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### Variability Tests for Intrinsic Absorption Lines in Quasar Spectra

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## VARIABILITY TESTS FOR INTRINSIC ABSORPTION LINES IN QUASAR SPECTRA

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### ABSTRACT

Quasar spectra have a variety of absorption lines whose origins range from energetic winds expelled from the central engines to unrelated, intergalactic clouds. We present multiphase, medium-resolution spectra of eight quasars at  $z \sim 2$  that have narrow “associated” absorption lines (AALs, within  $\pm 5000 \text{ km s}^{-1}$  of the emission redshift). Two of these quasars were also known previously to have high-velocity mini-broad absorption lines (mini-BALs). We use these data, spanning  $\sim 17 \text{ yr}$  in the observed frame with 2–4 observations per object, to search for line-strength variations as an identifier of absorption that occurs physically near (“intrinsic” to) the central active galactic nucleus. Our main results are the following: Two out of the eight quasars with narrow AALs exhibit variable AAL strengths. Two out of two quasars with high-velocity mini-BALs exhibit variable mini-BAL strengths. We also marginally detect variability in a high-velocity narrow absorption line system, blueshifted  $\sim 32,900 \text{ km s}^{-1}$  with respect to the emission lines. No other absorption lines in these quasars appeared to vary. The outflow velocities of the variable AALs are  $3140$  and  $1490 \text{ km s}^{-1}$ . The two mini-BALs identify much higher velocity outflows of  $\sim 28,400$  and  $\sim 52,000 \text{ km s}^{-1}$ . Our temporal sampling yields upper limits on the variation timescales from  $0.28$  to  $6.1 \text{ yr}$  in the quasar rest frames. The corresponding minimum electron densities in the variable absorbers, based on the recombination timescale, are  $\sim 40,000$  to  $\sim 1900 \text{ cm}^{-3}$ . The maximum distances of the absorbers from the continuum source, assuming photoionization with no spectral shielding, range from  $\sim 1.8$  to  $\sim 7 \text{ kpc}$ .

*Subject headings:* line: formation — quasars: absorption lines — quasars: general

### 1. INTRODUCTION

The absorption lines in quasar spectra can place important constraints on the basic properties of quasar environments, such as the outflow velocities, column densities, mass-loss rates, and elemental abundances. In addition, if quasars reside in the nuclei of massive galaxies, then we can use the chemical abundances to indirectly probe the extent and epoch of star formation in young galaxies (Schneider 1998; Hamann & Ferland 1999).

Quasar absorption lines can be divided into three categories based on the line widths: broad absorption lines (BALs), narrow absorption lines (NALs), and intermediate mini-broad absorption lines (mini-BALs). The divisions between these categories are arbitrary. Classic BALs typically have FWHMs of the order of  $10,000 \text{ km s}^{-1}$ , but lines as narrow as  $2000\text{--}3000 \text{ km s}^{-1}$  are often still considered BALs (Weymann et al. 1991). A useful working definition of the NALs is that they have FWHMs smaller than the velocity separation of major absorption doublets (e.g.,  $500 \text{ km s}^{-1}$  for C IV  $\lambda\lambda 1548, 1551$ , or  $960 \text{ km s}^{-1}$  for N V  $\lambda\lambda 1239, 1243$ ), but often these lines are much narrower. Mini-BALs have widths intermediate between the NALs and BALs.

BALs appear in about 10%–15% of optically selected quasars (Weymann et al. 1991). They appear at blueshifted ve-

locities (relative to the emission redshift) ranging from near  $0 \text{ km s}^{-1}$  to more than  $30,000 \text{ km s}^{-1}$ , and they clearly form in high-velocity outflows from the quasar engines. Mini-BALs appear to be less common, although to our knowledge no one has yet done a quantitative inventory. Nonetheless, mini-BALs appear at the same range of blueshifted velocities as the BALs, and it is thought that they too form in quasar winds (Hamann et al. 1997a; B. Jannuzi et al. 2003, in preparation). Even though they may have complex profiles, high-resolution spectra show that both BAL and mini-BAL profiles are “smooth” compared to thermal line widths, and therefore these lines are not simply blends of many NALs (Barlow & Junkkarinen 1994; Hamann et al. 1997a; F. Hamann et al. 2003, in preparation; Junkkarinen et al. 2001).

NALs appear at a wide range of velocity shifts. They are further classified as associated absorption lines (AALs) if the absorption redshift,  $z_{\text{abs}}$ , is within  $\pm 5000 \text{ km s}^{-1}$  of the emission-line redshift ( $z_{\text{abs}} \approx z_{\text{em}}$ ; Weymann et al. 1979; Foltz et al. 1986, 1988; Anderson et al. 1987). A significant fraction of AALs are believed to have a physical relationship with the quasars, based on statistical correlations between the occurrence of AALs and quasar properties (see also Aldcroft, Bechtold, & Elvis 1994; Richards et al. 1999). However, in general, AALs and other NALs can form in a variety of locations, such as cosmologically intervening clouds, galaxies that are unrelated to the quasar, and clouds that are physically associated with, or perhaps ejected from, the quasar (Weymann et al. 1979). NALs must therefore be examined individually to determine whether they are intrinsic to the quasar. Several diagnostics have been proposed for this purpose, including (1) line-strength variations over time, (2) profiles that are smooth and broad compared to thermal line widths, (3) partial line-of-sight coverage of the background emission source, and (4) high densities based on excited-state absorption lines (e.g.,

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Barlow & Sargent 1997; Barlow, Hamann, & Sargent 1997; Hamann et al. 1997a, 1997c).

