Absorption-line Environments of High-redshift BOSS Quasars

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Abstract
The early stage of massive galaxy evolution often involves outflows driven by a starburst or a central quasar plus cold mode accretion (infall), which adds to the mass build-up in the galaxies. To study the nature of these infall and outflows in the quasar environments, we have examined the correlation of narrow absorption lines (NALs) at positive and negative velocity shifts to other quasar properties, such as their broad absorption-line (BAL) outflows and radio-loudness, using spectral data from SDSS-BOSS DR12. Our results show that the incidence of associated absorption lines (AALs) and outflow AALs is strongly correlated with BALs, which indicates most AALs form in quasar-driven outflows. Multiple AALs are also strongly correlated with BALs, demonstrating quasar outflows tend to be highly structured and can create multiple gas components with different velocity shifts along our line of sight. Infall AALs appear less often in quasars with BALs than quasars without BALs. This suggests that BAL outflows act on large scale in host galaxies and inhibit the infall of gas from the IGM, supporting theoretical models in which quasar outflow plays an important role in the feedback to host galaxies. Despite having larger distances, infall AALs are more highly ionized than outflow AALs, which can be attributed to the lower densities in the infall absorbers.

Unified Astronomy Thesaurus concepts: Quasar absorption line spectroscopy (1317); Quasars (1319)

1. Introduction
High-redshift quasars identify episodes of rapid accretion onto supermassive black holes (SMBHs) in the center of massive galaxies. Possibly triggered by a recent merger of a gas-rich galaxy, this rapid accretion activity is believed to be accompanied by rapid star formation during the early stages of galaxy evolution (Sanders et al. 1988; Elvis 2006; Hopkins et al. 2008; Veilleux et al. 2009). Powerful outflows during this evolution stage, driven by the quasar and/or the starburst, expel gas and dust from the host galaxies, can quench the star formation, and cut off the fuel supply to the central black hole (Silk & Rees 1998; Kauffmann & Haehnelt 2000; King 2003; Scannapieco & Oh 2004; Di Matteo et al. 2005; Hopkins et al. 2008; Ostriker et al. 2010; Debaur et al. 2012; Rupke & Veilleux 2013; Cicone et al. 2014; Rupke et al. 2017; Weinberger et al. 2017). The mechanism for the high-speed quasar-driven outflows quenching star formation in their host galaxies is expected to involve shredding and dispersal of interstellar clouds, which can produce complex outflowing gas structures on large scales (Hopkins & Elvis 2010; Faucher-Giguère et al. 2012). Infalling gas from the intergalactic medium (IGM; e.g., cold mode accretion) is also believed to be important for fueling the central SMBH and star formation during these early active evolution stages (Katz et al. 2003; Kereš et al. 2009, 2012).

Absorption lines in quasar spectra are unique tools to study the gaseous environments of quasars and test models of massive galaxy evolution. High-speed quasar-driven outflows are readily detected in quasar spectra via blueshifted broad absorption lines (BALs) with velocity widths larger than 2000 km s⁻¹ (Anderson et al. 1987; Weymann et al. 1991). Low-speed outflows or infall in the extended host galaxies should produce narrow associated absorption lines (AALs) with redshifts near the quasar emission-line redshifts (zₐₐₜₜ ≈ zₑₐₚ) and velocity widths less than a few hundred km s⁻¹, (e.g., Weymann et al. 1979; Foltz et al. 1986; Hamann 1997; Hamann & Sabha 2004; Simon & Hamann 2010; Muzahid et al. 2013). Gas fragments shredded by powerful quasar outflows might produce rich multiple AALs (Hopkins & Elvis 2010; Faucher-Giguère et al. 2012; Chen et al. 2018, 2019).

