) and \( v_{\text{max}} \) does not have a significant effect on our main results. Still, we focus our discussion on \( v_{\text{min}} \) as per its importance for our comparative assessments (see Section 5) rather than the more affected \( v_{\text{max}} \).

The mean \( v_{\text{min}}, v_{\text{max}}, \) and \( \langle v_{\text{cent}} \rangle \) values are given in Table 9. \textit{CIV}\(_{00}\) BAL troughs tend to have higher onset velocities than \textit{CIV}\(_{S0}\) and \textit{CIV}\(_{SA}\) troughs. The mean \( v_{\text{min}} \) values change by a factor of \( \approx 2.5 \) from \textit{CIV}\(_{00}\) to \textit{CIV}\(_{SA}\) troughs. Such differences between the \( v_{\text{min}} \) distributions for \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) BAL troughs are perhaps expected given that the average outflow velocity is higher for weak BAL troughs (e.g., Weymann et al. 1991). Unlike the \( v_{\text{min}} \) distributions, the \( v_{\text{max}} \) distributions do not show strong apparent differences between the \textit{CIV} groups.

AD test results show that the \( \langle v_{\text{cent}} \rangle \) distributions are significantly different (at a level of \( >99.9\% \)) from each other. \textit{CIV}\(_{SA}\) BAL troughs tend to be found at the lowest such velocities, and \textit{CIV}\(_{00}\) troughs tend to be found at the highest such velocities, although the mean \( \langle v_{\text{cent}} \rangle \) values differ by only \( \approx 25\% \).

4.4. \textit{CIV} BAL-variation Profiles

We assess the overall differences between \textit{CIV} BAL-variation characteristics by comparing composite variation profiles for \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) troughs. Since BAL-trough widths cover a considerable range for each \textit{CIV} group (see Figure 7), we divide each group into three bins considering \( \Delta v \) values. The bin limits are \( \Delta v < 3000, 3000 < \Delta v < 5000, \) and \( \Delta v > 5000 \) \( \text{km s}^{-1} \) for \textit{CIV}\(_{00}\) troughs; \( \Delta v < 8000, 8000 < \Delta v < 12,000, \) and \( \Delta v > 12,000 \) \( \text{km s}^{-1} \) for \textit{CIV}\(_{S0}\) troughs; and \( \Delta v < 10,000, 10,000 < \Delta v < 14,000, \) and \( \Delta v > 14,000 \) \( \text{km s}^{-1} \) for \textit{CIV}\(_{SA}\) troughs.

First, we calculate the absolute value of the depth variation between the SDSS and BOSS spectra for each data point of each trough as a function of outflow velocity, \( v_{t} \). Second, we calculate the mean absolute depth variation for BAL troughs in each bin by interpolating the data points for given \( v_{t} \) values. Figure 9

![Figure 7](https://example.com/image7.png)

**Figure 7.** Average depth, \( \langle d_{\text{BAL}} \rangle \) (upper panels), and velocity width, \( \Delta v \) (lower panels), distributions for \textit{CIV}\(_{00}\) (dot-dashed blue), \textit{CIV}\(_{S0}\) (dashed green), and \textit{CIV}\(_{SA}\) (solid red) BAL troughs. The right panels show the fraction of \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) BAL troughs relative to all \textit{CIV} BAL troughs in our main sample. The \( \langle d_{\text{BAL}} \rangle \) and \( \Delta v \) distributions for \textit{CIV}\(_{00}\), \textit{CIV}\(_{S0}\), and \textit{CIV}\(_{SA}\) BAL troughs are significantly \( (99.9\%) \) different from each other.

(A color version of this figure is available in the online journal.)
Figure 8. Minimum velocity, $v_{\text{min}}$ (upper panels), maximum velocity, $v_{\text{max}}$ (middle panels), and average centroid velocity, $\langle v_{\text{cent}} \rangle$ (lower panels), distributions for $\text{C IV}_{00}$ (dot-dashed blue), $\text{C IV}_{S0}$ (dashed green), and $\text{C IV}_{SA}$ (solid red) BAL troughs. The right panels display the fraction of $\text{C IV}_{00}$, $\text{C IV}_{S0}$, and $\text{C IV}_{SA}$ BAL troughs relative to all $\text{C IV}$ BAL troughs in our main sample. The $v_{\text{min}}$ and $\langle v_{\text{cent}} \rangle$ distributions for $\text{C IV}_{00}$, $\text{C IV}_{S0}$, and $\text{C IV}_{SA}$ BAL troughs are significantly (99.9%) different from each other, whereas the $v_{\text{max}}$ distributions do not show highly significant differences.