Line-strength variations can be caused by bulk motions across the line of sight or by changes in the ionization state of the gas. A change in the radial velocity of the absorbing material could also produce a shift in the wavelength (redshift) of the measured lines (although this type of shift appears to be extremely rare; see Gabel et al. 2003; this paper). In either case, variations over short timescales are incompatible with absorption in large intergalactic clouds. A firm lower limit on the size of intergalactic H I-absorbing clouds is approximately a few kiloparsecs (Foltz et al. 1984; McGill 1990; Bechtold & Yee 1995; Rauch 1998), which is similar to recent direct estimates of the sizes of intergalactic C IV-absorbing clouds (Tzanavaris & Carswell 2003). Assuming the clouds are uniform and do not have sharp edges, the timescale for absorption line-strength variations occurring via bulk motions will be roughly the time needed for this minimum cloud to cross our line of sight. If the clouds have maximum transverse velocities of  $\sim 1000 \text{ km s}^{-1}$  (comparable to the line-of-sight velocity dispersion in massive galaxy clusters), then in the  $\sim 30 \text{ yr}$  spanned by modern observations the cloud would travel just  $\sim 3 \times 10^{-5} \text{ kpc}$ , roughly 5 orders of magnitude less than its diameter. Variability due to changes in the ionization state is also problematic for intergalactic absorbing clouds. Changes in the ionization state are nominally limited by the timescale for recombination, e.g., if the cloud is in ionization equilibrium. Recombination on timescales of  $\lesssim 30 \text{ yr}$  requires densities of  $n_e \gtrsim 100 \text{ cm}^{-3}$  (see § 5.1), which is exceedingly high compared to the densities  $n_e \lesssim 10^{-3} \text{ cm}^{-3}$  expected in intergalactic H I clouds (Miralda-Escude et al. 1996; Rauch 1998). The variation timescales might be shorter for lines forming in the (relatively) dense interstellar medium of intervening galaxies, but these absorption systems should be recognizable, e.g., via damping wings in Ly $\alpha$ . Therefore, line-strength variations in NAL systems that do not include damped Ly $\alpha$  strongly suggest that the absorption is intrinsic to the quasar.

We are involved in a multifaceted program to identify intrinsic NALs and use them to place constraints on the physical properties of quasar environments. In this paper, we examine multipoint rest-frame UV spectra of eight redshift  $\sim 2$  quasars known to have AALs and mini-BALs. We find variability in two out of eight AALs and two out of two mini-BALs. We use these results to constrain the densities and locations of the absorbing gas and briefly discuss the implications for quasar wind models.

## 2. OBSERVATIONS AND DATA REDUCTIONS

We obtained spectra of eight quasars at the Shane 3 m telescope at the University of California Observatories (UCO) Lick Observatory as well as at the Smithsonian Institution and University of Arizona Multiple Mirror Telescope (MMT) Observatory. Additional spectra obtained at the Palomar Observatory were generously provided to us in digital form by C. C. Steidel, first published in Sargent, Boksenberg, & Steidel (1988, hereafter SBS88). Table 1 shows a log of the different observing runs, including the dates, approximate wavelength ranges, and resolutions. The data span  $\sim 17 \text{ yr}$  ( $\sim 6 \text{ yr}$  in the quasar rest frames) with two to four observations per quasar.

In Table 2 we list the objects observed, their emission redshifts ( $z_{\text{em}}$ ; Hewitt & Burbidge 1993), the absorption redshifts ( $z_{\text{abs}}$ ), and velocity shifts (relative to  $z_{\text{em}}$ ) of their AALs, mini-BALs, or, in the case of Q0151+048 only, a high-velocity NAL system that appeared to vary. All of the AAL and NAL redshifts

are from SBS88, except for PG 0935+417 (Hamann et al. 1997a) and Q0848+163 (see § 4). Note that the AAL redshift given for PG 0935+417 is an approximate average of a complex of lines that is not resolved in our Lick spectra. Please see SBS88 for a more complete list of absorption lines in the other quasars. Table 2 also lists the observation numbers (from Table 1) and a note on the variability of each system. The variabilities are discussed further in § 4.

We chose the quasars for this study because they are bright, they are known to have AALs, and their redshifts allow ground-based observations of strong UV absorption lines, such as Ly $\alpha$   $\lambda 1216$ , N v  $\lambda\lambda 1239, 1243$ , Si iv  $\lambda\lambda 1394, 1403$ , C iv  $\lambda\lambda 1548, 1551$ , and potentially others in this wavelength range (see SBS88 and Junkkarinen, Hewitt, & Burbidge 1991).

We reduced the data using standard techniques with the IRAF<sup>6</sup> software. We bias-subtracted the data and then divided the raw two-dimensional images by flat fields. Wavelength calibration was achieved using internal lamp spectra. We flux-calibrated the spectra using standard stars measured the same night. Because the weather was sporadically cloudy, we used the flux calibrations primarily to recover an accurate spectral shape, rather than absolute fluxes. Finally, we added together spectra obtained at the same wavelengths on the same dates to increase the signal-to-noise ratio. The SBS88 spectra have a higher resolution than our Lick spectra; we therefore smoothed the SBS88 data using a boxcar routine to match the resolution of the Lick spectra and facilitate comparisons.