These different absorption-line environments should produce different signatures in the line kinematics, ionizations, column densities, and metal abundances. For example, infall lines at zₐₐₜₜ > zₑₐₚ generally have low metallicities and low ionizations since the gas coming from the IGM resides at large distances from the quasars. High-speed quasar-driven outflows originating in the galactic nuclei should exhibit the opposite behavior, with higher metallicities, higher ionizations, broader profiles, and stronger lines resulting from higher column densities. However, the complex nature of quasar/host galaxy environments could cause individual absorption-line systems to deviate from the typical behaviors that signal a particular origin or formation region. At negative velocity shifts, zₐₐₜₜ < zₑₐₚ, the absorption lines that form in outflows are also mixed with unrelated lines that form in cosmologically intervening gas and galaxies along our line of sight. Thus it is hard to distinguish the origins of individual absorption lines. And when investigating the typical properties of quasars’ gaseous environments, it is better to use a large sample of absorption lines instead of individual lines.

In this paper, we investigate the nature and origin of the diverse C IV narrow absorption lines (NALs) in high-redshift quasars measured in the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013; Pâris et al. 2017), which is a part of the Sloan Digital Sky Survey III (SDSS-III; Eisenstein...
et al. 2011). This study is made possible by a new catalog of quasar absorption lines developed by D. York et al. (2020, in preparation) using spectra from BOSS data release 12 (DR12). Our main focus is on the study of correlation between the incidence of C IV λ1548, 1551 NALs and other quasar properties.

The structure of this paper is organized as follows. Section 2 describes the quasar samples and the different types of NAL groups that we use in this study. Section 3 presents the main results based on both of the correlation analysis and the study of median composite spectra constructed for the different NAL groups. Section 4 discusses the results and the implications for our understanding of outflows and infall in the quasar environments. A brief summary is given in Section 5.

2. Quasar Samples and NAL Groups

We select quasars based on the Quasar Absorption-Line Catalog from D. York et al. (2020, in preparation), which is created using quasar spectra from BOSS DR12 (Pâris et al. 2017). The BOSS spectra have a wavelength coverage from ∼3600 Å through ∼10000 Å at resolutions of ∼1300 in the blue end to ∼2600 in the red end (Dawson et al. 2013). The selection criteria are that (1) the quasars must have redshifts in the range of 2.0 < z< 3.4 to ensure the BOSS spectral coverage of C IV NALs at a wide range of radial velocity shifts (relative to the redshift of the quasar), and (2) the median signal-to-noise ratio near the rest wavelengths of 1700 Å (SNR1700) is ≥3. We have also rejected quasars with known damped Lyα absorption lines (DLAs) in their spectra using the catalog flag of DLA_flag = −1, which in the end yields a full sample of 100,376 quasars.

From this full sample, we select well-measured C IV NALs for our study based on FWHM ≤500 km s⁻¹, rest equivalent width (REW) ≥0.5 Å measured at ≥3σ significance, and C IV class score ≥0.7 recorded in the catalog. Both of the FWHM and REW cutoffs apply to the stronger λ1548 component in the C IV doublet. The C IV class score represents the quality assessments of the NALs identified from the machine-learning algorithm in D. York et al. (2020, in preparation). Based on these restrictions, more than 90% of the C IV NALs included in our sample are reliable (see D. York et al. 2020, in preparation, for more discussion). The total number of quasars selected this way is 40,696 from a previous full sample of 100,376. A total of 54,154 C IV NALs are well-measured in the spectra of this subsample. A cutoff value of REW at 0.3 or 0.4 Å will yield a larger C IV NAL sample, but not alter the main results of the paper.