(A color version of this figure is available in the online journal.)

Table 9

|                  | $\text{C IV}_{00}$     | $\text{C IV}_{S0}$ | $\text{C IV}_{SA}$ | All $\text{C IV}$ |
|------------------|------------------------|--------------------|--------------------|-------------------|
| $v_{\text{min}}$ (km s$^{-1}$) | $-11898 \pm 400$       | $-7434 \pm 238$   | $-4838 \pm 241$   | $-8424 \pm 154$  |
| $v_{\text{max}}$ (km s$^{-1}$) | $-15836 \pm 426$       | $-16035 \pm 308$  | $-16506 \pm 453$  | $-15619 \pm 168$ |
| $\langle v_{\text{cent}} \rangle$ (km s$^{-1}$) | $-13830 \pm 402$       | $-11998 \pm 235$  | $-11405 \pm 291$  | $-12229 \pm 140$ |
| Number of Data Points | 113                   | 246               | 95                 | 852               |

Notes. Uncertainties on the mean are calculated using the standard $\sigma/\sqrt{N}$ formula. Note that values in this table are affected by censoring (see the text).
displays the mean composites of depth-variation profiles for C iv troughs with 3000 < \Delta v < 5000 (top panels), C iv troughs with 8000 < \Delta v < 12,000 (middle panels), and C iv troughs with 10,000 < \Delta v < 14,000 (bottom panels) in km s^{-1}. Left panels: solid black curves show the mean composite profiles for absolute depth variations of C iv BAL troughs as a function of outflow velocity, \( v_t \). The dashed curves show the error on the mean. Right panels: mean composite profiles for absolute fractional depth variations of C iv BAL troughs, where the fractional variation is the depth variation divided by the average depth. While the C iv00 troughs show similar variability across the entire trough, the C ivSA and C ivS0 troughs show less variability at lower velocities where the Si iv and Al iii absorption tend to be the strongest.

Figure 9. BAL-trough variation profiles for C iv00 troughs with 3000 < \Delta v < 5000 (top panels), C ivS0 troughs with 8000 < \Delta v < 12,000 (middle panels), and C ivSA troughs with 10,000 < \Delta v < 14,000 (bottom panels) in km s^{-1}. Left panels: solid black curves show the mean composite profiles for absolute depth variations of C iv BAL troughs as a function of outflow velocity, \( v_t \). The dashed curves show the error on the mean. Right panels: mean composite profiles for absolute fractional depth variations of C iv BAL troughs, where the fractional variation is the depth variation divided by the average depth. While the C iv00 troughs show similar variability across the entire trough, the C ivSA and C ivS0 troughs show less variability at lower velocities where the Si iv and Al iii absorption tend to be the strongest.

4.5. C iv BAL EW Variability

4.5.1. EW Variability as a Function of \( \langle EW \rangle \)

In this section, we investigate the characteristics of BAL EW variability assessing the differences between C iv00, C ivS0, and C ivSA troughs. Figure 10 presents the EW variation, \( \Delta EW \), between the two-epoch spectra as a function of average EW, \( \langle EW \rangle \). For comparison, the standard-deviation curves for these three C iv groups are also given; these standard-deviation curves are calculated using a sliding window where each window contains 10% of the total number of BAL troughs found in a given group (i.e., 11 for C iv00, 25 for C ivS0, and 10 for C ivSA). We statistically remove the mean EW error in each window from the standard deviation, so the dispersion shown in Figure 10 refers to the intrinsic dispersion. Consistent with Section 4.5 of Filiz Ak et al. (2013), we find that the standard deviation of \( \Delta EW \) generally increases with increasing \( \langle EW \rangle \) for all C iv groups. Given that such a trend exists for all C iv groups, a proper intergroup comparison requires consideration of EW variation for troughs with similar \( \langle EW \rangle \) values. The C ivS0 \( \Delta EW \) spread appears less than that for C iv00 BALs with similar \( \langle EW \rangle \) values (i.e., 7 < \( \langle EW \rangle \) < 10 Å). Similarly, the C ivSA \( \Delta EW \) spread appears less than that for C ivS0 BALs for 12 < \( \langle EW \rangle \) < 35 Å. These results suggest that C iv EW variation has a dependence upon the existence of absorption lines from Si iv and Al iii transitions.