## 3. RESULTS

We compared the spectra from the different observations of each quasar to look for variations in the absorption-line strengths. Every absorption line within our wavelength coverage was examined, except those in the Ly $\alpha$  forest. Table 2 presents the main results. Two out of the eight quasars showed AAL variability. Two out of two mini-BALs varied, and one quasar showed probable variations in a high-velocity C IV NAL. Notes on the variable systems are provided in § 4. Spectra showing the variations are also plotted in Figures 1–4. The wavelength ranges in these plots were chosen to show only the specific NALs or mini-BALs that varied. The peak flux in the plotted wavelength range of the reference spectrum (*solid curves*) is normalized to unity in all cases. Other spectra are overplotted and scaled to approximately match the reference spectrum in the continuum near the lines of interest.

Our ability to detect line variability depends on the line strength and the signal-to-noise ratio of the spectra. For the six AALs that did not vary, we estimate upper limits on the changes, by inspection, of the strongest measured lines (generally C IV and N V). In particular, we estimate that the AAL equivalent widths varied by  $\lesssim 20 \%$  in Q0207–003, Q0348+061, PG 0935+417, and Q0958+551, and  $\lesssim 15 \%$  in Q1159+123.

## 4. NOTES ON VARIABLE SOURCES

### 4.1. Q0151+048

Figure 1 shows four epochs of observations for Q0151+048. We measured clear variations in a C IV mini-BAL at  $z_{\text{abs}} = 1.6581$  and tentative changes in a high-velocity C IV NAL at

<sup>6</sup> The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1  
OBSERVATION INFORMATION

ObsID	Observatory	Date	$\lambda$ Range ( $\text{\AA}$ )	Resolution ( $\text{\AA}$ )
1.....	Palomar	1981 Nov	3300–4800	0.8–1.5
2.....	Palomar	1983 Feb	3100–3700	0.8
3.....	Palomar	1983 Nov	3100–5000	1.5
4.....	Palomar	1984 May	4600–5800	1.5
5.....	Palomar	1984 Oct	4700–6000	1.5
6.....	Palomar	1985 Apr	4800–6600	0.8–2.2
7.....	Lick	1993 Jan	3250–5350	2.95
8.....	Lick	1996 Mar	3250–4600	2.95
9.....	MMT	1996 Dec	3400–4400	1.4
10.....	Lick	1997 Feb	3200–6000	2.95
11.....	Lick	1997 Dec	3100–6000	2.95
12.....	Lick	1999 Jan	3200–6000	2.95

$z_{\text{abs}} = 1.6189$ . No other lines are detected at these redshifts. SBS88 report that both components of the narrow C IV doublet at  $z_{\text{abs}} = 1.6189$  are blended with Si II  $\lambda 1526$  absorption (see Fig. 1). However, much higher resolution Keck spectra (F. Hamann et al. 2003, in preparation) obtained in 1996 December provide no evidence for these Si II lines. In particular, we do not detect other low-ionization lines such as Fe IV  $\lambda 1608$  or C II  $\lambda 1334$ . Also, the redshifts and profiles of the individual C IV doublet lines at  $z_{\text{abs}} = 1.6189$  match each other very well, indicating that all of the absorption is due to C IV (at least for the epoch 1996 December). The data shown in Figure 1 suggest that these lines varied. In particular, the equivalent width of the short-wavelength component of the C IV doublet is roughly twice as strong in 1981 and 1996 compared to 1997. However, the two doublet components seem to have varied by different amounts, which is unphysical. Therefore, the variability in this system is questionable. If this system is intrinsic, its displacement from the emission lines implies an outflow velocity of  $\sim 32,900 \text{ km s}^{-1}$ .

SBS88 describe the C IV mini-BAL in Q0151+048 as a blend of four narrow C IV absorption systems with redshifts ranging from  $z_{\text{abs}} = 1.6533$  to 1.6600. We consider this blend rather to be a mini-BAL, based on its appearance in the SBS88 spectrum and on the absence of discrete narrow components in our high-

resolution Keck spectrum (F. Hamann et al. 2003, in preparation). We measure the observed frame equivalent widths in this feature over the epochs monitored from 0.38 to 3.8  $\text{\AA}$ , signifying a factor of  $\sim 10$  variation. The FWHM of the mini-BAL (as observed in 1981 October) is  $\sim 1020 \text{ km s}^{-1}$ , and its displacement from the emission redshift is  $-28,400 \text{ km s}^{-1}$ .

The AALs in this quasar did not appear to vary.

#### 4.2. PKS 0424–131

Figure 2 shows the variable N V and C IV AALs at  $z_{\text{abs}} = 2.1330$ . The change in the N V doublet is obvious. The short-wavelength component of the C IV doublet is blended with an unrelated line of Fe II at  $z_{\text{abs}} = 1.0352$ . Ly $\alpha$  in this AAL system is not clearly detected because of blending with another unrelated line. We also do not detect Si IV absorption at the AAL redshift. The equivalent widths of the N V and C IV AALs varied by 55% and 17%, respectively, between the two observations.

Petitjean, Rauch, & Carswell (1994) published high-resolution (0.3  $\text{\AA}$ ) spectra of PKS 0424–131 obtained in 1992. They report a total observed frame equivalent width in the N V doublet of 1.62  $\text{\AA}$ , compared to 3.57 and 1.72  $\text{\AA}$  in our data from 1981 and 1997, respectively. Petitjean et al. (1994) also measured an equivalent width of 0.31  $\text{\AA}$  in the unblended long-wavelength component of the C IV doublet, compared to our

