Direct Measurement of Quasar Outflow Wind Acceleration

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Abstract

We search for velocity changes (i.e., acceleration/deceleration) of narrow absorption lines (NALs) that are intrinsic to the quasars using spectra of six bright quasars that have been observed more than once with 8–10 m class telescopes. While variations in line strength and profile are frequently reported (especially in broader absorption lines), definitive evidence for velocity shifts has not been found, with only a few exceptions. Direct velocity shift measurements are valuable constraints on the acceleration mechanisms. In this study, we determine velocity shifts by comparing the absorption profiles of NALs at two epochs separated by more than 10 yr in the observed frame using the cross-correlation function method, and we estimate the uncertainties using Monte Carlo simulations. We do not detect any significant shifts, but we obtain 3σ upper limits on the acceleration of intrinsic NALs (compared to intervening NALs in the same quasars) of ~0.7 km s\(^{-1}\) yr\(^{-1}\) (~0.002 cm s\(^{-2}\)) on average. We discuss possible scenarios for nondetection of NAL acceleration/deceleration and examine the resulting constraints on the physical conditions in accretion disk winds.

Key words: quasars: absorption lines – quasars: individual (HE 0130–4021, Q0450–1310, HE 0940–1050, HE 1009+2956, Q1107+4847, and HS 1700+6416)

Supporting material: extended figure

1. Introduction

The signatures of outflowing winds from accretion disks are observed in the spectra of ~50% of quasars and active galactic nuclei (AGNs; Hamann et al. 2012). The winds play an important role in providing energy and momentum feedback to the interstellar medium of their host galaxies and by transporting heavy elements out of the host galaxies (e.g., Springel et al. 2005). The blueshifted near-UV absorption lines (e.g., the C IV, Si IV, and N V doublets) that are the observational signature of outflowing winds are usually classified into three categories according to their widths: broad absorption lines (BALs) with FWHM ≥ 2000 km s\(^{-1}\), narrow absorption lines (NALs) with FWHM ≤ 500 km s\(^{-1}\), and an intermediate subclass (mini-BALs). The difference in line width may depend on the inclination angle of our line of sight relative to the axis of the wind (an orientation scenario; e.g., Weymann et al. 1991), although evolutionary scenarios have also been discussed (e.g., Lipari & Terlevich 2006); see the summary in Bruni et al. (2012) and references therein.

The physical conditions of quasar winds have been studied through variability of the absorption lines, since almost all BALs and mini-BALs vary over a few years in the quasar’s rest frame (e.g., Gibson et al. 2008; Misawa et al. 2014). Variations are usually seen in the strengths and profiles of (mini-)BAL troughs (e.g., Capellupo et al. 2012). The probability of observing variations increases with the time interval between observations, approaching unity for an interval of a few years (e.g., Capellupo et al. 2011). In extreme cases, BAL profiles appear or disappear completely (e.g., Filiz et al. 2012; Vivek et al. 2012). Possible origins of such variations include (a) motion of the absorbing gas parcels across our line of sight (e.g., Hamann et al. 2008) and (b) changes in the ionization state of the absorber (e.g., Misawa et al. 2007b).

Velocity shifts of absorption lines from winds have not been studied except in a few cases for BALs and mini-BALs (e.g., Joshi et al. 2014, 2018; Grier et al. 2016), despite the fact that acceleration is a key physical property of the gas in quasar winds. A direct detection of velocity shifts would provide valuable constraints on acceleration mechanisms. Three different processes have been proposed for accelerating winds: radiation pressure (absorption of line photons; e.g., Murray et al. 1995), magneto-centrifugal forces (e.g., Everett 2005), and thermal pressure (e.g., Balsara & Krolik 1993). Among these, radiation pressure must contribute significantly at least to the acceleration of X-ray absorbers with large ejection velocities (ultrafast outflows), because their total kinetic energy, \(E_k = \frac{1}{2}Mv^2\) (where \(M\) is the mass ejection rate), is well correlated with the bolometric luminosity (\(L_{bol}\)) of the quasars (e.g., Tombesi et al. 2013). However, it is still not clear whether the radiative force is also the main source of acceleration for absorbers detected through UV lines whose distances from the central engine may be much larger than those of absorbers detected via X-ray lines. Studies of velocity shifts using (mini-)BALs may be complicated by the following: (1) the absorption lines sometimes suffer from self-blending (i.e., the blue and red components of a doublet are blended with each other), and (2) a change in line profile could be mistaken for a velocity shift.

In contrast to previous studies that focused on BALs and mini-BALs, here we monitor the velocities of intrinsic NALs...
for the first time. In the case of NALs, small velocity shifts can be detected very easily because of their small widths. We describe target selection in Section 2, the observations and data reduction in Section 3, and the data analysis in Section 4. The results and discussion are presented in Sections 5 and 6. We close by summarizing our results in Section 7. We use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ throughout the paper.

2. Sample Selection

We assembled a sample of six quasars based on two criteria: (a) they have at least one C IV, Si IV, or N V NAL in their spectra that has already been confirmed to be physically associated with the quasar, and (b) there are multiple high-resolution spectra ($R \sim 40,000$) of each quasar that were already available or would soon be available through upcoming observing programs over a time interval of more than 10 yr in the observed frame.

We selected the target quasars with “reliable” (class A) and “possible” (class B) intrinsic NALs from the catalog of Misawa et al. (2007a). The catalog was constructed after examining the NALs in 37 quasar spectra and selecting those that are intrinsic based on partial coverage analysis. Two of the quasars we selected, HE 0130–4021 and HS 1700+6416, had previously been observed more than once with 10 m class telescopes (i.e., the Keck and Subaru Telescopes and the Very Large Telescope (VLT)) with some time intervals that exceed 10 yr in the observed frame (see details in Misawa et al. 2014). We also chose four additional quasars, Q0450–1310, HE 0940–1050, HE 1009+2956, and Q1107+4847, which we reobserved with the Subaru Telescope. These four quasars are known to have at least one intrinsic NAL, and their oldest spectra were taken more than 10 yr ago. They are accessible from the Subaru Telescope and are bright enough ($V \leq 18.2$) so that spectra with a signal-to-noise ratio (S/N) of $\geq 20$ pixel$^{-1}$ could be obtained with $\sim 2$ hr exposures.

Table 1 summarizes the properties of our sample quasars, including coordinates, emission redshift, optical magnitude, bolometric luminosity, and radio-loudness. As shown in Figure 1, our sample quasars have extremely large bolometric luminosity, with $\log(L_{bol}/\text{erg s}^{-1}) \sim 48.0$–48.3, compared to SDSS quasars at a similar redshift as our targets ($z_{em} \sim 2.0$–3.0) from Shen et al. (2011). Thus, we emphasize that our sample is biased toward large-luminosity quasars. We will discuss this further in Section 6.