In Figure 11, we show the fractional EW variation, \( \Delta EW/\langle EW \rangle \), as a function of \( \langle EW \rangle \) for C iv00, C ivS0, and C ivSA troughs. Similarly to Figure 10, solid curves represent the sliding-window standard deviations. The overall trend in \( \Delta EW/\langle EW \rangle \) versus \( \langle EW \rangle \) appears mainly due to the increase of \( \langle EW \rangle \). The curves indicate that the spread of \( \Delta EW/\langle EW \rangle \) for C iv00 is larger than that for C ivS0, and the \( \Delta EW/\langle EW \rangle \) spread for C ivS0 is larger than that for C ivSA in matched \( \langle EW \rangle \) ranges.
Previous BAL-variability studies (Gibson et al. 2008, 2010; Capellupo et al. 2011; Filiz Ak et al. 2013) have demonstrated that BAL EW variability increases with increasing timescale. However, the trends in Figures 10 and 11 are not caused or amplified by this effect; the testing in Section 3 showed that the timescale distributions for C\textsc{iv}00, C\textsc{iv}S0, and C\textsc{iv}SA troughs do not have any significant differences from each other (see Figure 4).

Considering that the \langle EW\rangle distributions are significantly different between the three C\textsc{iv} groups (see Figure 6) and that there are strong correlations between \Delta EW or \vert\Delta EW/\langle EW\rangle\vert and \langle EW\rangle for all C\textsc{iv} troughs (also see Section 4.5 of Filiz Ak et al. 2013), we investigate the EW variation distributions of these three groups using matched samples of troughs with similar EWs.

4.5.2. BAL-trough Samples with Matching EWs

We investigated the EW-variation characteristics of C\textsc{iv}00 versus C\textsc{iv}S0 and C\textsc{iv}S0 versus C\textsc{iv}SA troughs using matched samples. These matched samples contain the same number of BAL troughs from both groups matched by first-epoch EW, EW1. Requiring similar EW1 for each trough pair allows comparison of variation behaviors for C\textsc{iv} groups having similar initial conditions. We first randomly select a C\textsc{iv}00 trough for each C\textsc{iv}S0 trough such that their EWs are in agreement to within 1\sigma. Due to significant differences in the EW distributions, we cannot match all data points of a group. In the matching procedure, we sample any given BAL trough only once. Second, we applied a two-sample AD test to compare the \Delta EW distributions. We repeated the matching and AD testing 1000 times and found the median results given in Table 10.

Comparing the \Delta EW distributions of C\textsc{iv}00 and C\textsc{iv}S0 BAL troughs with matched EWs (where each distribution has 40 troughs), we found that the two distributions significantly (\textit{P} > 99.9\%) differ from each other. Similarly, we repeat the matching for C\textsc{iv}S0 and C\textsc{iv}SA troughs. The test results for the comparison between the \Delta EW distributions of C\textsc{iv}S0 and C\textsc{iv}SA troughs with similar EWs (where each has 65 troughs) show that the two distributions differ with a significance of 97.8\%.

Figure 12 presents the \Delta EW distributions for C\textsc{iv}00 and C\textsc{iv}S0 BAL troughs with matched EWs in the left panel, and C\textsc{iv}S0 and C\textsc{iv}SA BAL troughs with matched EWs in the right panel.

As given in Table 10, the mean of \vert\Delta EW\vert for C\textsc{iv}00 troughs is \approx 1.3 times larger than that for matched C\textsc{iv}S0 troughs. Likewise, the mean of \vert\Delta EW\vert for C\textsc{iv}S0 troughs is \approx 1.8 times larger than that for matched C\textsc{iv}SA troughs. The standard deviation of the \Delta EW distribution for C\textsc{iv}00 troughs is \approx 1.1 times larger...
than that for matched CIVSO troughs, and for CIVSO troughs is \( \approx 1.7 \) times larger than that for matched CIVSA troughs.