We show the SNR1700 distribution of the quasar spectra and the REW distribution of C IV absorption lines from the full sample in Figure 1, and the velocity shift distribution of the C IV NALs from the subsample in Figure 2. In Figure 2 we have not corrected for the detection completeness variation as a function of velocity shift because the velocity dependence is weak for this data set. The results shown in Figure 2 are in good agreement with previous studies that do make those detection completeness corrections (see Figure 5 in Nestor et al. 2008 and Figure 9 in Wild et al. 2008). From Figure 2, we can tell that most of the measured NALs are within −1000 to 1000 km s⁻¹ to the quasar redshift, and the velocity shift distribution includes contributions from four different types of NALs, namely, (1) unrelated intervening systems with no significant velocity shift dependence (represented on average by the dotted blue line in Figure 2), (2) low-speed NALs that have a nearly Gaussian distribution of measured line shifts centered at v ∼ 0 km s⁻¹, where the velocity spread is caused at least in part by uncertainties of the quasar systemic redshifts (see the solid red curve in Figure 2), (3) an excess above the Gaussian curve at the positive velocities that could identify gaseous infall, and (4) an excess above both the Gaussian curve and the flat intervening distribution at the negative velocities caused by high-speed outflows ejected from the quasars. It is evident from Figure 2 and previous studies (Weymann et al. 1979; Nestor et al. 2008; Wild et al. 2008; Perrotta et al. 2018) that the majority of strong NALs in the velocity range of −8000 < v < −1000 km s⁻¹ are formed in the high-speed quasar-driven outflows.

The crux of our study is a statistical comparison of different groups of C IV NALs. Table 1 summarizes the main NAL
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Table 1

| Line Group      | Velocity Shift (km s\(^{-1}\)) | # Quasars | # NALs |
|-----------------|---------------------------------|-----------|--------|
| AALs            | −8000 to 5000                   | 22,335    | 25,264 |
| Outflow AALs    | −8000 to −1000                 | 11,097    | 12,213 |
| Infall AALs     | ≥400                            | 2896      | 2945   |

Note. Quantities listed are the group name, velocity shift range (km s\(^{-1}\)), number of quasars, and number of NALs in each group.

.groups we consider, sorted mainly by velocity shifts, where negative velocities indicate blueshifts relative to the quasar emission-line redshifts and positive velocities indicate redshifts. “AALs” are any NALs from our subsample within the velocity shift of −8000 to 5000 km s\(^{-1}\). We adopt this velocity range because NALs in this range have a high probability of being intrinsic to the quasar environments (Figure 2; see also Weymann et al. 1979; Nestor et al. 2008; Wild et al. 2008). We define candidate “outflow AALs” as in the more limited velocity range of −8000 to −1000 km s\(^{-1}\) again based on Figure 2. Previous studies have shown that most NALs in this velocity range form in quasar-driven outflows. In particular, velocity shifts \(v \leq −1000\) km s\(^{-1}\) are too large to include starburst-driven winds and other ambient gas in the quasar host galaxies (Richards et al. 1999; Heckman et al. 2000; Nestor et al. 2008). We define candidate “infall AALs” as another subset of AALs at velocity shifts >400 km s\(^{-1}\). This group aims to isolate true infall systems from those formed in ambient gas that can have a range of measured velocities near \(v \sim 0\) due to the redshift uncertainties. In particular, \(v > 400\) km s\(^{-1}\) can exclude most of the Gaussian distribution (1\(\sigma\)) shown in red in Figure 2.

Figure 3 shows the quasar number distribution in the number of CIV NALs systems contained in each quasar, for AALs, outflow AALs, and infall AALs, respectively. As shown in Figure 3, most of them do not contain any of the three NALs groups defined above. It is important to keep in mind that these numbers are limited to relatively strong CIV NALs with REW > 0.5 Å due to the relatively low resolution (\(R \sim 2000\) corresponding to \(\sim 150\) km s\(^{-1}\)) and low signal-to-noise ratios in the BOSS spectra.