3. New Observations

We observed the four quasars noted in the previous section with the Subaru Telescope and High Dispersion Spectrograph (HDS) on 2016 January 27. Among the four quasars, HE 0940–1050 had been observed once with the VLT in 2000, while the other three quasars had been observed once with the Keck in the 1990s (see details in Misawa et al. 2014). The weather conditions were very good throughout the night with a typical seeing of $\sim 0''6$. The time delays from the first observations of those quasars are $\sim 15$–20 yr in the observed frame. We acquired high-resolution spectra ($R \sim 45,000$) with a slit width of $0''8$ and adopted bins of 2 pixels in both the spatial and dispersion directions (i.e., $\sim 0.03$ Å pixel$^{-1}$) to increase the S/N. To cover as many NALs as possible, we used standard setups: Std-Ya for Q0450–1310 and HE 1009+2956 and Std-Yc for HE 0940–1050 and Q1107+4847. These cover a wavelength range of 4030–4800 or 4420–5660 Å on the blue CCD and 4940–5660 or 5860–7050 Å on the red CCD, respectively. We took four 1800 s exposures for each quasar (i.e., a total integration time of 7200 s), except for Q0450–1310, whose total integration time was 10,800 s ($1800 \times 6$). The log of our observations, as well as the past observations of the six quasars, is summarized in Table 1, including observation date, spectral resolution, total integration time, and S/N per pixel. In the same table, we also give the rest-frame time interval between the observations.

We reduced the data in a standard manner with the IRAF software package. Wavelength calibration was performed with the help of the spectra of a Th–Ar lamp. We fitted the effective continuum, which also includes a substantial contribution from broad emission lines, with a third-order cubic spline function to normalize the spectra. We did not adjust the wavelength resolution of the new spectra to match that of the old spectra, because the typical line width of the absorption components is large enough ($b \geq 10$ km s$^{-1}$; Misawa et al. 2007a) that they are fully resolved. The final S/N around $\sim 4900$ Å is $\sim 15$–47 pixel$^{-1}$ for each quasar.

4. Cross-correlation Analysis

We measured velocity shifts by comparing NAL profiles in the first and second epochs using the cross-correlation function (CCF) method that was originally adopted for BALs in Grier et al. (2016).

4.1. Methodology

We first isolated a spectral region around each NAL with $\sim 2$ Å margins on both sides and resampled it to bins of 0.05 Å, which is the typical dispersion (pixel scale) of all spectra in our sample (see Figure 2). Next, we normalized the clipped spectrum using a low-order spline function, avoiding absorption regions. Finally, we used the spectra from the first and second epochs to calculate Pearson’s cross-correlation coefficient,

$$ r = \frac{\sum(f_1(\lambda) - \bar{f}_1(\lambda))(f_2(\lambda) - \bar{f}_2(\lambda))}{\sqrt{\sum(f_1(\lambda) - \bar{f}_1(\lambda))^2 \sum(f_2(\lambda) - \bar{f}_2(\lambda))^2}}, $$

where $f_1(\lambda)$ and $f_2(\lambda)$ are the normalized flux densities in the first and second epochs and $\bar{f}_1(\lambda)$ and $\bar{f}_2(\lambda)$ are their average values. We repeated the calculation of $r$ after shifting one spectrum from $-15$ to $+15$ pixels in steps of 1 pixel (corresponding to 0.05 Å pixel$^{-1}$, or $\sim 3$ km s$^{-1}$ pixel$^{-1}$) to build the CCF. From the CCF, we measured the velocity shift corresponding to the CCF centroid, $\Delta v(\text{CCF})$, by finding the weighted center of the CCF using the portion corresponding to $r > 0.8r_{\text{peak}}$, where $r_{\text{peak}}$ is the peak value of the CCF. We performed this analysis separately for the blue and red members of the doublet (i.e., C IV $\lambda\lambda1548, 1551$, Si IV $\lambda\lambda1394, 1403$, and N V $\lambda\lambda1239, 1243$), if both were detected. As an example, the CCF for the class B Si IV NAL at $z_{abs} = 2.8347$ for HE 0940–1050 is shown in Figure 3. The $\Delta v(\text{CCF})$ values for all of the NALs are summarized in Table 2.

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

6 We require at least $\pm 1$ Å on both sides even if the $\pm 2$ Å regions are partially affected by data defects or line blending.
### Table 1
Sample Quasars

| Quasar     | R.A. (hh mm ss) | Decl. (dd mm ss) | z_em | m_V (mag) | L_{bol}^a (erg s^{-1}) | R^b          | Obs. Date    | Tel./Inst. | R | T_exp (s) | S/N | Δt_{rest} (yr) |
|------------|-----------------|------------------|------|-----------|------------------------|--------------|--------------|-------------|--------------|------------|-----|----------------|
| HE 0130–4021 | 01 33 02        | −40 06 28        | 3.030 | 17.02     | 1.1 \times 10^{48}    | 11.2         | 1995 Dec 28 | Keck/HIRES | 36,000      | 14,400    | 41  | 2.9            |
| Q0450–1310     | 04 53 12        | −13 05 46        | 2.300 | 16.50     | 1.1 \times 10^{48}    | <1.7         | 1998 Dec 13–14 | Keck/HIRES | 36,000      | 7200      | 19  | 5.2            |
| HE 0940–1050   | 09 42 53        | −11 04 25        | 3.080 | 16.90     | 1.3 \times 10^{48}    | <2.6         | 2000 Apr 3 | VLT/UVES   | 40,000      | 3600      | 32  | 3.9            |
| HE 1009+2956   | 10 11 55        | +29 41 41        | 2.644 | 16.40     | 1.5 \times 10^{48}    | <1.6         | 1995 Dec 29 | Keck/HIRES | 36,000      | 12,200    | 56  | 5.5            |
| Q1107+4847     | 11 10 38        | +48 31 16        | 3.000 | 16.60     | 1.6 \times 10^{48}    | <2.0         | 1995 May 9 | Keck/HIRES | 37,500      | 7200      | 59  | 5.2            |
| HS 1700+6416   | 17 01 00        | +64 12 09        | 2.722 | 16.13     | 2.1 \times 10^{48}    | <1.2         | 1995 May 10 | Keck/HIRES | 36,000      | 11,500    | 72  | 2.8            |

Notes.

a Bolometric luminosity, calculated as $L_{bol} = 4.4 \lambda L_\lambda(1450 \text{ Å})$, following Richards et al. (2006).

b Radio-loudness, calculated as $R = f_\nu(5 \text{ GHz}) / f_\nu(4400 \text{ Å})$, following Kellermann et al. (1989, 1994).

c S/N at $\lambda_{obs} \sim 4900$ Å.

d Time interval between observations in the quasar’s rest frame.
To determine the uncertainties, we performed a Monte Carlo simulation using synthetic spectra in which the flux density of each pixel was perturbed by a random amount drawn from a Gaussian distribution with a mean equal to the measured flux density and a standard deviation equal to the uncertainty. We constructed 100 synthetic spectra for each epoch and repeated the CCF calculations 10,000 times using all combinations of the artificial spectra in both epochs (i.e., 100 × 100). We took the average of the CCF centroid distribution of the distribution as the 1σ uncertainty of Δν(CCCD) and the standard deviation of the distribution as the 1σ uncertainty of Δν(CCCD) for each NAL. We summarize these in Table 2.