Although the matched CIVSO and CIVSA BAL troughs have both a larger sample size (65) and difference between the \( \sigma_{\Delta EW} \) values (5.16–3.09 = 2.07) than the matched CIV00 and CIVSO troughs, the AD-test results indicate a more significant overall difference for the \( \Delta EW \) distributions of CIV00 and CIVSO troughs. This result is mainly due to a more significant difference between the mean \( \Delta EW \) values of matching CIV00 and CIVSO troughs (3.6\( \sigma \)) than that for matching CIVSO and CIVSA troughs (1.9\( \sigma \)). Another notable result of these comparisons is that the means of the \( \Delta EW \) distributions for both the CIV00 and CIVSO troughs with similar \( EW \) differ from zero at more than 2\( \sigma \): \(-1.13 \pm 0.47 \) Å and \( 1.33 \pm 0.49 \) Å, respectively. Moreover, the means of the \( \Delta EW \) distributions for CIVSO and CIVSA troughs with similar \( EW \) also differ from zero at more than 1\( \sigma \). The means of the \( \Delta EW \) distributions for CIVSO in the two different matching samples change from a positive value to a negative value. These results are initially surprising given the fact that the mean of the \( \Delta EW \) distribution for all 852 CIV BAL troughs in our main sample is consistent with zero (\(-0.0055 \pm 0.0373 \) Å; also see Section 4.4 of Filiz Ak et al. 2013). Indeed, the weakening and strengthening of BAL troughs are expected to be balanced to maintain an equilibrium population of BAL troughs in quasar spectra.

The differences between the mean values of the \( \Delta EW \) distributions can occur, for instance, if not only \( |\Delta EW| \) but also \( \Delta EW \) has a dependence on BAL-trough strength. To assess such dependency, we show \( \Delta EW \) as a function of first-epoch \( EW \) for CIV00, CIVSO, and CIVSA troughs in Figure 13. The best fits of basic linear-regression models are plotted in each panel of Figure 13 to demonstrate the apparent trends. Using Spearman rank-correlation tests (see Press et al. 2007), we find connections between \( \Delta EW \) and \( EW \) for CIV00 (\( P > 99.9\% \)) and likely also for CIVSO (\( P \approx 98.4\% \)) troughs.

The apparent \( \Delta EW \) versus \( EW \) relation primarily arises because the BAL-trough \( EW \) variation range is limited. Given that a BAL trough cannot weaken by more than its first-epoch \( EW \) and cannot strengthen by more than its second-epoch \( EW \), \( EW_2 \), the variation strength is restricted to be \( EW_2 \geq \Delta EW \geq -EW_1 \). In addition, we exclude quasars that do not satisfy our necessary quasar-selection criterion of \( B_1 > 0 \) in either epoch (see Section 2). Thus, this criterion leads to exclusion of disappearing (i.e., \( \Delta EW \approx -EW_1 \); e.g., Filiz Ak et al. 2012) and emerging (i.e., \( \Delta EW \approx EW_2 \)) BAL troughs from our main sample.

In our matched samples, we must compare the \( \Delta EW \) distribution of the stronger CIV00 troughs with that of the weaker CIVSO troughs, and that of the stronger CIVSO troughs with that of the weaker CIVSA troughs. Therefore, the differences in the means of these \( \Delta EW \) distributions are expected given the relations shown in Figure 13.

### 4.6. EW Variation Correlations

Previous studies (e.g., Gibson et al. 2010; Capellupo et al. 2012; Filiz Ak et al. 2013) have demonstrated that SiIV BAL troughs tend to vary in concert with CIV troughs at corresponding velocities and that the strength of fractional \( EW \) variations tends to be larger for SiIV BAL troughs. In order to investigate similar relations for CIVSO (Section 4.6.1) and CIVSA (Section 4.6.2) troughs, we assess variation correlations between CIV troughs and corresponding SiIV and Al III troughs.
Figure 13. ΔEW as a function of EW\textsubscript{1} for C\textsc{iv}\textsubscript{00} (left), C\textsc{iv}\textsubscript{S0} (middle), and C\textsc{iv}\textsubscript{SA} (right) BAL troughs. The solid lines show the best fits of basic linear-regression models in each panel. The dashed lines denote where ΔEW = −EW\textsubscript{1} (corresponding to BAL disappearance). The apparent connection between ΔEW and EW\textsubscript{1} arises primarily because a BAL trough cannot weaken by more than its first-epoch EW.

(A color version of this figure is available in the online journal.)

Figure 14. ΔEW (left panel) and ΔEW/⟨EW⟩ (right panel) correlations between C\textsc{iv}\textsubscript{S0} BAL troughs and the corresponding Si\textsc{iv} BAL troughs. Spearman-test results show highly significant correlations (P > 99.9%) for both panels. The solid-blue lines show the best fit found using a Bayesian linear-regression model.

