AN UNUSUAL "MINI-BAL" QUASAR AT z = 4.59

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ABSTRACT

The z = 4.591 quasar PC 1415+3408 exhibits very strong associated metal-line absorption from the N v λ1238, 1242, Si iv λ1539, 1402, and C iv λ1548, 1550 doublets spanning the velocity interval −1700 km s⁻¹ ≤ v ≤ 0 km s⁻¹. Also present are detached absorption troughs in N v and C iv spanning −5000 km s⁻¹ ≤ v ≤ −3000 km s⁻¹; this is characteristic of broad absorption line (BAL) quasars, but the small overall velocity spread suggests that PC 1415+3408 be classified as a "mini-BAL" quasar. The N v doublet is consistent with black saturation over the velocity interval −1200 to −500 km s⁻¹; black N v absorption is extraordinary in all classes of quasars at all redshifts. Over this velocity interval, the C iv doublet is severely blended but also consistent with black saturation. The material over this range of velocity appears to fully occult the continuum source, the broad emission line region, and any material that could give rise to scattered light. In view of a unified scenario for BAL and mini-BAL absorption, these facts imply that the quasar is being viewed along a preferred direction. On the other hand, the black mini-BALs in PC 1415+3408 could be explained if the BAL flow has an unusual geometry compared with the population of BAL quasars and/or the spatial extent of a scattering region is small at the lower velocities (−1700 km s⁻¹ ≤ v ≤ 0 km s⁻¹).

Key words: quasars: absorption lines — quasars: general — quasars: individual (PC 1415+3408)

1. INTRODUCTION

The absorption lines from metals with z_{abs} ≈ z_{em} are useful probes of the kinematics and chemical and ionization conditions of the material surrounding quasars, whether the material gives rise to broad absorption lines (BALs) or narrower absorption lines (e.g., Weymann & Williams 1978; Weymann et al. 1979; Briggs, Turnshek, & Wolfe 1984; Turnshek 1984; Morris et al. 1986; Anderson et al. 1987; Turnshek 1988; Weymann et al. 1991; Korista et al. 1993; Turnshek 1995; Arav 1996; Turnshek et al. 1996; Turnshek 1997a, 1997b; Hamann 1997; Hamann et al. 1997a, 1997b, 1997c; Barlow & Sargent 1997; Arav et al. 1998). These absorption lines sample environments in which the chemical and ionization conditions have presumably been influenced by the central engine of the quasar active nucleus (see Arav, Shlosman, & Weymann 1997).

BAL gas is thought to be material within ~1 kpc of the quasar that is undergoing a high-velocity outflow, typically from −5000 to −25,000 km s⁻¹ (Turnshek 1988; Weymann et al. 1991). BAL quasars comprise roughly 10% of all quasars (however, see Goodrich 1997; Krolik & Voit 1998), are radio-quiet (Stocke et al. 1992; however, see Becker et al. 1997), and are quiet, or self-absorbed, in soft X-rays (hv < 2 keV: Kopko, Turnshek, & Espey 1994; Green & Mathur 1996) and hard X-rays (2 keV ≤ hv ≤ 10 keV: Gallagher et al. 1999). Though there are many interpretations of these trends, a unified picture has been proposed in which all quasars have BAL flows and that various viewing angles through the outflowing material result in different observed absorption properties. Most unified pictures, as suggested by polarization studies (e.g., Cohen et al. 1995), have the BAL material originating from a disk geometry (e.g., Emmering, Blandford, & Shlosman 1992; de Kool & Begelman 1995; Murray et al. 1995).

An apparently rare class of so-called "mini-BAL" quasars have been identified (Turnshek 1988; Barlow, Hamann, & Sargent 1997). These quasars often exhibit flat-bottomed (but not necessarily black-bottomed) absorption profiles with overall velocity spreads less than 2000 km s⁻¹. The relationship between mini-BAL and BAL quasars is not yet understood. From the point of view of ultraviolet (UV) rest-frame spectra, mini-BAL quasars may prove to be the most useful for deducing the chemical and ionization conditions of material involved in BAL flows (Arav 1997), since they do not suffer the extreme blending seen in BAL quasars. Ultimately, however, any working model of BAL flows will need to survive observational provings not only with UV rest-frame data but with radio and both soft and hard X-ray data as well.

In addition to multiband observations, studies are needed that extend the sample of BAL and mini-BAL quasars to the highest redshifts. Nearly 100 quasars at z ≥ 4.0 have now been discovered, and the fraction with BAL features appears to be the same as at lower redshifts (e.g., Storrie-Lombardi et al. 1996). Extending BAL quasar studies to z > 4 would yield a chronological baseline on par with studies of the Lyα absorbers for firmly establishing cosmic evolution (or lack of) in a class of astronomical
Using a slit with 2.6 pixel ~1 object. Unlike (but complementary to) studies of Ly\textalpha\, investigations of BAL quasars probe the most absorption, investigations of BAL quasars probe the most extreme absorption feature that is slightly redshifted. As seen in (of all redshifts) reported in the literature and has a weak feature appears to be among the strongest seen in quasars (of all redshifts) reported in the literature and has a weak feature appears to be among the strongest seen in quasars.