4.2. Tests

To assess the performance of the CCF and CCCD methods used above, we carried out the following tests.

1. We investigated whether the sampling of the spectra led to systematic errors in the shift determination. We synthesized two normalized spectra corresponding to those in the first and second epochs, in which we added a single component of a C IV λ1548 line at zabs = 2.2367 and 2.236722, respectively. Both spectra have a wavelength range of λ = 5007.5–5014.5 Å. The velocity offset between the C IV lines is 2.03 km s−1. We used common line parameters except for redshift; a column density and Doppler parameter of log(N_C IV / cm−2) = 13.5 and b = 12.0 km s−1 (i.e., typical values of our NAL sample); and a coverage fraction of Cf = 1.0 (i.e., a full coverage). We also assumed a wavelength resolution of R = 45,000 (a typical value of our data) and a dispersion of Δλ = 0.01 Å pixel−1, and finally, we added a noise corresponding to an uncertainty of 0.033 in each pixel (i.e., S/N ∼ 30 pixel−1).

First, we constructed synthetic spectra for a range of different dispersions, from Δλ = 0.01 to 0.15 Å pixel−1 in steps of 0.01 Å pixel−1, and used them to perform the CCF and CCCD analyses and evaluate the shift between them. We also performed the same test on an observed spectrum, the C IV λ1548 line at zabs = 2.2316 for HE 0130–4021, for which we found a velocity shift of Δν = 1.34 km s−1 based on the default dispersion (i.e., Δν = 0.05 Å). The results for the synthetic and observed spectra are shown in Figure 4 as a function of dispersion. Both results are obviously affected by the wavelength bin size. In the case of the synthetic spectrum, the shift Δν is within 1σ of the actual value for Δλ up to 0.12 Å pixel−1. For the observed spectrum, the Δν is consistent with 1.34 km s−1 for all dispersions up to Δλ ∼ 0.14 Å pixel−1. In both cases, the deviation in the measured Δν is not significant compared to the uncertainties in the data. Certainly, this pattern should depend on the spectral resolution; however, in our case (i.e., R ∼ 45,000), any systematic error in the shift would be negligible, since we adopt a dispersion of Δλ < 0.07 Å pixel−1 or smaller.

We then carried out the same test, this time shifting the starting wavelength for sampling by one-fifth of the bin size. More specifically, we first sampled the spectrum from 5007.50 to 5014.50 Å with a bin width of Δλ = 0.05 Å, and then we repeated with the same bin width but sampled starting at 5007.51 Å, having shifted by one-fifth of the bin size (i.e., by 0.01 Å). The fifth trial would thus give the same result as the first one. The results are shown in Figure 5, which illustrates that there is no obvious systematic error.

2. We compared the results from the above methods with shift measurements made with the “χ2 cross-correlation” method of Eracleous et al. (2012; see their Section 6.1). The method starts with a linear transformation of the flux scale of the second spectrum of the form f′ = a × f + b; i.e., it applies a scale factor and vertical offset so that the two spectra match each other as closely as possible except for a wavelength/velocity shift. Then the second of the two spectra is shifted in small steps and compared to the first by the χ2 test. The final output is a χ2 curve as a function of shift. The minimum of this curve, determined by fitting a parabola to the points near the minimum of the curve, represents the optimal wavelength/velocity shift. We also carried out simulations as described in Eracleous et al. (2012) to determine the smallest shifts measurable with the available data and verify the reliability of the uncertainties. We found the results of the two independent methods of shift measurement to be in very good agreement with each other. Between the two methods above, we chose the CCF/CCCD method for our analyses, because it has been frequently adopted for measuring velocity shifts of BALs (Grier et al. 2016; Joshi et al. 2018) so that we can directly compare our results to the literature without any additional uncertainties.

\[ \frac{Δν}{c} = -\frac{(1 + z_1)^2 - (1 + z_2)^2}{(1 + z_1)^2 + (1 + z_2)^2}, \]  
where z1 and z2 are the apparent redshift of the C IV absorber at the first and second epochs, respectively.

This is not due to the cosmic expansion but rather is calculated by the relativistic Doppler formula.

The fraction of photons from the background light source(s) that pass through the absorber (e.g., Wampler et al. 1995; Barlow & Sargent 1997).
From the above tests, we conclude that the CCF and CCCD methods, as we implement them here, are robust and not affected by the wavelength binning scheme that we adopted. Henceforth, we adopt the results of the CCF and CCCD analyses, as summarized in Table 2, and we discuss them below.

4.3. Systematics

We found the distributions of the velocity shift measured from the CCF and CCCD analyses ($\Delta v_{\text{CCF}}$ and $\Delta v_{\text{CCCD}}$) to be systematically shifted from zero (see Figure 6), which we
attribute to a small, systematic linear offset of the spectra in each pair resulting from an uncertainty of wavelength calibration using Th–Ar spectra. To quantify this systematic effect, we measured the velocity shift of intrinsic (i.e., class A and B) NALs compared to intervening (i.e., class C) NALs between the two epochs for each quasar, instead of using the values obtained by directly comparing the intrinsic NALs from the two epochs.

We also noticed that there is a systematic nonlinear distortion in relative wavelength between spectra at different epochs (e.g., Griest et al. 2010; Evans et al. 2014). For example, the $\Delta v$ (CCCD) values for the blue and red members of the C IV NAL at $z_{\text{abs}} = 1.6968$ toward Q0450–1310 (i.e., $-4.26 \pm 1.40$ and $-0.91 \pm 2.53$) do not match, although they should be the same. To evaluate the distortion error, we compared all pairs of intervening (class C) lines, examined the distribution of velocity shift differences (i.e., $|\Delta v| = |\Delta v(\text{CCCD})_i - \Delta v(\text{CCCD})_j|$ between the $i$th and $j$th lines in the same spectrum), and calculated their root mean square (rms) values as summarized in Table 3. For example, we detect 14 class C lines (here we double-count lines if both blue and
### Table 2
Sample NALs