TABLE 2  
ABSORPTION LINE PROPERTIES

QSO	$z_{\text{em}}$	$z_{\text{abs}}$	$v$ ( $\text{km s}^{-1}$ )	Type	ObsID	Variability?
Q0151+048 .....	1.9232	1.6189	–32,900	NAL	1, 9, 11, 12	Yes?
		1.6581	–28,400	Mini-BAL		Yes
		1.9343	+900	AAL		No
Q0207–003.....	2.849	2.8871	+2950	AAL	5, 11, 12	No
		2.0237	–3580	AAL		3, 12
Q0348+061 .....	2.060	2.0330	–2660	AAL	1, 2, 11	No
		2.1330	–3140	AAL		Yes
		2.1731	+660	AAL		No
PKS 0424–131.....	2.166	1.9105	–1490	AAL	1, 10, 11, 12	Yes
		1.9165	–870	AAL		Yes?
		1.490	–52,000	Mini-BAL		7, 8, 11, 12
PG 0935+417.....	1.966	1.938	–2780	AAL	3, 12	No
		1.7310	–2190	AAL		No
Q0958+551 .....	1.751	1.7327	–2000	AAL	4, 6, 10	No
		3.5265	+1630	AAL		No

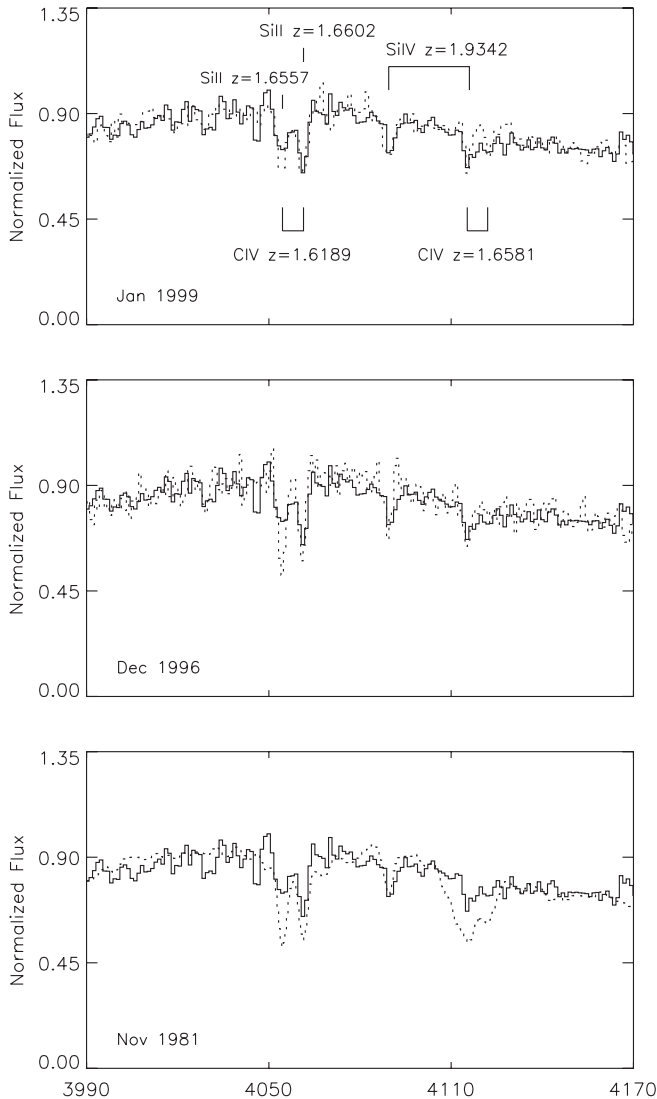


FIG. 1.—Q0151+048. The solid curve in each panel is the normalized 1997 December spectrum, while the dotted curves are other spectra from the dates indicated. The C IV mini-BAL at  $z_{\text{abs}} = 1.6581$  and the high-velocity C IV NALs at  $z_{\text{abs}} = 1.6189$  are labeled below the spectra in the top panel. Other unrelated lines are labeled above. The two Si II identifications are probably spurious, based on much higher resolution spectra obtained in 1996 December. The bottom panel clearly shows the variability in the mini-BAL (moving at  $\sim 28,400 \text{ km s}^{-1}$ ). The apparent variation in the C IV NALs at  $z_{\text{abs}} = 1.6189$  is suspect because one component of this doublet changed more than the other (see § 4.1).

equivalent-width measurements of 3.9 and 0.36 Å in our 1981 and 1997 spectra. These comparisons suggest that the largest variations in these AALs occurred between the 1981 SBS88 and 1992 Petitjean et al. (1994) observations.

#### 4.3. Q0848+163

Higher resolution spectra (F. Hamann et al. 2003, in preparation) confirm that there are several AAL systems in this quasar. The two systems that SBS88 identified at  $z_{\text{abs}} \approx 1.916$  and  $z_{\text{abs}} \approx 1.917$  are blended together in our Lick spectra. We will therefore refer to them hereafter as one system at  $z_{\text{abs}} = 1.9165$ . There is another AAL system at  $z_{\text{abs}} = 1.9105$  that SBS88 did not identify, but that is unmistakable in our high-resolution Keck spectrum (F. Hamann et al. 2003, in preparation).

Figure 3 provides some evidence for variability in these AAL systems.<sup>7</sup> Comparisons involving the 1983 February spectrum are ambiguous because the underlying emission lines varied substantially between that epoch and the more recent Lick observations. However, the two 1997 observations suggest that similar variations occurred in the N V and C IV doublets. The evidence for variability is perhaps stronger for the system at  $z_{\text{abs}} = 1.9105$ , where the equivalent width in the unblended short-wavelength component of the N V doublet declined by approximately 50%. The AALs at  $z_{\text{abs}} = 1.9165$  might also have varied in 1997, but the changes coinciding with the short-wavelength doublet components in this system might be due at least in part to the variability at  $z_{\text{abs}} = 1.9105$ . The variability in the accompanying Ly $\alpha$  lines is masked by blending with Ly $\alpha$  forest lines. We do not detect the Si IV (or other) lines in these systems.