An important part of our analysis is to compare the incidence of different groups of CIV NALs to CIV BALs in the same spectra. We identify BAL and non-BAL quasars (BALQSOs and non-BALQSOs) using the “balnicity index” (BI) as reported in the BOSS DR12 quasar catalog (Pâris et al. 2017). Specifically, we require BI = 0 for non-BALQSOs and BI ≥ 500 measured at ≥3\(\sigma\) significance for BALQSOs. We also require that the BAL troughs do not have significant absorption at velocities \(v > −8000\) km s\(^{-1}\). This may eliminate many BALs from our sample, but can avoid the spectral overlap with AALs at low velocities, which is essential for some of our analysis in Section 3. We enforce this velocity cut by requiring \(v_{\text{min,civ}} < 0\) km s\(^{-1}\) as recorded in the BOSS DR12 quasar catalog (where \(v_{\text{min,civ}}\) is the lowest velocity where the CIV BAL trough dips >10% below the continuum; Pâris et al. 2017). Since it is known that some quasar properties, such as the UV luminosity (e.g., Gibson et al. 2009), are correlated with the BAL velocity, we have also investigated the impact of this velocity cut of BAL troughs in our study. We have done an analysis without this BAL velocity cut and found little changes to our analysis results presented in Section 3.

3. Analysis and Results

3.1. REW and FWHM Distributions

Figure 4 compares the normalized FWHM and REW distributions of the CIV AALs, outflow AALs, and infall AALs. The distributions are normalized for easier comparisons. The median values are 0.66, 0.62, 0.71 Å for the REW distribution of AALs, outflow AALs, and infall AALs, respectively, and 277, 296, 262 km s\(^{-1}\) for FWHM distribution of AALs, outflow AALs, and infall AALs respectively. To study the dependence of the NALs occurrence rate on the FWHM and REW distribution, We also compare the fractions of different NALs groups in the lower end (pink marked area).
and upper end (yellow marked area) of the FWHM and REW distributions, respectively. The selection of the lower end (200–250 km s$^{-1}$ for FWHM or 0.5–0.7 Å for REW) and upper end (350–500 km s$^{-1}$ for FWHM or 1.35–1.75 Å for REW) on the plot is done with the principles of (1) selecting typical areas on both ends within the parameter ranges set in Section 2, (2) there being enough sources in each area to ensure good statistics, (3) AALs being resolved at the BOSS spectral resolution, and (4) using round numbers. The results are shown in the pink and yellow insets of Figure 4. As can be seen from the insets, there is a significant tendency for the infall AALs to be narrower (from the distribution of FWHM) and stronger (from the distribution of REW) than the other AAL groups.

We have also done a Kolmogorov–Smirnov (K-S) test to compare the REW distribution of AALs, outflow AALs, infall AALs in BALQSOs, and non-BALQSOs respectively, and found no significant difference between the REW distribution of NALs in BALQSOs and non-BALQSOs. This indicates statistically that the presence of BAL components has no significant impact on the strengths (as shown by REWs) of AALs, outflow AALs, or infall AALs in the same quasar.

### 3.2. Correlation Analysis

In the remainder of this section, we use the Z-test to study the correlations between the incidence rates of different C IV NAL groups to the intrinsic quasar properties including BALs and radio-loudness. The Z-test for two group fractions is used when determining whether two groups (e.g., BALQSOs and non-BALQSOs) differ significantly on some categorical characteristics (e.g., whether they have AALs) when the variances are known and the sample size is large. For example, when studying the correlation between the incidence rate of AALs and the BALs property, we use four numbers as our Z-test inputs, including the number of BALQSOs with and without AALs, and non-BALQSOs with and without AALs. Similar Z-tests have been done in our correlation analysis. The results of the Z-tests, including the Z values and P-values, are shown in Table 2. If $Z \geq 2.58$ or $Z \leq -2.58$ ($P < 0.01$), then statistically the incidence rate of specific types of NALs and some intrinsic quasar property (such as BALs or radio-loudness) should have strong positive or negative correlation. The P-value here represents the probability that the correlation can occur by a random chance. We will explore these correlation results in detail next.