Resolution Imaging Spectrograph (LRIS) on the Keck I Telescope (Oke et al. 1995). An 1800 s exposure was obtained on 1996 April 14 using the 1200 line mm~1 grating and a 0.7 slit under \textasciitilde 1 seeing conditions. The resolution of the spectrum is \( R \approx 4000 \) with \( \textasciitilde 0.64 \) \( \text{A} \text{ pixel}^{-1} \), and the wavelength coverage is 5797.6–7108.8 \( \text{A} \). An additional 1800 s exposure using the 300 line mm~1 grating with a 1.0 slit was obtained on 1997 April 3. The seeing was \( \textasciitilde 0.7 \), resulting in a resolution of \( R \approx 900 \) with \( \textasciitilde 2.4 \) \( \text{A} \) pixel~1.

The wavelength coverage is 3917.8–8908.9 \( \text{A} \). For all observations, the spectrograph slit was set at the parallactic angle to minimize differential refraction. The spatial scale on the CCD is 0'213 pixel~1.

The raw data frames were processed in the standard fashion, including bias subtraction and flat fielding. The spectra were extracted using the optimal algorithm of Horne (1986). The wavelength scale was set (for both gratings) with cubic fits to lines from Hg, Kr, and Ar discharge lamps. The resulting RMS errors are 0.09 \( \text{A} \) for the 1200 lines mm~1 grating and 0.23 \( \text{A} \) for the 300 line mm~1 grating. For the latter observations, the seeing was less than the slit width, resulting in a \textasciitilde 1 pixel uncertainty in the wavelength scale zero point. The flux calibration and the removal of atmospheric absorption bands were performed using the flux standards of Oke & Gunn (1983). The fully reduced and calibrated spectra are shown in Figures 1 (300 line mm~1) and 2 (1200 line mm~1).

3. PC 1415+3408

3.1. UV Rest-Frame Properties

In Figure 3, we show the 300 line mm~1 spectrum redward of the Ly\textalpha\ emission line with the vertical scale set to emphasize the continuum features. PC 1415+3408 has strong, broad, high-ionization emission lines from N \( \nu \lambda 1240.1 \), Si \( \nu \lambda 1400.0 \), and C \( \nu \lambda 1549.1 \). The cores and blue wings of these emission lines are strongly absorbed. In absorption, the N \( \nu \lambda 1238 \), 1242 doublet members are partially resolved, the Si \( \nu \lambda 1393 \), 1402 doublet members are well resolved, and the C \( \nu \lambda 1548 \), 1550 doublet members are fully blended. There are also weaker, low-ionization emission lines from Si \( \Pi \lambda 1263.0 \), O \( \Pi + \) Si \( \Pi \lambda 1304.5 \), and C \( \Pi \lambda 1334.5 \). The Si \( \Pi \) emission is on the red wing of the broad N \( \nu \) emission line, making it difficult to accurately determine the Si \( \Pi \) strength. The O \( I + \) Si \( \Pi \) feature appears to be among the strongest seen in quasars (of all redshifts) reported in the literature and is a weak absorption feature that is slightly redshifted. As seen in

**Figure 1.**—LRIS/Keck spectrum of PC 1415+3408 obtained with the 300 line mm~1 grating. The resolution of the data is \( R \approx 4000 \) with 0.65 \( \text{A} \) pixel~1.

**Figure 2.**—LRIS/Keck spectrum of PC 1415+3408 obtained with the 1200 line mm~1 grating. The resolution of the data is \( R \approx 4000 \) with 0.65 \( \text{A} \) pixel~1.

**Figure 3.**—The 300 line mm~1 spectrum of PC 1415+3408 redward of Ly\textalpha\ emission. The broad emission lines are labeled. The narrow "absorption" line at 8762 \( \text{A} \) and the narrow "emission" lines at 8827 \( \text{A} \) and on the C \( \nu \) broad emission line at 8670 \( \text{A} \) are artifacts of the sky subtraction. The 1 \( \sigma \) error array is given by the spectrum just above the zero point.
There is a clear Lyman limit break at 5080 Å, which corresponds to \( z = 4.575 \). The lack of a recovery by 704 Å in the rest frame implies \( N(\text{H} 
olinebreak \text{ii}) > 10^{18.2} \text{cm}^{-2} \). There is strong Ly\( \alpha \) absorption at 6777 Å that corresponds to the break (see Figs. 1 and 2). In Table 1, we list the overall properties of PC 1415 + 3408. The \( g_4 \) and \( r_4 \) filters each have widths of approximately 450 Å and are centered at 4930 and 6550 Å, respectively. The quantity \( AB_{1450} \) is the observed \( AB \) magnitude, corrected for Galactic reddening, at \( \lambda = 1450(1 + z) \), where \( AB = -2.5 \log f - 48.60 \) (see Schneider, Schmidt, & Gunn 1989).