(A color version of this figure is available in the online journal.)

4.6.1. EW Variation Correlations for the C\textsc{iv}\textsubscript{S0} Sample

Figure 14 presents the ΔEW and ΔEW/⟨EW⟩ correlations for C\textsc{iv}\textsubscript{S0} and the corresponding Si\textsc{iv} troughs. Consistent with the findings of Filiz Ak et al. (2013) for all C\textsc{iv} troughs, the Spearman-test results show that both the ΔEW and ΔEW/⟨EW⟩ correlations are highly significant (P > 99.9%). Given the apparent scatter in both panels of Figure 14, we determine the best fits using a Bayesian linear-regression model that considers the intrinsic scatter of the sample (Kelly 2007). We found the following relations, calculating the mean and the standard deviation of the linear-regression model parameters for 10,000 random draws from the sample:

\[
\Delta \text{EW}_{\text{C\textsc{iv}S0}} = (1.20 \pm 0.082) \times \Delta \text{EW}_{\text{Si\textsc{iv}}} \\
+ (0.051 \pm 0.216), \sigma_{\text{IS}} = 3.4 \text{ Å} \tag{2}
\]

\[
\frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{C\textsc{iv}S0}} = (0.515 \pm 0.023) \times \frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{Si\textsc{iv}}} \\
+ (0.006 \pm 0.011), \sigma_{\text{IS}} = 0.15 \tag{3}
\]

Here \(\sigma_{\text{IS}}\) is the standard deviation of the intrinsic scatter. The slopes of the ΔEW and ΔEW/⟨EW⟩ correlations are consistent with the findings in Section 4.6 of Filiz Ak et al. (2013) within 1σ, indicating that the EW variations of C\textsc{iv}\textsubscript{S0} troughs are comparable to those of Si\textsc{iv} troughs, whereas the fractional EW variations of C\textsc{iv}\textsubscript{S0} troughs are approximately half of those of Si\textsc{iv} troughs. The EW variations for C\textsc{iv}\textsubscript{S0} versus corresponding Si\textsc{iv} troughs are not highly inconsistent with being equal; the deviation between the best fit and equality is \(\approx 2.4\sigma\) and the intrinsic scatter is large.

4.6.2. EW Variation Correlations for the C\textsc{iv}\textsubscript{SA} Sample

Figure 15 displays the ΔEW and ΔEW/⟨EW⟩ relations for C\textsc{iv}\textsubscript{SA} BAL troughs and the corresponding Si\textsc{iv} and Al\textsc{iii} BAL troughs. The Spearman-test results indicate highly significant (P > 99.9%) correlations for both ΔEW and ΔEW/⟨EW⟩ between C\textsc{iv}\textsubscript{SA} and the corresponding Si\textsc{iv} troughs. The ΔEW correlation between C\textsc{iv}\textsubscript{SA} and the corresponding Al\textsc{iii} troughs is marginally significant (P = 99.8%), while the ΔEW/⟨EW⟩ correlation is highly significant (P > 99.9%). The ΔEW correlation between C\textsc{iv}\textsubscript{SA} and Al\textsc{iii} troughs is not highly significant, possibly because of the small range of ΔEW values for both ions. In addition to this effect, the relatively small number of data points in the C\textsc{iv}\textsubscript{SA} sample, and the apparently large intrinsic scatter of the ΔEW values, may hide any possible
correlation. The following relations are found using the Bayesian linear-regression fit:

\[
\Delta \text{EW}_{\text{C IV}_{\text{SA}}} = (0.646 \pm 0.081) \times \Delta \text{EW}_{\text{Si IV}} + (0.080 \pm 0.280), \sigma_{\text{IS}} = 2.5 \, \text{Å} 
\] (4)

\[
\frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{C IV}_{\text{IV}}} = (0.355 \pm 0.044) \times \frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{Si IV}} - (0.002 \pm 0.008), \sigma_{\text{IS}} = 0.08 
\] (5)

\[
\Delta \text{EW}_{\text{C IV}_{\text{IV}}} = (0.172 \pm 0.171) \times \Delta \text{EW}_{\text{Al III}} + (0.493 \pm 0.348), \sigma_{\text{IS}} = 3.3 \, \text{Å} 
\] (6)

\[
\frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{C IV}_{\text{IV}}} = (0.111 \pm 0.035) \times \frac{\Delta \text{EW}}{\langle \text{EW} \rangle}_{\text{Al III}} + (0.005 \pm 0.011), \sigma_{\text{IS}} = 0.10. 
\] (7)