Figure 5 plots the fractions of quasars with C IV AALs and outflow AALs for quasars with and without C IV BALs. In this plot, we have separated the C IV AALs according to a certain

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**Table 2**

|        | AALs       | Outflow AALs | Infall AALs |
|--------|------------|--------------|-------------|
| BALs   | 3.64 (0)   | 6.84 (0)     | -1.47 (0.14) |
| Radio-loudness | 0.88 (0.38) | 0.37 (0.70)  | -0.02 (0.98) |

**Note.** Value of $|Z| \geq 2.58$ indicates a strong correlation at $\geq$99% confidence. For example, the Z-value of 3.64 in the first column suggests BALQSOs are more likely to have C IV AALs in their spectra than non-BALQSOs.
REW threshold. From the left panel of Figure 5, there are significantly higher probabilities for AALs appearing in BALQSOs compared to non-BALQSOs. From the right panel of Figure 5, these differences are larger for outflow AALs. For both AAL groups in Figure 5, stronger AALs (larger REWs) show bigger ratios of the fraction percentage. For example, outflow AALs with REW > 1 Å are >2 times more common in BALQSOs than in non-BALQSOs, and those with REW > 2 Å are >4 times more common. The results shown graphically in Figure 5 are supported by the Z-test results in Table 2. In particular, the Z-test values indicate that both AALs and outflow AALs are strongly correlated with BALs at >99.7% confidence.

Figure 6 shows the fractions of quasars with different numbers of AALs in BALQSOs versus in non-BALQSOs. Note that the bars showing the fractions with ≥1 AAL are the same as bars showing the fraction with REW > 0.5 in the left panel of Figure 5. From Figure 6, the ratio between the fraction percentage of BALQSOs with AALs and the fraction percentage of non-BALQSOs with AALs is larger regarding multiple AAL systems than regarding single AAL systems. This suggests that BALs play a more important role in the formation of multiple AAL systems.

Figure 7 plots the fractions of quasars with one or more infall AALs in BALQSOs versus non-BALQSOs. There exists a weak tendency for fewer infall AALs appearing in quasars with BALs, which has a Z-value of −1.47. The probability of this trend occurring by random chance is \( P = 14\% \) from the Z-test (see Table 2). Since infall AALs are a subset of all AALs, the trend of more AALs existing in BALQSOs shown above in Figure 5 is actually weakened slightly by the opposite trend shown here for the infall AALs.

Radio-loudness in quasars is an indicator of relativistic jets, which can produce radio flux via synchrotron emissions. These radio jets might sweep up cooler gas in the quasar host galaxies to produce outflow AALs when viewed along a particular line of sight. We compare the fractions of quasars with AALs, outflow AALs, and infall AALs versus radio-loudness. We use 20 cm radio fluxes from the FIRST radio survey as recorded in the BOSS DR12 quasar catalog (Pâris et al. 2017). It has been shown that detection at 20 cm in this survey is equivalent to standard definition of radio-loud for quasars at the redshifts and rest-UV magnitudes of our study (Richards 2001). Conversely, non-detection indicates that the quasar is radio-quiet. The Z-test results are listed in Table 2. We do not find any significant correlation between radio-loudness of quasar in our sample to the presence of AALs, outflow AALs, or infall AALs from the same quasar, with the measured probability of correlation occurring by chance \( P \geq 40\% \).

### 3.3. Composite Spectra

We create median composite spectra in the absorber frame for all non-BALQSOs sorted by the NAL group, e.g., AALs, outflow AALs, and infall AALs, respectively. Portions of the resulting normalized composite spectra are shown in Figure 8.
We have measured the REWs for the high-ionization and low-ionization lines detected in the composite spectra, and the results are presented in Table 3. Comparing with the outflow AALs, the infall AALs have moderately stronger high-ionization lines, e.g., CIV, NV, OVI, and weaker low-ionization lines, e.g., SiII, CII. Thus, contrary to our common understanding, this indicates that the infall gas has moderately higher ionizations than quasar-driven outflows. There is no significant absorption in any of the excited-state lines like SiII* λ1265, 1533 and CII* λ1336 from the composite spectra of outflow AALs. We will discuss these results further in Section 4 below.