The spectral energy index, \( \alpha \), was determined by fitting the function \( f_\lambda \propto \lambda^\alpha \) to interactively selected continuum points redward of \( \sim 6780 \) Å using the 300 line mm\(^{-1}\) spectrum. A possible observational systematic error in the slope could be differential refraction, though we note that the seeing was better than the projected width of the slit, and we aligned the slit with the parallactic angle. To estimate possible systematics in the fitting procedure itself, we performed multiple interactive fits. Just over 65% of the total available wavelength coverage redward of the blended Ly\( \alpha \) + N \( \nu \) emission line was employed. This exercise yielded \( \alpha = -0.45 \pm 0.05 \). Our \( \alpha \) value is significantly different than that measured by SSG97 (\( \alpha = -1.2 \)) using lower quality data. Normalization of the power law gives \( AB_{1450} = 20.6 \), from which an absolute blue-band magnitude of \( M_g = -25.9 \) was calculated following Schneider et al. (1989). These values are in good agreement with those calculated by SSG97.

**Table 1**

| Parameter | Value |
|-----------|-------|
| Right ascension (B1950.0) | 14°15′46′6 |
| Declination (B1950.0) | +34°08′30″ |
| \( z_{em} \) | 4.591 ± 0.001 |
| \( g_4 \) | 23.76 ± 0.17 |
| \( r_4 \) | 21.37 ± 0.08 |
| \( \alpha \) | -0.45 ± 0.05 |
| \( AB_{1450} \) | 20.57 ± 0.09 |
| \( M_{1450} \) | -26.3 |
| \( M_B \) | -25.9 |
| \( D_A \) | 0.70 ± 0.06 |
| \( D_B \) | 0.8 ± 0.1 |
| \( \Delta L_{Ly\alpha} (\text{Å}) \) | 0.81 ± 0.02 |

The zero-point offset applied here is corrected to be one-half that applied in their work (see Schmidt, Schneider, & Gunn 1995).

**Table 2**

| Transition | \( \lambda_{em} \) (Å) | \( \lambda_{es} \) (Å) | \( z_{em} \) | \( W_0 \) (Å) | \( W_r \) (Å) | \( \sigma_r \) (Å) |
|------------|------------------------|------------------------|-------------|-------------|-------------|--------------|
| Ly\( \alpha \) + N \( \nu \) | 1215.7 + 1240.1 | 6792.4 ± 0.1 | 4.589 | 448 ± 45 | 80.1 ± 8.0 | 1.23 ± 0.02 |
| Si \( \Pi \) | 1263.0 | 7060.5 ± 0.7 | 4.592 ± 0.001 | 8.1 ± 0.4 | 1.45 ± 0.07 | 2.83 ± 0.09 |
| O \( \iota \) + Si \( \Pi \) | 1304.5 | 7294.3 ± 1.4 | 4.593 ± 0.001 | 39.3 ± 3.4 | 7.03 ± 0.60 | 5.00 ± 0.27 |
| C \( \Pi \) | 1334.5 | 7566.3 ± 1.7 | 4.589 ± 0.001 | 9.8 ± 1.5 | 1.76 ± 0.27 | 2.48 ± 0.30 |
| Si \( \iota \) + O \( \nu \) | 1400.0 | 7814.4 ± 4.3 | 4.583 ± 0.003 | 41.1 ± 5.8 | 7.35 ± 1.04 | 7.67 ± 0.73 |
| C \( \nu \) | 1549.1 | 8657.5 ± 6.9 | 4.590 ± 0.004 | 45.6 ± 11.9 | 8.15 ± 2.12 | 7.95 ± 1.06 |

\( \lambda_{ Ly\alpha } \) provides a quantitative measure of this absorption, where \( f_{(\text{observed})} \) is the observed flux and \( f_{(\text{continuum})} \) is the predicted unattenuated flux based upon extrapolation of the spectral energy index. This deficit is measured over two regimes. The first, \( D_{A} \), is measured from 1050 to 1170 Å in the rest frame of the quasar and gives the mean absorption blueward of the Ly\( \alpha \) emission line and redward of the Ly\( \beta \) + O \( \nu \) emission line; it is designed to measure Ly\( \alpha \) only absorption. The second, \( D_{B} \), is measured from 920 to 1015 Å in the rest frame of the quasar and gives the mean absorption blueward of the Ly\( \beta \) + O \( \nu \) emission line and redward of the Lyman limit of the quasar.