Figure 15 presents the best fits of the C IV and Si IV variation relations both for the C IV S0 and the C IV SA samples for comparison purposes. Consistent with the results of our investigations in Section 4.5, the ranges of \( \Delta \text{EW}_{\text{C IV}} \) and \( \Delta \text{EW}/(\langle \text{EW} \rangle)_{\text{C IV}} \) in Figures 14 and 15 indicate that C IV SA troughs tend to be less variable than C IV S0 troughs. Moreover, the ranges of \( \Delta \text{EW}_{\text{Si IV}} \) and \( \Delta \text{EW}/(\langle \text{EW} \rangle)_{\text{Si IV}} \) in Figures 14 and 15 suggest that the Si IV BAL troughs of the C IV SA Sample show less variation than those of the C IV S0 sample. The flat slopes of Equations (4) and (6) indicate that the C IV SA troughs tend to show very small variations. The slopes of Equations (5) and (7) indicate that Al III troughs tend to be more fractionally variable than both the corresponding C IV SA and Si IV troughs, and Si IV troughs tend to be more fractionally variable than the corresponding C IV SA troughs.

5. SUMMARY OF RESULTS, DISCUSSION, AND FUTURE WORK

We have investigated the profiles, standard characteristic properties, and variation behaviors of C IV BAL troughs, considering how these change when BAL troughs from Si IV and Al III are present at corresponding velocities. We have utilized a sample of 852 C IV BAL troughs; 113 of these have no detection of any corresponding Si IV or Al III BALs or mini-BALs in both epochs (C IV S0 troughs), 246 of these are accompanied by a Si IV BAL trough but have no corresponding Al III BALs or mini-BALs (C IV S0 troughs), and 95 of these are accompanied by both Si IV and Al III BALs (C IV SA troughs). The main observational findings of our study are the following:

1. The composite profiles of C IV S0, C IV SA, and C IV SA troughs differ significantly; stronger C IV troughs are found when accompanying BAL troughs from lower ionization transitions are present. Furthermore, the composite profiles for
CIVS0 and CIVSA troughs are deeper at the lower velocities where AlIII and, to a lesser extent, SiIV troughs are preferentially found. See Section 4.1.

2. The two-epoch average EW (EW), distributions for CIV00, CIVS0, and CIVSA BAL troughs are significantly (>99.9%) different. Generally, CIV00 troughs have small EWs, CIVS0 troughs have moderate EWs, and CIVSA troughs have large EWs. We find that increases in both depth and velocity width contribute comparably to the increase in EW from CIV00 to CIVS0 to CIVSA troughs. See Section 4.2.

3. The minimum and average centroid velocities decrease from CIV00 to CIVS0 to CIVSA troughs; this decrease is most notable for the minimum velocity, which changes on average by a factor of ≈2.5, while the decrease is mild (≈25%) for the average centroid velocity. See Section 4.3.

4. Composite depth-variation and fractional-depth-variation profiles have been used to investigate the relative variability of CIV00, CIVS0, and CIVSA BAL troughs. BAL variability generally decreases from CIV00 to CIVS0 to CIVSA BALs, particularly in a fractional sense. For CIVS0 and CIVSA troughs, the lower velocity portions of the troughs tend to be the least variable, and these are the regions where AlIII and, to a lesser extent, SiIV troughs are preferentially found. See Section 4.4.

5. The spread of ΔEW generally increases with increasing ⟨EW⟩, and the spread of ΔEW/(⟨EW⟩) generally decreases with increasing (⟨EW⟩), for CIV00, CIVS0, and CIVSA BAL troughs; this result is consistent with the general behavior of all CIV BAL troughs (e.g., Filiz Ak et al. 2013). In overlapping ranges of ⟨EW⟩, CIV00 troughs appear to vary more strongly than CIVS0 troughs (P > 99.9%), and similarly CIVS0 troughs appear to vary more strongly than CIVSA troughs (P = 97.8%). See Section 4.5.1.