| Quasar     | $z_{\text{abs}}$ | $v_0$ (km s$^{-1}$) | Ion | Comp. | Class | $\Delta v$ (CCF)$^j$ (km s$^{-1}$) | $\Delta v$ (CCCD)$^j$ (km s$^{-1}$) | $\Delta v \pm \sigma (\Delta v)^j$ (km s$^{-1}$) | Sample$^e$ | Notes                                           |
|------------|-----------------|---------------------|-----|-------|-------|-------------------------------|-------------------------------|---------------------------------|-----------|------------------------------------------------|
| HE 0130–4021 | 2.2316          | 65181               | C IV | b     | B     | 1.41 ± 0.34                  | 1.34 ± 0.34                  | 1.34 ± 0.34                      | d         | Blend with other lines                          |
|            | 2.5597          | 37037               | C IV | b     | A     | 0.29 ± 0.21                  | 0.26 ± 0.21                  | 0.26 ± 1.27                     | al        |                                                 |
|            | 2.6884          | 26503               | C IV | b     | C     | 2.27 ± 0.58                  | 2.24 ± 0.58                  | 2.24 ± 1.38                     | d         | Affectcd by data defect in first spectrum       |
|            | 2.8570          | 13155               | Si IV | b     | C     | 1.19 ± 0.30                  | 1.19 ± 0.30                  | 1.19 ± 1.29                     | c         | May be time variable                             |
|            | 2.8571          | 13147               | C IV | b     | C     | 0.38 ± 0.44                  | 0.49 ± 0.44                  | 0.49 ± 1.33                     | d         | Affectcd by data defect in first spectrum       |
|            | 2.9749          | 4130                | N V  | b     | A     | −0.16 ± 0.35                 | −0.14 ± 0.35                 | −0.14 ± 1.30                    | b         | Margin is <2 Å because of data defect           |
| Q0450–1310 | 1.6968          | 59748               | C IV | b     | C     | −4.20 ± 1.40                 | −4.26 ± 1.40                 | −4.26 ± 2.18                    | b         | Margin is <2 Å because of line blending         |
|            | 1.9986          | 28646               | C IV | b     | C     | −1.05 ± 2.53                 | −0.91 ± 2.53                 | −0.91 ± 3.03                    | al        |                                                 |
|            | 2.0667          | 21957               | Si IV | b     | C     | −3.44 ± 0.70                 | −3.47 ± 0.70                 | −3.47 ± 1.81                    | al        |                                                 |
|            | 2.0668          | 21947               | C IV | b     | C     | −4.66 ± 1.41                 | −4.63 ± 1.41                 | −4.63 ± 2.19                    | al        |                                                 |
|            | 2.1059          | 18163               | Si IV | b     | C     | −4.10 ± 0.83                 | −4.21 ± 0.83                 | −4.21 ± 1.86                    | al        |                                                 |
|            | 2.1061          | 18144               | C IV | b     | C     | −3.67 ± 0.81                 | −3.76 ± 0.81                 | −3.76 ± 1.86                    | al        |                                                 |
|            | 2.2307          | 6366                | Si IV | b     | A     | −3.51 ± 0.87                 | −3.65 ± 0.87                 | −3.65 ± 1.88                    | a         |                                                 |
| HE 0940–1050 | 2.2210          | 69629               | C IV | b     | C     | −0.78 ± 0.18                 | −0.81 ± 0.18                 | −0.81 ± 0.92                    | al        |                                                 |
|            | 2.3302          | 60096               | C IV | b     | C     | −1.13 ± 0.18                 | −1.14 ± 0.18                 | −1.14 ± 0.92                    | al        |                                                 |
|            | 2.4090          | 53331               | C IV | b     | C     | −0.95 ± 0.41                 | −0.89 ± 0.41                 | −0.89 ± 0.99                    | al        |                                                 |
|            | 2.6580          | 32625               | C IV | b     | C     | −1.60 ± 0.73                 | −1.62 ± 0.73                 | −1.62 ± 1.16                    | al        |                                                 |
|            | 2.6677          | 31839               | C IV | b     | C     | −1.07 ± 0.57                 | −1.01 ± 0.57                 | −1.01 ± 1.07                    | al        |                                                 |
|            | 2.6677          | 31839               | Si IV | b     | C     | 0.07 ± 1.00                  | 0.13 ± 1.00                  | 0.13 ± 1.35                     | a         | Affectcd by data defect in first spectrum       |
|            | 2.8245          | 19374               | C IV | b     | C     | −2.72 ± 2.35                 | −2.60 ± 2.35                 | −2.60 ± 2.52                    | al        | Margin is <2 Å because of line blending         |
|            | 2.8283          | 19077               | Si IV | b     | C     | −1.37 ± 0.52                 | −1.32 ± 0.52                 | −1.32 ± 1.04                    | al        | Margin is <2 Å because of line blending         |
|            | 2.8294          | 18991               | C IV | b     | C     | −0.82 ± 0.23                 | −0.83 ± 0.23                 | −0.83 ± 0.93                    | a2        | Consider blue and red components together because of line locking |
|            | 2.8347          | 18578               | Si IV | b     | B     | −1.95 ± 0.35                 | −1.92 ± 0.35                 | −1.92 ± 0.97                    | al        |                                                 |
|            | 2.8347          | 18578               | Si IV | b     | C     | −1.85 ± 0.53                 | −1.88 ± 0.53                 | −1.88 ± 1.04                    | al        |                                                 |
| HE 1009+2956 | 1.9065          | 66707               | C IV | b     | C     | −1.11 ± 0.37                 | −1.13 ± 0.37                 | −1.13 ± 1.06                    | a1        |                                                 |
Table 2
(Continued)

| Quasar   | $z_{\text{abs}}$ | $v_0^a$ (km s$^{-1}$) | Ion  | Comp. | Class | $\Delta v_{\text{CCF}}^b$ (km s$^{-1}$) | $\Delta v_{\text{CCCD}}^c$ (km s$^{-1}$) | $\Delta v \pm \sigma(\Delta v)^d$ (km s$^{-1}$) | Sample | Notes                  |
|----------|------------------|------------------------|------|-------|-------|--------------------------------------|--------------------------------------|-----------------------------------------------|--------|------------------------|
| 2.2533   | 33879            | Si IV                  | b    | A     | C     | -0.22                                | -0.14 ± 0.59                        | -0.14 ± 1.15                              | a       | Blend with other lines |
| 2.6495   | -452             | N V                    | b    | A     | C     | -1.71                                | -1.67 ± 0.40                        | -1.67 ± 1.07                              | d       | Affect by data defect in first spectrum |
| Q1107+4847 | 2.1433           | 70938                  | C IV | b     | C     | -5.01                                | -5.09 ± 0.20                        | -5.09 ± 1.46                              | a       | Blend with other lines |
| 2.7243   | 21388            | C IV                   | b    | C     | C     | -4.47                                | -4.44 ± 0.42                        | -4.44 ± 1.51                              | d       | Affect by data defect in second spectrum |
| 2.7243   | 21388            | Si IV                  | b    | A     | C     | -5.78                                | -5.84 ± 0.58                        | -5.84 ± 1.56                              | a       | Blend with other lines |
| 2.7593   | 18595            | Si IV                  | b    | A     | C     | -3.20                                | -3.21 ± 0.29                        | -3.21 ± 1.48                              | b       | Margin is <2 Å because of line blending |
| 2.7610   | 18460            | C IV                   | b    | C     | C     | -2.61                                | -2.52 ± 0.39                        | -2.52 ± 1.50                              | b       | Margin is <2 Å because of line blending |
| 2.7621   | 18372            | Si IV                  | b    | A     | C     | -2.24                                | -2.25 ± 0.13                        | -2.25 ± 1.46                              | al      | Margin is <2 Å because of line blending |
| 2.3154   | 34551            | Si IV                  | b    | C     | C     | 0.87                                 | 0.87 ± 0.14                         | 0.87 ± 1.19                               | a       | Affect by data defect in first spectrum |
| 2.3156   | 34533            | C IV                   | b    | C     | C     | 0.25                                 | 0.25 ± 0.15                         | 0.25 ± 1.19                               | a       | Affect by data defect in first spectrum |
| 2.4333   | 24169            | Si IV                  | b    | C     | C     | -0.40                                | -0.39 ± 0.16                        | -0.39 ± 1.19                              | a       | May be time variable |
| 2.4390   | 23675            | C IV                   | b,r  | B     | C     | 0.82                                 | 0.85 ± 0.26                         | 0.85 ± 1.21                               | a       | Consider blue and red components together because of line locking |
| 2.5785   | 11789            | C IV                   | b    | C     | C     | 1.22                                 | 1.13 ± 0.64                         | 1.13 ± 1.34                               | a       | May be time variable |
| 2.7125   | 767              | C IV                   | b    | A     | C     | 2.16                                 | 2.08 ± 1.78                         | 2.08 ± 2.14                               | a       | Affect by data defect in second spectrum |
| 2.7125   | 767              | N V                    | b    | A     | C     | 1.14                                 | 1.08 ± 0.47                         | 1.08 ± 1.27                               | al      | Affect by data defect in second spectrum |
| 2.7164   | 452              | N V                    | b    | A     | C     | -0.21                                | -0.20 ± 0.28                        | -0.20 ± 2.39                              | al      | Blend with other lines |