The dominant source of error in the measurement of the flux decrement is the uncertainty in the power-law conti-
To estimate the uncertainty in our measurement, we used the 1σ spread in z and in $AB_{1450}$ that conspire to give the extreme upper and lower values of $D$. For PC 1415 + 3408, we measured $D_{A} \approx 0.7$ with an uncertainty of 0.06. This value is typical of $z \approx 4.5$ quasars; $D_{A}$ is seen to rise from $\sim 50\%$ at $z = 4$ to $\sim 80\%$ at $z \sim 5$ (Schneider et al. 1991). This has been shown to be consistent with an increase in the numbers of Lyα clouds at higher redshifts (Giallongo & Cristiani 1990; Jenkins & Ostriker 1991; Schneider et al. 1991). We find $D_{B} \approx 0.8$, with uncertainty 0.1. This value is slightly high compared with the mean value 0.65 measured for 13 $z > 4$ non-BAL quasars (Schneider et al. 1991), possibly due to strong associated metal lines (esp. O VI, C III, and N III).

In the 300 line mm$^{-1}$ spectrum (see Fig. 1), there is strong, broad absorption at 6143 Å, which has the appearance of a damped Lyα absorber (DLA) at $z = 4.054$. If this is a DLA, the rest-frame equivalent width for Lyα is 14.5 ± 0.6 Å, which corresponds to log $N$(H I) $\sim 21.0$ cm$^{-2}$. However, in the 1200 line mm$^{-1}$ spectrum, the absorption appears to break into a series of smaller, blended Lyα clouds, as seen in Figure 2. This serves as a warning that DLA candidates at $z \sim 4$ in spectra with 5–6 Å resolution require follow-up verification at higher resolutions.

### 3.2. Radio and X-Ray Properties

PC 1415 + 3408 is not detected in the FIRST survey to a flux limit $f_{1}(1.4 \text{ GHz}) \leq 1.0$ mJy. Assuming a spectral power index of $\alpha = -0.5$ for both the radio and optical bands, we obtained $L_{\text{ radio}}(6 \text{ cm}) \leq 10^{25.2}$ W Hz$^{-1}$ and $L_{\text{ radio}}(4400 \text{ Å}) = 10^{24.0}$ W Hz$^{-1}$ for an isotropically radiating point source. Using $L_{\text{ radio}}(6 \text{ cm}) \approx 10^{25}$ W Hz$^{-1}$ as the dividing line between radio-loud and radio-quiet quasars (Kellerman et al. 1989), PC 1415 + 3408 is at most a radio-loud quasar. Another indicator for radio loudness, $R = L_{\text{ radio}}(6 \text{ cm})/L_{\text{ radio}}(4400 \text{ Å})$, is less than $\sim 15$, which also suggests a radio-loud quasar at most (Kellerman et al. 1994). If the radio spectrum is flat ($\alpha = 0$), the upper limit on the radio luminosity decreases by 30%. PC 1415 + 3408 is clearly not a radio-loud quasar. Even if no BAL absorption was seen in PC 1415 + 3408, it is statistically likely to be radio quiet, given that only 5%–10% of optically selected quasars are radio loud at high redshifts (e.g., Schmidt et al. 1995 and references therein).

In the X-ray band, there are no serendipitous or pointed observations of PC 1415 + 3408 by either ROSAT or ASCA, though an upper limit of 0.05 counts s$^{-1}$ was obtained from the ROSAT Bright Source Catalog (Voges et al. 1996). Radio-quiet quasars have $x_{\text{ox}} = -1.57 \pm 0.15$ (Green et al. 1995), where $x_{\text{ox}} = 0.348 \log [L_{\text{ radio}}(2500 \text{ Å})/L_{\text{ radio}}(2 \text{ keV})]$. Assuming this value of $x_{\text{ox}}$, an isotropically radiating point source, an X-ray energy index of $E_{\text{ox}} = -1$, and a Galactic hydrogen column density of $N$(H I) = $1.3 \times 10^{20}$ cm$^{-2}$ toward PC 1415 + 3408 (Stark et al. 1992), we calculated an expected X-ray luminosity of $L_{\text{ radio}}(2 \text{ keV}) = 8.5 \times 10^{22}$ W Hz$^{-1}$ using PIMMS (Mukai 1997). This is an order of magnitude below the upper limit on $L_{\text{ radio}}(2 \text{ keV})$ from the ROSAT Bright Source Catalog.