6. For a proper comparison of the variation characteristics of the three CIV groups, we compare ΔEW distributions of samples of BAL troughs with matched first-epoch EWs. CIVS0 troughs are somewhat less variable than CIV00 troughs with matched EWs, and CIVSA troughs are substantially less variable than CIVS0 troughs with matched EWs. See Section 4.5.2.

7. The Si IV BAL troughs associated with the CIVS0 sample show EW and fractional EW variations that are generally in concert with those of the corresponding CIVS0 troughs. We quantify the relevant correlations and find that Si IV troughs show similar EW and larger fractional EW variations than corresponding CIVS0 troughs. See Section 4.6.1.

8. The EW and fractional EW variations of AlIII troughs are less clearly linked with those of CIVSA troughs, although correlation testing does indicate some correspondence. AlIII troughs show larger EW and fractional EW variations than corresponding CIVSA and Si IV troughs. See Section 4.6.2.

We now examine the implications of our observational findings considering the best-developed model for quasar BAL outflows, that of an equatorial radiation-driven disk wind (e.g., Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2013, see also Section 1). While other scenarios for BAL outflows also exist, such as those proposing that BALs primarily are formed at large distances (0.1–10 kpc) from the SMBH (e.g., Arav et al. 2013; also see Faucher-Giguère et al. 2012; but see Section 5.3 of Lucy et al. 2014 for a critique), these have not been developed via numerical simulations to the point where robust comparisons with our observational findings are possible.

Of course, any model for BAL winds, current or future, can be usefully constrained by our observational results presented above.

Figure 16 shows density and poloidal velocity maps of the disk-wind model. In this figure, two lines of sight are marked, corresponding to different viewing inclinations, along which an observer would see CIV00 and CIVSA troughs, respectively. (A color version of this figure is available in the online journal.)
observational evidence supporting intrinsic object-to-object differences as well as inclination effects among BAL quasars (e.g., Boroson & Meyers 1992; Turnshek et al. 1994; Zhang et al. 2010; DiPompeo et al. 2012). For example, the probability of observing a C IV S0 trough will be higher for objects having a larger global covering factor of low-ionization gas (compared to the weak [O iii] objects discussed in Boroson & Meyers 1992). However, such global-covering-factor effects do not affect our main reasoning below which is focused upon the typical measured properties of C IV 00 versus C IV 50 versus C IV S0 troughs rather than how often each of these trough types is observed.

Considering the LOS S0 and LOS S0 lines of sight in Figure 16, we present below a comparative assessment of the expected properties of C IV 00 and C IV S0 troughs, relating these to the observational findings above (we then discuss C IV 50 troughs as an intermediate case). Specifically, we consider BAL-trough profile properties (e.g., depth, width, EW, velocity, and profile shape) and BAL-variability characteristics (e.g., EW and fractional EW variation strengths, depth variation profiles). Our comparative assessment points are the following:

1. The column density of outflowing gas is considerably larger along LOS S0 than along LOS 00, while the line-of-sight covering factors need not differ substantially. If the column density plays a role in setting trough depth, it is expected that C IV S0 troughs will generally be deeper than C IV 00 troughs (observational findings 1 and 2 above). While some BAL quasars are known to have highly saturated C IV troughs with depths largely set by the line-of-sight covering factor (rather than column density; see Section 1), it is not clear that all C IV troughs are highly saturated. Indeed, variability studies suggest that some C IV troughs are not highly saturated (see Section 1). The C IV troughs with detailed previous studies showing strong saturation are C IV 50 or C IV S0 troughs, while, to our knowledge, no C IV 00 troughs have been demonstrated to be highly saturated. Broadly consistent with this, we note that P V absorption corresponding to C IV 00 troughs is rare and weak (see Section 3.3).

2. Given the poloidal velocity field of the model, we expect C IV 00 troughs to have generally higher minimum outflow velocities than C IV S0 troughs, as observed (see observational finding 3). This is because LOS S0 intersects gas with a high outflow velocity without intersecting much gas with a low outflow velocity. LOS S0, on the other hand, primarily intersects gas with a low outflow velocity. LOS S0 might also intersect gas with a high outflow velocity if such gas extends close to the accretion-disk surface (i.e., prompt acceleration) at small radii, as appears required by our results showing high v max values for C IV S0 troughs. These same considerations can also explain the larger velocity widths of C IV S0 troughs compared to C IV 00 troughs (see observational finding 2). Figure 16 (lower panel) shows that the velocities for LOS S0 appear to be 5000–10,000 km s −1 along essentially the entire line of sight, and this is comparable to our measured v min values for C IV 00 troughs.