Notes.

- $^a$ Offset velocity that is defined as positive if NALs are blueshifted from the quasar.
- $^b$ Blue (b) or red (r) component of doublet.
- $^c$ NAL class: Class A, B, or C denotes reliable, possible, or intervening NALs, respectively (Misawa et al. 2007a).
- $^d$ Velocity shift measured from the CCF (Grier et al. 2016).
- $^e$ Velocity shift measured from the CCCD (Grier et al. 2016).
- $^f$ Velocity shift and its uncertainty after adding an error from spectral distortion. See discussion in Section 4 of the text.
- $^g$ Sample class: (a1) satisfies all criteria (i.e., reliable NAL), (a2) line locking, (b) sampling spectral region is smaller than 2 Å at either or both sides of NAL because of other lines or data defect, (c) shows a hint of time variability, and (d) NAL itself blends other line or data defect.

red members of a doublet are detected) in HE 0940–1050 and calculate $|\Delta v|$ for 91 pairs (i.e., $^{14}$C$^2$) in total. The velocity difference and its total uncertainty, $\Delta v$ and $\sigma(\Delta v)$, for each line, in which we add errors from the CCCD analysis and the nonlinear distortion in quadrature, are included in Table 2.

Our sample quasars have multiple NALs in their spectra (from three NALs in HE 1009+2956 to 10 NALs in HE 0940–1050). Therefore, we also determined a weighted mean value of $\Delta v$ and its uncertainty for all of the class A + B NALs in each quasar and, separately, all of the class C NALs in each
quasar using the following equations:

$$\Delta v = \frac{\sum_{i=1}^{n} \frac{1}{\sigma(Dv_i)^2} \Delta v_i}{\sum_{i=1}^{n} \frac{1}{\sigma(Dv_i)^2}},$$ (3)

and

$$\sigma(\Delta v) = \sqrt{\frac{\sum_{i=1}^{n} \left( \frac{1}{\sigma(Dv_i)^2} \right) (\Delta v_i - \bar{\Delta v})^2}{(n - 1) \sum_{i=1}^{n} \left( \frac{1}{\sigma(Dv_i)^2} \right)}},$$ (4)

where $n$ is the number of absorption lines in a quasar, $\Delta v_i$ and $\sigma(\Delta v_i)$ are the velocity shift and its uncertainty between the observations for the $i$th line of a given quasar, and $\bar{\Delta v}$ is their average (i.e., $\sum_{i=1}^{n} \Delta v_i/n$). If $n < 2$, as in the class A/B NALs in HE 1009+2956 and Q1107+4847, we take only the statistical error into consideration instead of using Equation (4). We also perform the same calculation using only reliable NALs (marked as sample class a1 in Table 2) after removing those that (i) show line

| Quasar       | Number of Pairs | $\sigma(\Delta v)_{\text{rms}}$ (km s$^{-1}$) |
|--------------|-----------------|--------------------------------------------|
| HE 0130–4021 | 3               | 1.25                                       |
| Q0450–1310   | 28              | 1.67                                       |
| HE 0940–1050 | 91              | 0.90                                       |
| HE 1009+2956 | 1               | 0.99                                       |
| Q1107+4847   | 21              | 1.45                                       |
| HS 1700+6416 | 15              | 1.18                                       |

Note.

* The rms of $|\Delta v|$ between all pairs of class C lines.
lockings (sample class a2),10 (ii) are partially affected by line blending or have a data defect within 2 Å of an NAL (sample class b), or (iii) show >4σ variability in their equivalent width (EW) or line profile (sample class c).11 The NALs that are blends of more than one line or that have data defects were already rejected in Section 4.1 and marked as sample class d in Table 2. The resulting average Δv and its uncertainty, σ(Δv), for all of the class A + B and class C NALs in the quasars of our sample are shown in Figure 6 and tabulated in Table 4.

5. Results

We applied the CCF and CCCD analyses to 56 lines12 in 40 NALs detected in six optically bright quasars. For the two NALs that exhibit line locking, we applied the analyses to the blue and red members of the doublets simultaneously. The velocity plots of the NALs are shown in Figure 2, except for the CIV NAL at z_{abs} = 2.7243 in Q1107+4847, because it is severely affected by a data defect in the second spectrum and is thus also excluded from the following analyses.

As an example of our analyses, we show the absorption profile of the blue member of the class B Si IV NAL (i.e., Si IV λ1394) at z_{abs} = 2.8347 in HE 0940–1050 and the results of the CCF and CCCD analyses in Figure 3. Below, we describe in detail the results for each quasar. The results of the

10 The red member of a doublet is aligned with the blue member of the following doublet. This is one of the indicators that an NAL is physically associated with a quasar (e.g., Arav 1996).

11 To assess the significance of variability in the EW, we computed the change in EW between two epochs as ΔEW = [EW2 − EW1] (where epoch 1 is earlier than epoch 2) and its uncertainty as σ_{ΔEW} = (σ_{EW1} + σ_{EW2})/√2 and defined the variation significance as ΔEW/σ_{ΔEW}.

12 Here we count the two lines of a doublet separately, if they are both clearly detected without any line blending or data defects.
CCF and CCCD analyses for each NAL and quasar are summarized in Tables 2 and 4. The weighted averages of $\Delta v$ for class A + B and class C NALs are also shown in Figure 6. We require a $>3\sigma$ significance level in order to claim that the velocity shift for class A/B NALs is significantly different from that for class C NALs.