### 4. The Associated Broad Absorption Lines

As seen in Figures 1–3, strong, broad absorption is present in the cores of the three high-ionization emission lines. The velocity alignment of these absorption features is shown in Figure 4. Over the velocity interval $-1700$ to $0$ km s$^{-1}$, the N V and C IV doublets are blended, but the two members of the Si IV doublet are resolved. Both N V and C IV are consistent with “black” saturation (zero flux) over the velocity range $-1200$ to $-500$ km s$^{-1}$. An additional component, or “secondary detached trough,” is evident at velocities from $-2200$ to $-3500$ km s$^{-1}$ for N V and from $-3000$ to $-5000$ km s$^{-1}$ for C IV. In broad

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**Figure 4.** Emission lines and the N V, C IV, and Si IV absorption lines of PC 1415 + 3408 as measured in the 300 line mm$^{-1}$ grating spectrum. For presentation, the spectra, normalized by the “source” continuum, are offset vertically by a factor of 2 (the respective zero points are 0, 2, 4, 6, 8, and 10) and are aligned in velocity referenced to the quasar emission redshift.
absorption line (BAL) quasars, “double-trough” broad absorption is not uncommon, appearing ~20% of the time (Weymann et al. 1991; Korista et al. 1993).

That the BALs in PC 1415+3408 have \( z_{\text{abs}} \approx z_{\text{em}} \) is highly suggestive that they are physically associated with the quasar and that they do not arise in intervening objects. Furthermore, there are other features that suggest that the lines are associated with the quasar. The lines are characteristic of BAL flow in that they (1) are smooth-bottomed and do not exhibit the complex kinematic structure observed in galaxy halos, (2) are composed of a primary and a detached trough, a common feature of BALs, and (3) are significantly broader than the \( \leq 600 \text{ km s}^{-1} \) velocity spreads of galactic halos. Since the \( \text{C IV} \) line absorption extends to less than 5000 km s\(^{-1}\) from the emission redshift (Weymann et al. 1991), PC 1415+3408 should be classified as a so-called mini-BAL quasar (e.g., Turnshek 1988; Barlow et al. 1997).

Examples of mini-BAL quasars are Q 0449−13 at \( z_{\text{em}} = 3.09 \) (Barlow et al. 1997) and the \( z_{\text{em}} = 1.98 \) radio-loud quasar PHL 1157 (Aldcroft, Bechtold, & Foltz 1997). The \( \text{C IV} \) profile of the latter is virtually identical to that of PC 1415+3408, except that the secondary trough is centered at \(-5100 \text{ km s}^{-1}\) and has a spread of \( \approx 1900 \text{ km s}^{-1}\).

In Figure 5, we show the 4900–6100 Å region of the 300 line mm\(^{-1}\) spectrum. Bar ticks mark the expected wavelength regions of \( \text{Ly}_{\alpha} \), \( \text{C III} \) \( \lambda \lambda 977, 979 \), \( \text{Ly}_{\beta} \), and \( \text{O VI} \) \( \lambda \lambda 1031, 1037 \), based upon the \(-5000 \text{ km s}^{-1} \leq v \leq -3000 \text{ km s}^{-1}\) and the \(-1700 \text{ km s}^{-1} \leq v \leq 0 \text{ km s}^{-1}\) absorption troughs of \( \text{C IV} \). Higher velocity absorption is evident in the \( \text{Ly}_{\beta} \) and \( \text{O VI} \) blend spanning 5700–5800 Å; the blue wing is consistent with the detached trough of the \( \text{C IV} \). The \( \text{S VI} \) \( \lambda \lambda 6335, 944 \) doublet may be present, but heavily blended by the Lyman series. The presence of \( \text{P V} \) \( \lambda \lambda 1117, 1128 \), sometimes seen in BAL quasars, is ambiguous.

4.1. Exploring the Kinematics

For the remainder of this section, we focus on the primary absorption, that in the velocity range \(-1700 \text{ km s}^{-1} \leq v \leq 0 \text{ km s}^{-1}\). In Figure 6, we show the absorption blueward of the \( \text{Ly}_{\alpha} \) emission line (top) and of the blended \( \text{N V} \) doublet (bottom), as measured in the 1200 line mm\(^{-1}\) spectrum. The data are aligned in the rest-frame velocity of the quasar. The quasar continuum blueward of \( \text{Ly}_{\alpha} \) emission was estimated by extrapolating a two-component Gaussian fit to the \( \text{Ly}_{\alpha} + \text{N V} \) blend with an underlying power law using the fiducial spectral energy index \( x = -0.5 \) (since our value of \(-0.45\) is consistent with this fiducial value). The resulting continuum is shown as a dotted curve in Figure 6.