#### 4.4. PG 0935+417

Figure 4 shows distinct variation in a C IV mini-BAL that is blueshifted by  $\sim 52,000 \text{ km s}^{-1}$  with respect to the emission lines (see also Hamann et al. 1997a). The identification of this feature with highly blueshifted C IV is confirmed by the appearance of N V and O VI absorption at the same velocity (P. Rodriguez Hidalgo & F. Hamann 2003, in preparation). This is the second highest observed velocity for a mini-BAL, at nearly  $\sim 0.2c$ , after PG 2302+029 (B. Jannuzi et al. 2003, in preparation). High-resolution Keck observations of PG 0935+417 (Hamann et al. 1997a) show that the mini-BAL remains smooth down to a resolution of  $7 \text{ km s}^{-1}$ . This mini-BAL is therefore truly a broad line with a continuous range of absorption velocities, and not a blend of many NALs. The most dramatic variation occurred between 1993 January and 1996 March (Fig. 4), where the observed frame equivalent width in the mini-BAL increased from  $\sim 5.12 \text{ \AA}$  in 1993 to  $\sim 6.14 \text{ \AA}$  in 1996 ( $\sim 19\%$ ). However, the change is most obvious in the shape and centroid of the mini-BAL profile. The centroid of the line moved from  $\sim 3917$  to  $\sim 3865 \text{ \AA}$  (corresponding to a shift of  $\sim 4000 \text{ km s}^{-1}$ ) between 1993 and 1996. The FWHM of the mini-BAL was  $\sim 1885 \text{ km s}^{-1}$  in 1993 and  $\sim 1320 \text{ km s}^{-1}$  on the other dates. The complex of AALs in this quasar did not vary (see also F. Hamann et al. 2003, in preparation).

### 5. ANALYSIS

The line variability timescales place constraints on the physical properties of the absorbing clouds. Here we assume the variations were caused by changes in the ionization state, which leads to estimates of the minimum electron density and maximum distance from the continuum source (for a photoionized plasma). The results are listed in Table 3, where  $t_{\text{var}}$  is the smallest observed variability time in the quasar rest frame,  $n_e$  is the electron density, and  $R$  is the distance from the continuum source. Note that the values of  $n_e$  and  $R$  are limits because we measure only upper bounds on the variability times.

#### 5.1. Minimum Electron Densities

We assume for simplicity that the gas is in ionization equilibrium and the ions we measure are the dominant ionization

<sup>7</sup> The spectral region covering the C IV AALs in 0848+163 was measured and reported by SBS88. However, these data were not available for the present study and are therefore excluded from Fig. 3.

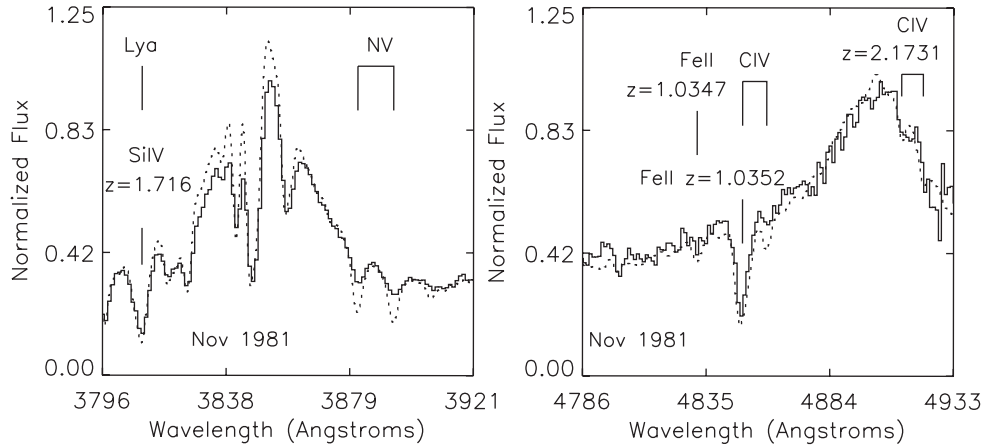


FIG. 2.—PKS 0424–131 normalized spectra showing variation in a  $z_{\text{abs}} = 2.1330$  AAL system. The Ly $\alpha$ , N v, and C iv lines in this variable AAL system are labeled without redshifts. Some other unrelated lines are also labeled with redshifts. The solid curve in both panels is the 1997 December spectrum, while the dotted curves show the 1981 November observation. The wavelength range in both panels corresponds to  $\sim 10,000$  km s $^{-1}$ .

stages. In that case, the variability time is limited by the recombination time given by

$$n_e \approx \frac{1}{\alpha_{i-1} t_{i-1}^{\text{recom}}}, \quad (1)$$

where  $\alpha_{i-1}$  is the rate coefficient for recombination from the observed ion stage  $i$  to the next lower stage  $i - 1$ , and  $t_{i-1}^{\text{recom}}$  is the corresponding recombination time (see Hamann et al. 1997c). Arnaud & Rothenflugh (1985) give recombination rates for C IV  $\rightarrow$  C III and N v  $\rightarrow$  N IV as  $2.8 \times 10^{-12}$  and  $5.5 \times 10^{-12}$  cm $^{-3}$  s $^{-1}$ , respectively. These values, together with a nominal temperature of 20,000 K (Hamann et al. 1995) and the maximum recombination times set by our observations, give the minimum electron densities presented in Table 3. Because of the particular values of the recombination rates, the calculated minimum electron densities for N v are consistently a factor of  $\sim 2$  less than those for C iv. Thus, we list constraints on the minimum electron densities in Table 3 based only on the C iv recombination rates.