3. Given that the EW of a trough is set by a combination of its depth and width, we expect from the two comparative assessment points above that C IV S0 troughs will have larger EWs than C IV 00 troughs, as observed (see observational findings 1 and 2).

4. From the model, we expect that Al III BALs will be mainly formed in the region close to the disk with high density and small poloidal velocity, while C IV BALs will be formed within both high-velocity and low-velocity gas. Thus, we expect that Al III troughs will reside within the lower velocity portions of C IV troughs, as observed (observational finding 1 and Voit et al. 1993).

5. The model shows that the optical depth is velocity-dependent, and that it is generally higher for low poloidal velocities. Therefore, the low-velocity portions of C IV S0 troughs that align with corresponding Al III troughs are likely to be more saturated than the high-velocity portions, perhaps partly leading to their larger depths (observational finding 1). Therefore, these portions should be less variable than the high-velocity portions. This behavior is observed (observational finding 4).

6. Previous studies have presented evidence that ionization-level changes likely have a significant role in driving some BAL variability (see Section 1). Strongly saturated lines will be less susceptible to variability driven by ionization-level changes. Given that C IV S0 troughs are likely more saturated than C IV 00 troughs, they are expected to be less variable. This is observed in an absolute sense and even more strongly in a fractional sense (observational findings 4–6).

7. The model indicates that the C IV optical depth along LOS S0 is substantially larger than the Al III optical depth. Therefore, Al III troughs are expected to be more variable than C IV S0 troughs, as they should be less saturated. This behavior is observed in an absolute sense and even more strongly in a fractional sense (observational finding 8).

The basic expectations of the disk-wind model for the characteristics of the C IV 00 and C IV S0 samples show qualitative agreement with our observational findings. In this model, a line of sight along which an observer would see a C IV 50 trough is expected to intercept at least some less ionized gas than LOS 00. Consistent with this expectation, our observational findings show that the C IV 50 sample is an intermediate case between the C IV 00 and C IV S0 samples (observational findings 1–7).

There are a number of ways the results above might be advanced, and here we highlight four that appear particularly promising. First, for the reasons discussed in Section 1, our current work has made use of the strong C IV, Si IV, and Al III BAL transitions as a basic measure of average line-of-sight ionization level. These transitions, spanning a factor of ≈2.5 in ionization potential, have served effectively for our work. However, this ionization-potential range could be expanded with the use of additional lower ionization (e.g., Mg ii, Fe ii, and Fe iii) and higher ionization (e.g., Ne vii, Ne v, O vi) transitions, thereby presumably probing wind zones even closer to and further from, respectively, the accretion disk. Second, the profiles and variability of the emission lines for large samples of BAL quasars with C IV 00, C IV 50, and C IV S0 troughs should be measured systematically and compared with predictions (e.g., Murray & Chiang 1997; Flohic et al. 2012). For a flattened Broad

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19 The evidence for high global covering factors of low-ionization gas has been most notably presented for BAL quasars with detected Mg ii absorption (e.g., Boroson & Meyers 1992; Turnshek et al. 1994; Zhang et al. 2010).

20 We have also performed basic testing with the C IV 00, C IV S0, and C IV S0 samples described in Section 3.1, and we generally find them to show suitably intermediate properties as well.
Line Region geometry, to first order one might expect the emission lines for BAL quasars with CIV
do troughs to be generally the broadest (though different emission lines, tracing different
phases of the broad line region, may behave differently). Third, the ongoing BOSS ancillary project and upcoming SDSS-IV
Time Domain Spectroscopic Survey (TDSS)21 observations will
both enlarge the sample size and improve the temporal sampling pattern for BAL quasars. This will allow variability to be
used even more effectively as a tool for assessing correlated changes of ionization level, kinematics, and column density.
Finally, while we have found generally good qualitative agreement
with expectations for the disk-wind model, our ability to perform quantitative comparisons has been limited by the available
simulation results. Future simulations capable of predicting trough profiles and variability (e.g., Higginbottom et al. 2013).
D. Proga 2013, private communication) can be quantitatively
tested and constrained using large-sample measurements such as those provided here. Alternatives to the disk-wind model
should also be developed to the point where quantitative testing is possible.

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21 The current planning for SDSS-IV is briefly described at
http://www.sdss3.org/future/