A series of Gaussians was fitted to the flux values in the \( \text{Ly}_{\alpha} \) absorption just blueward of \( \text{Ly}_{\alpha} \) emission. The free parameters for each Gaussian are the central wavelength, amplitude, and width [unless the width of the component, \( \sigma_e \), is less than the instrumental resolution; in this case \( \sigma_e \) is set to \( \lambda_e/(2.35 R) \), where \( \lambda_e \) is the component centroid and \( R = 4000 \) is the spectrum resolution]. We started with a two-component fit and increased the number of components until a standard \( F \)-test yielded no further significant gain (98% confidence level) in the “goodness” of the fit, as measured by the reduced \( \chi^2 \). Our adopted fit has five Gaussian components. Although these five \( \text{Ly}_{\alpha} \) components are not to be taken literally as distinct absorbers, we emphasize the excellent alignment in velocity with the blended \( \text{N V} \) doublet. In Figure 6 (bottom), we transpose the ticks from the \( \text{Ly}_{\alpha} \) decomposition to the \( \text{N V} \) doublet (upper ticks denote the \( \lambda 1238 \) transition and lower ticks denote the \( \lambda 1242 \) transition); this alignment is strongly suggestive that the \( \text{Ly}_{\alpha} \) absorption is metal-rich and gives rise to the \( \text{N V} \).

In Figure 7, we present the \( \text{Ly}_{\alpha} \) and \( \text{N V} \) absorption (both...
Figure 7—Lyα, N v, C iv, and Si iv absorption lines of PC 1415+3408. For Lyα and N v, both the 1200 and 300 line mm\(^{-1}\) spectra are shown so that the greater detail at higher resolution can be compared with that at lower resolution. For presentation, the spectra have been normalized by both the "source" and broad emission line continua and are aligned in velocity space referenced to the quasar emission redshift. Long ticks above the continuum give the velocities of the tentatively suggested components. The red members of the doublets are shown with shorter ticks. In the case of Lyα, the additional ticks show the expected location of Si iv absorption lines of PC 1415+3408.

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For the unresolved Si iv profiles, the covering factor can be investigated using Voigt profile (VP) decomposition, which effectively deconvolves the instrumental profile from the optical depth model. In the case of partial covering, VP components cannot be made consistent with both members of the doublet. Since a VP decomposition is a nonunique model, however, any evidence for partial covering using this technique is less conclusive. If a reasonable (i.e., physically motivated) VP decomposition can be made consistent with full coverage, it can tentatively be interpreted that the data are consistent with a unity covering factor.

Using MINFIT (Churchill 1997), which uses Levenberg–Marquardt least-squares minimization (More 1978) while enforcing a minimum number of components, a VP decomposition of the Si iv doublet yields three components consistent with a unity covering factor. The reduced \(\chi^2\) was 1.2. These three components effectively correspond to the five components found in the higher resolution spectrum (see Fig. 6), with the central, narrow Si iv VP component corresponding to the central Lyα Gaussian component and the VP components in the wings of the Si iv each to the quasar emission redshift. The data are continuum-normalized for presentation.

4.2. Covering Fraction of the Absorbing Material

The observations suggest that the absorbing gas highlighted in Figure 7 is outflowing material originating in the immediate environment of the quasar. There are several examples where such material does not fully occult the broad emission line region and/or of the quasar continuum source (e.g., Barlow & Sargent 1997). Here, we investigate the possibility that the BAL flow material associated with PC 1415+3408 partially covers the emission source(s).

If \( \tau \) is the effective optical depth of an absorbing cloud that occults a fraction, \( C_f \), of the source, the residual intensity, \( R \), in normalized units is,

\[
R(\lambda) = [1 - C_f(\lambda)] + C_f(\lambda)e^{-\tau(\lambda)},
\]

where the first term on the right-hand side represents unocculted photons, and the second term represents unabsorbed photons. For a doublet, the covering factor can be obtained as the solution to

\[
\left[ \frac{R_f - 1 + C_f}{C_f} \right]^{\tau_u/\tau_r} = \frac{R_b - 1 + C_f}{C_f},
\]

where \( \tau_u/\tau_r = (g_L f_{LV} \lambda_b)/(g_b f_{BLV} \lambda_r) \), where \( g_L \) is the degeneracy of the lower level, \( f_{LV} \) is the oscillator strength of the transition (where \( L \) and \( U \) denote the lower and upper levels, respectively), and the subscripts \( b \) and \( r \) denote the blue and red transitions, respectively.

To apply this technique, however, the absorption profiles need to be resolved, for if they are not resolved then smearing from the instrumental spread function destroys the optical depth ratios at each velocity point (see Ganguly et al. 1999). The N v doublet is resolved, though its members are partially blended. Using software kindly provided by R. Ganguly, we computed a covering factor, \( C_f \), of 0.97 ± 0.12, over the limited velocity region —1100 to —600 km s\(^{-1}\) in the 1200 line mm\(^{-1}\) spectrum. The N v absorption is consistent with a unity covering factor. The C iv doublet (300 line mm\(^{-1}\) spectrum) is fully blended and is not viable for the partial covering test.