### 5.2. Maximum Distances from Continuum Source

We derive the maximum distance between the absorbing clouds and the continuum source by assuming the gas is in photoionization equilibrium with an ionization parameter given by

$$U = \frac{1}{4\pi R^2 n_{\text{H}} c} \int_0^{\lambda_{\text{LL}}} \frac{\lambda L_{\lambda}}{hc} d\lambda, \quad (2)$$

where  $n_{\text{H}} \approx n_e$  is the hydrogen density,  $\lambda_{\text{LL}} = 912$  Å is the wavelength at the Lyman limit, and  $L_{\lambda}$  is the quasar luminosity distribution. We assume all of the quasars in our sample have the same continuum shape characterized by a segmented power law,  $L_{\lambda} \sim \lambda^{\alpha}$ , where  $\alpha = -1.6$  from 1000 to 100,000 Å,  $-0.4$  from 10 to 1,000 Å, and  $-1.1$  from 0.1 to 10 Å (Zheng et al. 1997; Telfer et al. 2002). We also assume that the absorbing clouds are not “shielded” from the continuum emission source. Thus, the continuum spectrum incident on the absorbing clouds is diminished only by the geometric  $1/R^2$

dilution. Integrating over our adopted continuum shape in equation (2) yields a convenient expression,

$$U \approx 0.09 \frac{L_{47}}{n_{10} (R_1)^2}, \quad (3)$$

where  $L_{47}$  is the bolometric luminosity in units of  $10^{47}$  ergs s $^{-1}$ ,  $n_{10}$  is the density in units of  $10^{10}$  cm $^{-3}$ , and  $R_1$  is the distance from the continuum source in parsecs. Note that for this continuum shape, the quasar bolometric luminosity is  $L_{\text{bol}} \approx 4.4\lambda L_{\lambda}$  at  $\lambda = 1450$  Å.

We derive bolometric luminosities for the quasars in our sample based on the continuum shape given above, observed  $B$  magnitudes from Junkkarinen et al. (1991) and Hewitt & Burbidge (1993), and a cosmology with  $H_0 = 72$  km s $^{-1}$  Mpc $^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_{\Lambda} = 0.7$ . For PKS 0424–131, we use a measured  $V$  magnitude and a representative value of  $B - V = 0.12$  (based on other luminous quasars at this redshift; Hewitt & Burbidge 1993). The resulting values of  $L_{47}$  are listed in Table 3. Finally, we adopt an ionization parameter of  $U \approx 0.02$ , which is approximately optimal for the C iv and N v ions (e.g., Hamann et al. 1995, 1997a). Plugging into equation (3) with the previously derived density limits yields the upper limits on  $R$  listed in Table 3.

## 6. DISCUSSION

Two of the eight quasars in our study showed variability in their AALs. This fraction is similar to the three out of 15 AAL systems showing variability in a sample of lower redshift quasars studied by Wise et al. (2003). Note that these results provide only minimum variability fractions because of the limited time sampling. The fraction of AALs that are intrinsic based on variability is therefore  $\geq 25\%$ . We are now analyzing much higher resolution spectra of all of the quasars in our sample (F. Hamann et al. 2003, in preparation) to look for other evidence of intrinsic absorption (see § 1).

The mini-BALs appear to vary more often than the AALs. Our study showed variations in two out of two systems. The only other mini-BALs tested for variability that we know of are PG 2302+029 (B. Jannuzi et al. 2003, in preparation) and Q2343+125 (which is marginally a mini-BAL with FWHM  $\approx$