**HE 0130–4021.** Misawa et al. (2007a) detected six NALs (four CIV, one SiIV, and one NV), of which three are classified as class A/B NALs. We observed all of these twice with a time interval of $\Delta t_{\text{obs}} \sim 11.7$ yr in the observed frame, corresponding to $\Delta t_{\text{rest}} \sim 2.90$ yr in the quasar rest frame. Among the 12 blue/red lines of the six NALs, seven are detected without being affected by data defects or other unrelated lines. The wavelength margin is smaller than 2 Å around the NV $\lambda 1239$ line at $z_{\text{abs}} = 2.9749$. The profiles of the SiIV $\lambda 1394$ line at $z_{\text{abs}} = 2.8570$ and the NV $\lambda 1243$ line at $z_{\text{abs}} = 2.9749$ show a hint of time variability (see Figure 2). The weighted average velocity shift for class A/B NALs ($\Delta v_{\text{AB}} = 0.45 \pm 0.32$ km s$^{-1}$) is not significantly shifted from that for class C NALs ($\Delta v_{\text{C}} = 1.28 \pm 0.50$ km s$^{-1}$).

Even if we consider only the reliable NALs (two class A/B lines and two class C lines), the difference would still be insignificant. We conclude that there is no clear velocity shift of the class A/B NALs between our observations.

**Q0450–1310.** In the spectrum of this radio-quiet quasar, Misawa et al. (2007a) detected 10 NALs (five CIV and five SiIV), of which only the CIV NAL at $z_{\text{abs}} = 2.2307$ ($v_{\text{ej}} \sim 6370$ km s$^{-1}$) is classified as intrinsic (class A). Because two CIV NALs at $z_{\text{abs}} = 2.1050$ and 2.1061 and three SiIV NALs at $z_{\text{abs}} = 2.1051, 2.1062, \text{and } 2.1069$ are close to each other within $\sim 170$ km s$^{-1}$, we treat them as single NALs (CIV NAL at $z_{\text{abs}} \sim 2.1061$ and SiIV NAL at $z_{\text{abs}} \sim 2.1059$), respectively. After removing NALs that are blended with data defects or other unrelated lines, we are left with 10 lines in six NALs. The time interval between the observations is $t_{\text{obs}} \sim 17.1$ yr (i.e., $\Delta t_{\text{rest}} \sim 5.2$ yr). The weighted average velocity shift of the class A NAL ($\Delta v_{\text{AB}} = -3.30 \pm 0.38$ km s$^{-1}$) is not shifted significantly from that of class C NALs ($\Delta v_{\text{C}} = -3.87 \pm 0.30$ km s$^{-1}$). Even after we consider only reliable NALs (two class A lines and six class C lines) that satisfy all of the criteria (see Section 4.3), the
The difference is not significant. We conclude that the class A NAL is not significantly shifted between our observations.

**HE 0940–1050.** In total, 10 NALs (seven C IV and three Si IV) were detected, of which only one Si IV NAL at $z_{\text{abs}} = 2.8347$ ($v_{\text{ej}} \sim 18,600$ km s$^{-1}$) is classified as class B (Misawa et al. 2007a). No class A NALs were identified. Although the C IV NAL at $z_{\text{abs}} = 2.8346$ was originally classified as class C, it could be intrinsic to the quasar.

| Quasar      | All NALs         | Reliable NALs                  |
|-------------|------------------|--------------------------------|
|             | $\Delta v_{\text{AB}}$ | $\Delta v_{\text{C}}$ | S.L. | $\Delta v_{\text{AB}}$ | $\Delta v_{\text{C}}$ | S.L. | $\Delta v_{\text{AB}} - \Delta v_{\text{C}}$ | $(\Delta v_{\text{AB}} - \Delta v_{\text{C}}) / \Delta t_{\text{rest}}$ |
| HE 0130–4021| 0.45 ± 0.32       | 1.28 ± 0.50                  | 1.40$\sigma$ | 0.79 ± 0.54 | 1.33 ± 0.87 | 0.53$\sigma$ | $-0.54 \pm 1.02$ | $-0.0006 \pm 0.0011$ |
| Q0450–1310  | −3.30 ± 0.38      | −3.87 ± 0.30                 | 1.18$\sigma$ | −3.30 ± 0.38 | −3.70 ± 0.38 | 0.74$\sigma$ | $+0.40 \pm 0.54$ | $+0.0002 \pm 0.0003$ |
| HE 0940–1050| −1.51 ± 0.37      | −0.94 ± 0.12                 | 1.47$\sigma$ | −1.90 ± 0.71 | −0.98 ± 0.13 | 1.27$\sigma$ | $-0.92 \pm 0.72$ | $-0.0007 \pm 0.0006$ |
| HE 1009+2956| −1.67 ± 1.07$^d$ | −0.68 ± 0.49                 | 0.84$\sigma$ | −1.67 ± 0.71 | −0.68 ± 0.49 | 0.84$\sigma$ | $-0.99 \pm 1.18$ | $-0.0006 \pm 0.0007$ |
| Q1107+4847  | −5.84 ± 1.56$^d$ | −3.83 ± 0.59                 | 1.53$\sigma$ | −5.84 ± 1.56 | −3.68 ± 0.65 | 1.28$\sigma$ | $-2.16 \pm 1.69$ | $-0.0013 \pm 0.0010$ |
| HS 1700+6416| 1.12 ± 0.45       | 0.56 ± 0.31                  | 1.02$\sigma$ | 1.61 ± 0.71 | 0.55 ± 0.35 | 1.34$\sigma$ | $+1.06 \pm 0.79$ | $+0.0012 \pm 0.0009$ |

Notes:

a Weighted average of shift velocity for class A/B NALs.
b Weighted average of shift velocity for class C NALs.
c Significance level of difference in velocity shift between class A/B and class C NALs.
d This is a shift velocity and its uncertainty that are evaluated using Equations (3) and considering only the statistical error because only one class A/B NAL was detected in the quasar spectrum.
Figure 7. Ejection velocity difference ($\Delta v_{\text{ej}}$) of reliable intrinsic NALs between observations as a function of time interval (filled blue circles). Here we used values of $(\Delta v_{\text{ej}} - \Delta v_{\text{C}})$ from Table 4 as $\Delta v_{\text{ej}}$, but switched the sign because the ejection velocity is defined as positive for NALs that are blueshifted from the quasar. The four dotted lines are the predicted velocity shifts from Equation (6) with $f \cos \theta / r = 0.1, 0.03, 0.01,$ and 0.003 (from top to bottom) for the typical luminosity and black hole mass of our target quasars ($L = 10^{48} \text{ erg s}^{-1}, M = 10^8 M_\odot$), as well as a typical hydrogen column density of NAL absorbers ($N_H = 10^{20} \text{ cm}^{-2}$). The horizontal dashed line denotes $\Delta v_{\text{ej}} = 0$ (i.e., no acceleration/deceleration between observations).

because (i) it has a similar redshift to the class B Si IV NAL and (ii) it shows line locking with a C IV NAL at $z_{\text{abs}} = 2.8245$. We regard the two line-locked C IV NALs as a single NAL at $z_{\text{abs}} = 2.8294$. After removing NALs that are blended with data defects or other unrelated lines, we are left with 17 lines in 10 NALs. The time interval between the observations is $\Delta t_{\text{obs}} \sim 15.8 \text{ yr}$ (i.e., $\Delta t_{\text{rest}} \sim 3.9 \text{ yr}$). The weighted average velocity shift of class A/B NALs ($\Delta v_{\text{AB}} = -1.51 \pm 0.37 \text{ km s}^{-1}$) is not clearly shifted relative to that of class C NALs ($\Delta v_{\text{C}} = -0.94 \pm 0.12 \text{ km s}^{-1}$). Even if we consider only reliable NALs (two class B lines and 12 class C lines), the difference would still be insignificant. Thus, we conclude that the class B NAL does not show a velocity shift between our observations compared to class C NALs.