For the unresolved Si iv profiles, the covering factor can be investigated using Voigt profile (VP) decomposition, which effectively deconvolves the instrumental profile from the optical depth model. In the case of partial covering, VP components cannot be made consistent with both members of the doublet. Since a VP decomposition is a nonunique model, however, any evidence for partial covering using this technique is less conclusive. If a reasonable (i.e., physically motivated) VP decomposition can be made consistent with full coverage, it can tentatively be interpreted that the data are consistent with a unity covering factor.

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corresponding to two Gaussian components in the wings of the Lyα.

4.3. Lower Limits on Column Densities

Though BALs sample dynamically active gas over a wide range of ionization conditions and kinematics, the lines are often heavily blended so that deducing the physical conditions of the gas can be intractable (Arav et al. 1998; however, see Turnshek et al. 1996). In Table 3, we show the lower limits on the column densities using the apparent optical depth (AOD) method (Savage & Sembach 1991). The N v and C iv doublets are both blended and saturated. For the Si iv, the profiles do not drop to zero flux in their cores, but they do exhibit unresolved saturation, as deduced by the factor of two difference in their apparent column densities; as such, the measured Si iv column densities are likely to be significantly underestimated. The data do not allow definite statements about the metallicities and ionization conditions of the absorbing gas.

5. DISCUSSION

The UV rest-frame absorption associated with PC 1415+3408 exhibits four remarkable properties.

1. The N v doublet is consistent with black saturation over six resolution elements in a 1.7 Å resolution spectrum. The doublet is partially blended.

2. The C iv is consistent with black saturation in a ~8 Å, lower resolution spectrum.

3. The Lyα absorption along the blue wing of the Lyα emission line is clearly associated with the primary N v and C iv troughs (velocity range ~1700 km s⁻¹ ≤ v ≤ 0 km s⁻¹). This Lyα absorption is neither smooth nor flat-bottomed, but exhibits clear structure.

4. Both C iv and N v have secondary “detached” troughs, and these troughs are not aligned in velocity space; N v is at lower velocities than C iv. The detached troughs have velocity spreads less than 2000 km s⁻¹ and smooth, nonzero, flat bottoms.

What makes the absorption in PC 1415+3408 exceptional is that both the N v and C iv absorption profiles are consistent with black saturation, even at a spectral resolution of ~8 Å (300 line mm⁻¹ spectrum). In the 1200 line mm⁻¹ spectrum (resolution 1.7 Å), the unblended portion of the N v 1z1238 transition is consistent with zero flux across six resolution elements. It is unusual for this to occur with C iv [especially in comparable 5–7 Å resolution spectra (e.g., Storrie-Lombardi et al. 1996) and it is exceedingly rare with N v at all observed resolutions. Interestingly, the mini-BALs O835+5804 and PHL 1157+0128 have absorption nearly consistent with being black (Aldcroft et al. 1997). Though the velocity spreads of mini-BAL quasars are much smaller than that of “classical” BAL quasars, it is of interest to make a direct comparison between PC 1415+3408 and BAL quasars in light of a unified model of the BAL phenomenon. In the 72 BAL quasar spectra observed by Korista et al. (1993) at resolution 2.1 Å, only two objects have zero flux in the C iv absorption profile. Of the 58 Korista et al. spectra that cover N v and Lyα, none have black N v absorption even when the N v profiles are saturated.

Black absorption troughs imply that the absorbing material is being viewed from a direction where both the broad emission line region and the continuum sources are fully occulted by the BAL material and there is virtually no scattering back into the line of sight. Since black saturation is virtually never seen in BAL quasars, this suggests that we are either seeing PC 1415+3408 at a low probability viewing angle or that the BAL flow geometry around this quasar is not common to BAL quasars. For BALs originating from an equatorial flow (e.g., Emmering et al. 1992; Murray et al. 1995; de Kool & Begelman 1995), two low-probability viewing angles include one directly edge-on to the disk or one grazing the BAL flow material right at the opening angle. However, a line of sight grazing the opening angle might be more likely to have residual flux in the absorption trough due to partial coverage of the compact continuum source or due to light scattered back into the line of sight or to a nonuniform filling factor of BAL material. It might be that the spatial extent or cross section of any scattering material is diminutive. On the other hand, an edge-on viewing angle might be difficult to understand in view of the larger overall velocity spread predicted by some models for such an orientation (e.g., see Fig. 5b of Murray et al. 1995). Whatever the viewing angle, the kinematics of the Lyα absorption and the presence of N v and C iv detached troughs suggest that the BAL flow material does not have uniform ionization and/or density structure.