4. Discussion

In Section 3, we have described comparisons between different CIV NAL groups and their correlations with certain quasar properties, namely BAL outflows and radio-loudness. We find numerous strong correlations as well as differences in the line ratios (ionizations) that can provide new constraints on the physical nature of quasar outflows and infall absorbers in quasar environments. Here we provide a brief discussion.

4.1. Outflow AALs

The velocity distribution of CIV NALs in our study (Figure 2) confirms the results from previous work (Weymann et al. 1979; Nestor et al. 2008; Wild et al. 2008) that most AALs in the velocity range $-8000 < v < -1000$ km s$^{-1}$ form in quasar-driven outflows. Further analysis in Section 3.2 shows that the presence of AALs is strongly correlated with BALs. The correlation is especially strong for outflow AALs and strong AALs with large REWs, which suggests that most AALs form in quasar-driven outflows. We also detect a higher incidence rate of multiple AALs when BALs are present, which indicates that quasar outflows tend to be highly structured, and thus can create multiple gas components appearing at different velocities along our line of sight.

Our composite spectra of outflow AALs show no obvious absorption lines in the excited state, like SiII* or CII*, which indicates that typical outflow AALs have low densities, large distances ($>a$ few kpc) away from the quasars (see more details in Chen et al. 2018).

4.2. Infall AALs

Another interesting result of our study is a weak tendency for infall AALs (at measured velocity shifts $v > 400$ km s$^{-1}$) to appear less often in quasars with BALs than quasars without...
BALs. This result provides tentative evidence for BAL outflows acting on large scales in quasar host galaxies where they inhibit the infall of gas from the IGM. It supports theoretical models of galaxy evolution that invoke quasar outflows as an important source of feedback to the host galaxies (Section 1). Our composite spectra show further that the infall AALs have higher ionization than outflow AALs. This result might be surprising if we expect the infall AALs to be physically located farther away from the quasar than outflow AALs. However, if the infall absorbers possess lower gas densities, it could cause a higher degree of ionization (larger ionization parameters in photoionization models) in spite of being at larger distances away from the quasar than the outflow AALs. These results need further investigation, which is beyond the scope of the present study.

5. Summary

We use the SDSS-BOSS DR12 database to investigate the nature and origin of infall and outflows in quasar environments by examining the relationships of their C IV NALs at positive and negative velocity shifts to other quasar properties such as their BAL outflows, and radio-loudness. Our analysis yields the following results:

(1) AALs, outflow AALs, and multiple AALs are strongly correlated with BALs, which suggests most AALs have formed in quasar-driven outflows. Since quasar outflows tend to be highly structured, we often can detect multiple gas components with different velocities along our line of sight (Sections 3.2 and 4.1).

(2) Our median composite spectra of outflow AALs show no obvious absorption lines in excited states. This indicates that typical quasar-driven outflows have low densities and large distances (>a few kpc) away from the central quasars (Sections 3.3 and 4.1). The outflow AALs may be outer extensions of BAL flows much farther out in the host galaxies, and that these outflows are inhibiting inflow at least along the observed line of sight.

(3) Infall AALs appear less often in quasars with BALs than quasars without BALs, which indicates BAL outflows act on large scales in quasar host galaxies and hinder the infall of gas from the IGM. It supports theoretical models of which quasar-driven outflow plays an important role in the feedback to the host galaxies (Sections 3.2 and 4.2).

(4) Our median composite spectra show that the infall AALs are more highly ionized than outflow AALs. It could be attributed to the lower densities in the infall absorbers in spite of the larger distances compared to outflow AALs (Sections 3.3 and 4.2).

(5) Our radio-loudness correlation analysis finds that none of the NAL types correlate significantly with radio-loudness, indicating, in particular, that outflow AALs are not caused by powerful radio jets (Section 3.2).

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