HE 1009+2956. Because of limited wavelength coverage, Misawa et al. (2007a) detected only three NALs (one C IV, one Si IV, and one N V), of which a Si IV NAL at $z_{\text{abs}} = 2.2533$ ($v_{\text{C}} \sim 33900 \text{ km s}^{-1}$) and a N V NAL at $z_{\text{abs}} = 2.6495$ ($v_{\text{C}} \sim -450 \text{ km s}^{-1}$) are classified as class A. Unfortunately, we cannot monitor the variability of the N V NAL profile because of blending with other lines and a data defect in the first spectrum. We used only three lines in two NALs for our analyses. The time interval between the observations is $\Delta t_{\text{obs}} \sim 20.1 \text{ yr}$ (i.e., $\Delta t_{\text{rest}} \sim 5.5 \text{ yr}$). The weighted average of the velocity shift of class A/B NALs ($\Delta v_{\text{AB}} = -1.67 \pm 1.07 \text{ km s}^{-1}$) is not significantly shifted compared to the class C NALs ($\Delta v_{\text{C}} = -0.68 \pm 0.49 \text{ km s}^{-1}$). All detected NALs satisfy the criteria to be in our reliable sample. Thus, we conclude that there is no clear velocity shift of the class A Si IV NAL between our observations. For the quasar, we consider only the statistical error to calculate the weighted average of the velocity shift for the class A NAL because the sample includes only one member.

Q1107+4847. Misawa et al. (2007a) detected six NALs (three C IV and three Si IV), of which only one Si IV NAL at $z_{\text{abs}} = 2.7243$ ($v_{\text{C}} \sim 21400 \text{ km s}^{-1}$) is classified as class A. There are no class B NALs. A C IV NAL at $z_{\text{abs}} = 2.7243$, originally classified as class C, also could be intrinsic to the quasar because it has the same redshift as the class A Si IV NAL. Although all six NALs are covered by our spectra, four of the lines, including the C IV NAL at $z_{\text{abs}} = 2.7243$, are affected by data defects or severely blended with other lines. As a result, we used eight lines in five NALs for the CCF and CCCD analyses. The time interval between the observations is $\Delta t_{\text{obs}} \sim 20.7 \text{ yr}$, which corresponds to $\Delta t_{\text{rest}} \sim 5.2 \text{ yr}$. The velocity shift of the class A NAL ($\Delta v_{\text{AB}} = -5.84 \pm 1.56 \text{ km s}^{-1}$) is not obviously shifted compared to the class C NALs ($\Delta v_{\text{C}} = -3.38 \pm 0.39 \text{ km s}^{-1}$). The significance level becomes smaller when we remove NALs that do not satisfy all of the selection criteria. Because all NALs for the quasar are blueshifted significantly (i.e., $\Delta v < -3 \text{ km s}^{-1}$), we speculate that the class C NALs are also intrinsic to the quasar and accelerated with the class A NAL. Indeed, some intrinsic NALs could have full coverage (i.e., classified into class C) if absorbing clouds in the vicinity of the continuum source are large enough to cover it completely (Misawa et al. 2007a). To test the idea, we performed the CCF and CCCD analyses of a Mg II $\lambda 2803$ line at $z_{\text{abs}} = 0.8076$ whose origin should be unrelated to the outflowing winds because its offset velocity would be $>0.66c$ if we assume it is an intrinsic NAL. We derived an offset velocity of $\Delta v = -5.61 \pm 0.28 \text{ km s}^{-1}$ for the Mg II NAL that is close to those of class A/B and class C NALs. Thus, we do not find any significant velocity shifts between our observations. Here we considered only statistical error to calculate the weighted average of the velocity shift for the class A NAL because the sample includes only one member.

HS 1700+6416. This extremely bright quasar could be amplified by gravitational lensing by two clusters of galaxies along our sight line. Misawa et al. (2007a) detected 10 NALs (six C IV, two Si IV, and two N V), of which three C IV NALs at $z_{\text{abs}} = 2.4330, 2.4394$, and 2.7125 and two N V NALs at $z_{\text{abs}} = 2.7125$ and 2.7164 are classified as class A or B. A C IV NAL at $z_{\text{abs}} = 2.1680$ is not covered by our second-epoch spectrum. Because two C IV NALs at $z_{\text{abs}} = 2.4330$ and 2.4394 show line locking, we treat them as a single NAL at $z_{\text{abs}} = 2.4390$. Thus, we used 11 lines in eight NALs for the analyses. The time interval between the observations is $\Delta t_{\text{obs}} \sim 10.3 \text{ yr}$ (i.e., $\Delta t_{\text{rest}} \sim 2.8 \text{ yr}$). The weighted average velocity shift of the class A/B NALs ($\Delta v_{\text{AB}} = 1.12 \pm 0.45 \text{ km s}^{-1}$) is not significantly shifted from that for class C NALs ($\Delta v_{\text{C}} = 0.56 \pm 0.31 \text{ km s}^{-1}$). Even if we consider only the reliable NALs (three class A lines and five class C lines) that satisfy all of the selection criteria, the significance level would still be insignificant. We conclude that we do not detect a velocity shift between our observations.

In Table 4, we list the differences between the weighted average velocity shifts for class A/B and class C NALs and the
1σ uncertainty for each quasar (\(\Delta v_{\text{AB}} - \Delta v_{\text{C}}\)). The corresponding acceleration is also shown in the table (\(\Delta v_{\text{AB}} = \Delta v_{\text{C}} / \Delta t_{\text{rest}}\)).

The main result of the CCF and CCCD analyses is that we do not detect significant weighted average velocity shifts of class A/B relative to class C NALs. We placed a 3σ upper limit on the acceleration/deceleration of the intrinsic NALs with a magnitude of \(\sim 0.001-0.003 \text{ cm s}^{-2}\) (i.e., three times the magnitude of the 1σ uncertainty of \((\Delta v_{\text{AB}} - \Delta v_{\text{C}})\)) on a timescale of \(\Delta t_{\text{rest}} = 2.8-5.5 \text{ yr}\) in the quasar’s rest frame, as shown in Table 4. The average of these 3σ upper limits for the six quasars is \(\sim 0.002 \text{ cm s}^{-2}\), corresponding to \(\sim 0.7 \text{ km s}^{-1} \text{ yr}^{-1}\).