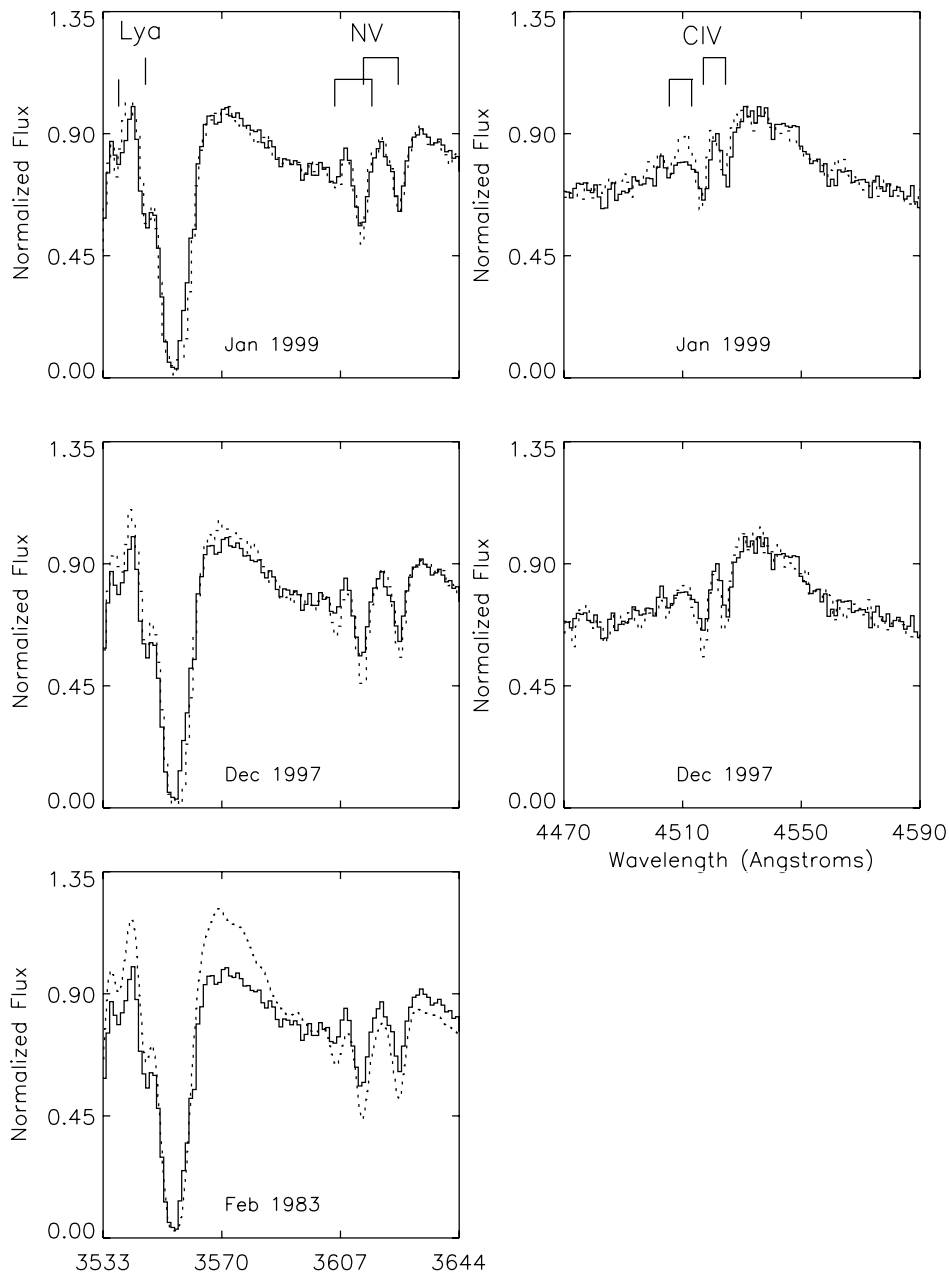


FIG. 3.—Q0848+163 normalized spectra showing variable AALs at  $z_{\text{abs}} = 1.9105$  and  $1.9165$ . The red components of the N v and C iv doublets at  $z_{\text{abs}} = 1.9105$  are blended with the blue components of these doublets at  $z_{\text{abs}} = 1.9165$ . The solid line is a 1997 February observation. Please note that, for the purpose of best showing the variability, the fiducial plot in this figure is different from the rest of the figures. Dates for the dotted spectra are given in each panel. Unfortunately, we do not have Palomar data covering the C iv AALs. The strong, unlabeled line at 3555 Å is Ly $\alpha$  at  $z_{\text{abs}} = 1.925$ . The wavelength range in all panels corresponds to  $\sim 10,000$  km s $^{-1}$ .

400 km s $^{-1}$ ; Hamann, Barlow, & Junkkarinen 1997b). Both of those systems also varied between just two observations.

The marginal detection of variability in the high-velocity NAL system of Q0151+048 is surprising but not unprecedented. Richards et al. (1999) argued that a significant fraction of NALs at blueshifted velocities from 5000 to 75,000 km s $^{-1}$  are intrinsic to quasars, based on statistical correlations between the appearance of these lines and the quasar radio properties. The high-velocity NAL system in Q0151+048 might be one specific example at a velocity shift of  $\sim 32,900$  km s $^{-1}$ .

It is interesting to note that, with one exception, the variable absorption lines remained fixed in velocity. The excep-

tion is the mini-BAL in PG 0935+417, whose changing centroid and FWHM was noted previously by Hamann et al (1997a). However, it is not clear that these velocity changes represent real changes in the absorber kinematics. It could be that the apparent velocity changes are caused by variations in the line strength (optical depth) across a fixed range of absorption velocities. A more likely example of a real velocity shift involves an AAL system in the Seyfert I galaxy, NGC 3783 (Gabel et al. 2003).

All of the variable absorption lines in our sample appear at *blueshifted* velocities, clearly indicating outflows from the quasars. However, the wind geometry implied by these AALs and mini-BALs must be different from the classic BALs. In