The velocities of the secondary, or detached troughs, are −3500 km s⁻¹ ≤ v ≤ −2200 km s⁻¹ for N v and −5000 km s⁻¹ ≤ v ≤ −3000 km s⁻¹ for C iv (see Fig. 7). Though they are narrower, these troughs are more typical of the nonblack, flat-bottomed, saturated profiles seen in higher velocity BALs (e.g., Arav et al. 1998). Since the detached N v trough is at a lower velocity than the detached C iv trough, the ionization condition may decrease with outflow velocity. This is contradictory to models that predict constant ionization (see de Kool 1997 and references therein) or increasing ionization (e.g., Murray et al. 1995) with outflow velocity. For the N v, either the continuum source is not absorbed (occulted) or the trough is significantly filled in by photons. The latter would imply that any material that scatters light back into the line of sight would be at relatively high velocities with respect to the quasar. It should be noted that there is absorption structure along the red wing of the

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**TABLE 3**

| Ion       | \(W_r (\text{Å})\) | \(\log N_{\text{AOD}} (\text{cm}^{-2})\) | \((v^* v^*)\) |
|-----------|--------------------|------------------------------------------|----------------|
| H i⁺ ⏞   | 3.7 ± 0.3          | >18.2                                    | (−2700, −200)  |
| N v 1239⁺ | 5.3 ± 0.2          | >15.7⁺                                   | (−2200, −400)  |
| C iv 1548 | 5.5 ± 0.9          | >15.4⁺                                   | (−2300, +100)  |
| Si iv 1394| 2.7 ± 0.3          | 14.7⁺                                    | (−1900, −600)  |
| Si iv 1402| 2.9 ± 0.3          | 15.0⁺                                    | (−1900, −600)  |

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*a The tabulated column density is based upon Lyman limit break in 300 line mm⁻¹ spectrum (see text). The apparent optical depth method yielded \(\log N_{\text{AOD}}(\text{H i⁺}) > 15.3 \text{ cm}^{-2}\).*

*b Measured from the 1200 line mm⁻¹ spectrum.*

*c Ambiguity due to doublet blending. A unity doublet ratio has been assumed.*

*d These column densities should be considered lower limits due to unresolved saturation.*
Lyα emission line that may be due to even higher velocity N v gas (see Fig. 6, top). In the case of C iv, at least part of the continuum source is absorbed or the source of photons filling in the absorption trough is not as strong as for the N v.

Double-trough broad absorption from C iv has been investigated as a possible signature of line-driven radiation pressure. Since all absorbing species experience the same flow, they each have the same optical depth modulation, showing a reduced optical depth due to increased flux from the Lyα emission line. The so-called "ghost of Lyα" effect (Turnshek et al. 1988; Arav 1997) corresponds to a "hump" in the C iv absorption at $v \approx 5900$ km s$^{-1}$, the velocity of the Lyα emission peak in the rest frame of N v ions. Given the exceptionally strong N v absorption, PC 1415+3408 is a good candidate for exhibiting this modulation if the material is driven by radiation pressure. The ghost of Lyα effect is not seen in PC 1415+3408; however, we point out that the C iv absorption terminates at $\sim 5000$ km s$^{-1}$ and that this termination could be induced by the effect.

6. THE PROMISE OF MINI-BAL QUASARS

Despite significant efforts, the overall multiband statistical properties of quasars exhibiting BAL flows are not yet on a solid statistical footing. Overall, BAL quasars are radio-quiet (e.g., Stocke et al. 1992) and quiet, or self-absorbed, in soft X-rays (Kopko et al. 1994; Green & Mathur 1996). However, the FIRST Survey has produced examples of radio-selected, radio-loud BAL quasars (Becker et al., 1997), and there are now a few X-ray loud BAL quasars observed in hard X-rays (e.g., Mathur, Elvis, & Singh 1995; Gallagher et al. 1999; and see predictions of Krolik & Voit 1998). For radio-loud BAL quasars, the radio spectra have a range of spectral indices (e.g., Barthel, Tytler, & Vestegaard 1997; Becker et al. 1997), and it is not unexpected that X-ray spectra would as well.

The X-ray spectra of mini-BAL quasars may be a key for understanding BAL flows. For example, assuming radiation pressure-driven flow dynamics, Murray et al. (1995) predict that quasars with harder (flatter) X-ray spectra will have wind terminal velocities no greater than $\sim 5000$ km s$^{-1}$. Flatter X-ray spectra might naturally explain the subpopulation of mini-BAL quasars if the flow dynamics are governed by the energy index, $\alpha_E$, of the X-ray spectrum. Mini-BALs may provide the first robust measurements of or limits on the X-ray spectral energy indices, especially using more powerful, forthcoming X-ray observatories (Chandra and XMM). Both deeper radio and hard X-ray observations of mini-BAL quasars at all redshifts could be very telling for constraining unified models of quasars. At the highest redshifts, PC 1415+3408 appears to be a good target for such investigations.

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