6. Discussion

We monitored intrinsic NALs in six quasars for 2.8–5.5 yr in the quasar rest frame. We found no highly significant shifts in NAL velocities, implying 3σ upper limits on the acceleration of \(\sim 0.7 \text{ km s}^{-1} \text{ yr}^{-1}\) (\(\sim 0.002 \text{ cm s}^{-2}\)). The limits on NAL acceleration found here appear to be two or three orders of magnitude lower than those of BALs reported in the literature (Vilkoviskij & Irwin 2001; Rupke et al. 2002; Gabel et al. 2003; Hall et al. 2007; Joshi et al. 2014, 2018; Grier et al. 2016), though this is not necessarily an indicator of some physical difference between BALs and NALs and could be in part due to data quality (i.e., higher spectral resolution of our data) and the nature of the absorption profiles (i.e., the narrower line width of NALs). Nevertheless, the small upper limits are noteworthy, since the NAL quasars in our sample have larger bolometric luminosities (i.e., causing stronger radiation pressure) than the BAL quasars reported in the literature.

The simplest hypothesis for the acceleration of NAL systems invokes radiation pressure. Thus, the equation of motion can be cast as

\[
\frac{dv}{dt} = \frac{fL}{4\pi r^2 c N_H} - \frac{GM}{r^2},
\]

where \(v\) is the outflow velocity, \(L\) is the quasar’s bolometric luminosity, \(f\) is the fraction of the luminosity that contributes to the acceleration, \(r\) is a distance from the flux source, \(N_H\) is the total column density of the absorber, and \(M\) is the mass of the central black hole (Hamann 1998). By considering the typical luminosity and black hole mass of our target quasars (i.e., \(L = 10^{48} \text{ erg s}^{-1}, M = 10^9 M_\odot\)), as well as a typical hydrogen column density of NAL absorbers (\(N_H = 10^{18} \text{ cm}^{-2}\); e.g., Wu et al. 2010), Equation (5) becomes

\[
\Delta v \sim 52 f \cos \theta \left( \frac{\Delta t}{1 \text{ yr}} \right) \left( \frac{r}{1 \text{ kpc}} \right)^2 \left( \frac{L}{10^{48} \text{ erg s}^{-1}} \right) \left( \frac{N_H}{10^{20} \text{ cm}^{-2}} \right)^{-1} \text{ km s}^{-1},
\]

where we ignore gravity because its contribution is much smaller than the radiative force as long as \(f > 10^{-7}\). We also include a factor of \(\cos \theta\), where \(\theta\) is the angle between the outflow streamlines and our sight line.

The implied acceleration of intrinsic NALs for our six quasars is smaller than the prediction of Equation (6) by a factor of 100 or more, if we assume a distance of NAL absorbers from the central engine of \(R \sim 1 \text{ kpc}\) following Arav et al. (2013), for example. In Figure 7, we summarize the observed and expected ejection velocities of reliable intrinsic NALs as a function of time interval in the rest frame, with lines shown for \(f \cos \theta = 0.1, 0.03, 0.01,\) and 0.003. If radiation pressure is the main acceleration mechanism, we infer from the figure that either \(f \cos \theta \leq 10^{-2}\), \(r > 10 \text{ kpc}\), or both. Because reports of absorber distances as large as 10 kpc are uncommon in the literature, we speculate that one or a combination of the following is the cause of the small inferred accelerations.

(i) The fraction \(f\) is smaller than \(10^{-2}\), which is much smaller than the value suggested for X-ray ultrafast outflows (\(f \geq 0.05\); e.g., Tombesi et al. 2013).13 (ii) Our sight line toward the flux source is almost perpendicular to some of the outflow streamlines, as suggested in Arav et al. (1999). (iii) The acceleration is episodic, and it is only observable in a small fraction of quasars at any given time. The last hypothesis is motivated by the results of Grier et al. (2016), who were able to detect an acceleration in only three out of 14 BAL quasars and noted that the acceleration was not constant in time. If this is the case for NALs as well, we would need to observe a much larger sample of objects or make many repeated observations of this sample in order to detect NAL acceleration.

7. Summary

In this study, we used high-resolution spectra of six NAL quasars that were obtained with 8–10 m telescopes (i.e., Subaru, Keck, and VLT) at two epochs separated by \(\Delta t_{\text{obs}} \sim 10.3–20.7 \text{ yr}\) (i.e., \(\Delta t_{\text{rest}} \sim 2.8–5.5 \text{ yr}\) to monitor the velocity changes of intrinsic NALs. Our main results are as follows:

1. Using the CCF and CCCD analyses, we discovered no significant acceleration/deceleration of intrinsic NALs, placing a 3σ upper limit on the magnitude of the acceleration/deceleration of \(\sim 0.001-0.003 \text{ cm s}^{-2}\), with an average magnitude of \(\sim 0.002 \text{ cm s}^{-2}\) (\(\sim 0.7 \text{ km s}^{-1} \text{ yr}^{-1}\)).

2. This magnitude of NAL acceleration is more than two orders of magnitude smaller than the expected value from radiative acceleration, which suggests that, if our sight line is almost parallel to the streamlines of the outflow, the fraction of the luminosity that contributes to the acceleration is \(f < 0.01\), or the absorber’s distance from the flux source is greater than 10 kpc. We do not find any correlations between gas acceleration and bolometric luminosity in either BAL or NAL quasars.

3. Because of the very small velocity shifts, the NAL absorbers studied here may be at or close to their terminal velocities; i.e., they may be located at a large distance from the quasar central engine. Other possible explanations are that we observe a standing flow with streamlines that are almost perpendicular to our sight line and gas is continuously replenished as suggested by hydrodynamical simulations (Arav et al. 1999; Proga et al. 2000), or that the acceleration process is episodic so that only a small fraction of NALs exhibit acceleration at any one time.

If the typical magnitude of NAL acceleration is close to the 3σ upper limit we have obtained (i.e., \(\sim 0.7 \text{ km s}^{-1} \text{ yr}^{-1}\)), we may be able to detect obvious velocity shifts in future observations.

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13 The fraction \(f\) would be \(<10^{-2}\) or \(<10^{-5}\) if we assume \(r > 100 \text{ or } <10 \text{ pc}\) as a distance of NAL absorbers from the central engine instead of \(r \sim 1 \text{ kpc}\).
compared to our first-epoch spectra taken in 1995–2000. For example, intrinsic NALs are expected to be blueshifted by more than 2 km s$^{-1}$ with a significance level of $\geq 3\sigma$ 40 yr from now. Alternatively, if the acceleration process is episodic, we may be able to detect acceleration in a few quasars if we observe a sample that is an order of magnitude larger than the sample we have used here. Such a precise spectroscopic observation will also be very important to other areas of research, such as a direct measurement of cosmic expansion (e.g., Sandage 1962; Loeb 1998; Balbi & Quercellini 2007; Liske et al. 2008) and a measurement of changes in the fine-structure constant (e.g., Murphy et al. 2003; Chand et al. 2004; Srianand et al. 2004; Webb et al. 2011) using extremely large (30 m class) telescopes in coming decades.

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