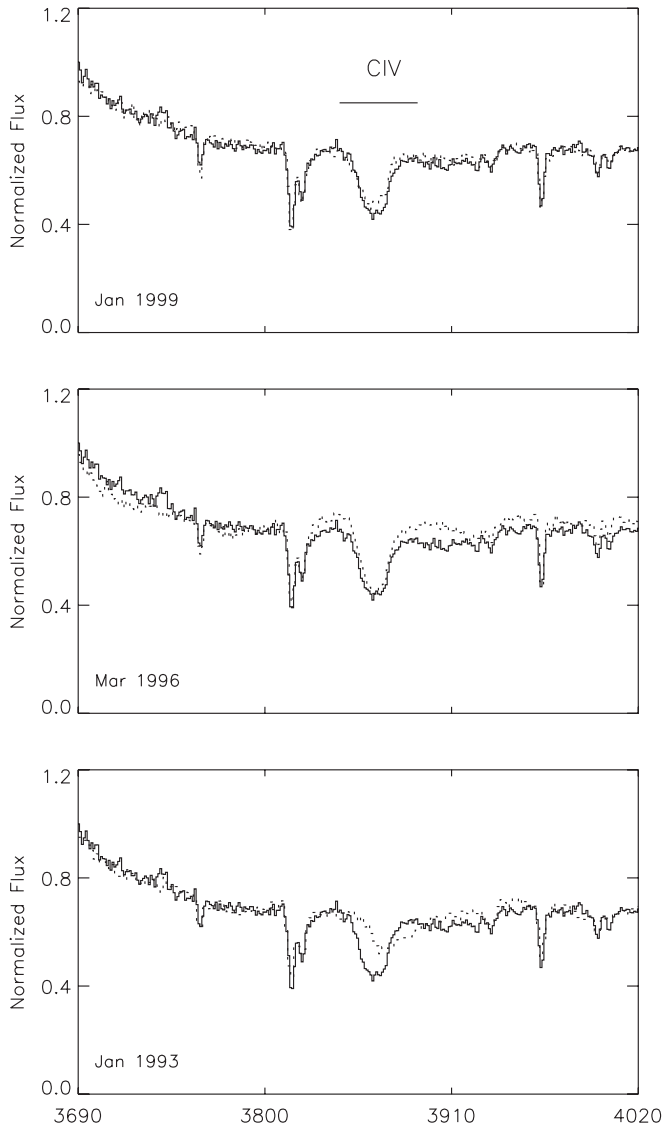


FIG. 4.—PG 0935+417. The solid curve is the normalized 1997 December spectrum. The horizontal bar at  $\sim 3875 \text{ \AA}$  in the top panel marks the approximate extent of the C IV mini-BAL. This absorber is outflowing at nearly  $52,000 \text{ km s}^{-1}$ . Several unrelated NALs are also present, but not labeled in this plot.

particular, the line widths are small compared to the wind speed. BALs typically have  $V/\text{FWHM}$  of order unity (where  $V$  is the outflow speed). In contrast, the mini-BAL in Q0151+048 has  $V/\text{FWHM} \approx 28$ , and the high-velocity NAL in that quasar has  $V/\text{FWHM} \approx 55$ . Another intrinsic absorber in Q2343+125 (Hamann et al. 1997b) has  $V/\text{FWHM} \approx 60$ .

Absorption lines like these with  $V/\text{FWHM} \gg 1$  probably do not form in continuous outflows that accelerate from rest along our line of sight to the continuum source. If that were the case, we should see absorption at all velocities from  $V$  to 0, unless, perhaps, there is a peculiar ionization structure that somehow favors C IV and similar ions only at the very narrow range of observed line velocities. A more likely possibility is that the observed lines form in discrete “blobs” of gas that were ejected/accelerated sometime prior to the observations. However, the nature of these blobs as coherent entities is unclear. The large velocity dispersions implied by the line widths ( $\text{FWHM} > 1000 \text{ km s}^{-1}$  for the mini-BALs) should quickly lead to a spatially extended structure. Another possibility is that the flows intersect our line of sight to the continuum source (and become observable in absorption) only after they reach the observed high speeds (see also Hamann et al. 1997b; Elvis 2000). Thus, the acceleration occurs somewhere outside of our sight line to the continuum source. In this case the flow could be continuous—simultaneously spanning a wide range of velocities and radial distances,  $R$ , but the absorption lines sample only a limited range of these parameters, depending on the specific geometry and orientation.

One plausible geometry involves a wind emanating from the quasar accretion disk (Murray et al. 1995; Proga, Stone, & Kallman 2000). If the lines we measure form anywhere near the point of origin of these winds, within several parsecs of the central black hole and possibly much closer, then simple considerations based on equation (3) suggest that the actual gas densities are  $n_e \gtrsim 10^9 \text{ cm}^{-3}$ . Unfortunately, the lower limits on  $n_e$  in Table 3 are not very constraining. They are inconsistent with only the most extreme lower densities and large radial distances ( $\gtrsim 10 \text{ kpc}$ ) derived for some AAL systems (based on excited-state absorption lines, e.g., Morris et al. 1986; Tripp, Lu, & Savage 1996; Hamann et al. 2001).

### 7. CONCLUSIONS

We observed eight AAL quasars to test for variability in their absorption-line strengths as an indicator of intrinsic absorption. Two of these quasars were also known previously to have high-velocity mini-BALs. In our limited time sampling of 2–4 observations per quasar, we found variability in both of the mini-BALs, two out of eight AAL systems, and possibly one additional high-velocity NAL system. These results agree with previous reports of frequent variability in mini-BALs (Hamann et al. 1997a; B. Jannuzi et al. 2003, in preparation) and with the recent finding of AAL variability in 3 out of 15 quasars studied by Wise et al. (2003). The short timescales over which the lines varied in our study (sometimes  $< 0.28 \text{ yr}$  in the quasar rest frame) implies that the absorbers are dense, compact, and physically associated with the quasars. We estimate minimum electron densities (from the recombination time) ranging from

TABLE 3  
PHYSICAL PROPERTIES

Object	$z_{\text{abs}}$	$t_{\text{var}}$ (yr)	$n_e$ ( $\text{cm}^{-3}$ )	$L_{47}$	$R$ (pc)
Q0151+048 .....	1.6189	0.40	$\geq 25,000$	1.9	$\leq 1800$
	1.6581	5.67	$\geq 2000$	...	$\leq 6540$
PKS 0424–131 .....	2.1330	3.37	$\geq 3400$	3.7	$\leq 7000$
Q0848+163 .....	1.9105	0.28	$\geq 40,000$	6.4	$\leq 2700$
PG 0935+417 .....	1.490	1.27	$\geq 8900$	9.6	$\leq 7000$



$\sim 1900$  to  $\sim 40,000 \text{ cm}^{-3}$ . We conclude that the fraction of AALs that are intrinsic based on variability is at least  $\sim 25\%$ . The fraction of mini-BALs that are intrinsic may be  $\sim 100\%$ . The outflow velocities implied by the intrinsic systems range from  $\sim 1500$  to  $\sim 52,000 \text{ km s}^{-1}$ .

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