DISCOVERY OF THE TRANSITION OF A MINI-BROAD ABSORPTION LINE INTO A BROAD ABSORPTION LINE IN THE SDSS QUASAR J115122.14+020426.3

PAOLA RODRÍGUEZ HIDALGO1,2, MICHAEL ERACLEOUS1, JANE CHARLTON1, FRED HAMANN3, MICHAEL T. MURPHY4, AND DANIEL NESTOR5

1 Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
2 Department of Physics and Astronomy, York University, 128 Petrie Science and Engineering Building, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada
3 Department of Astronomy, University of Florida, Gainesville, FL 32611, USA
4 Center for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia
5 Department of Physics & Astronomy, University of California, 430 Portola Plaza, Box 951547, Los Angeles, CA 90095, USA

Received 2013 April 12; accepted 2013 July 21; published 2013 August 29

ABSTRACT

We present the detection of a rare case of dramatic strengthening in the UV absorption profiles in the spectrum of the quasar J115122.14+020426.3 between observations ∼2.86 yr apart in the quasar rest frame. A spectrum obtained in 2001 by the Sloan Digital Sky Survey shows a C IV “mini-broad” absorption line (FWHM = 1220 km s⁻¹) with a maximum blueshift velocity of ∼9520 km s⁻¹, while a later spectrum from the Very Large Telescope shows a significantly broader and stronger absorption line, with a maximum blueshift velocity of ∼12,240 km s⁻¹ that qualifies as a broad absorption line. A similar variability pattern is observed in two additional systems at lower blueshifted velocities and in the Lyα and N v transitions as well. One of the absorption systems appears to be resolved and shows evidence for partial covering of the quasar continuum source (C f ∼ 0.65), indicating a transverse absorber size of, at least, ∼6 × 10¹⁶ cm. In contrast, a cluster of narrower C IV lines appears to originate in gas that fully covers the continuum and broad emission line sources. There is no evidence for changes in the centroid velocity of the absorption troughs. This case suggests that at least some of the absorbers that produce “mini-broad” and broad absorption lines in quasar spectra do not belong to intrinsically separate classes. Here, the “mini-broad” absorption line is most likely interpreted as an intermediate phase before the appearance of a broad absorption line due to their similar velocities. While the current observations do not provide enough constraints to discern among the possible causes for this variability, future monitoring of multiple transitions at high resolution will help achieve this goal.

Key words: galaxies: active – quasars: absorption lines – quasars: general

1. INTRODUCTION

Outflows are fundamental constituents of active galactic nuclei (AGNs). They are detected in a substantial fraction of AGNs through their absorption-line signatures (e.g., broad, blueshifted resonance lines in the UV and X-ray bands) and could be ubiquitous, if the absorbing gas subsumes a small solid angle to the central continuum (and broad emission line) source (e.g., Crenshaw et al. 1999; Reichard et al. 2003; Hamann & Sabra 2004; Trump et al. 2006; Nestor et al. 2008; Dunn et al. 2008; Ganguly & Brotherton 2008 and references therein). Outflows have been invoked as a regulating mechanism in order to explain the correlation between black hole masses (Mₜ) and the masses of the stellar spheroids of their host galaxies (M_bulge; e.g., Gebhardt et al. 2000; Merritt & Ferrarese 2001; Tremaine et al. 2002). The evolutionary models developed to explain this relation invoke energy and momentum “feedback” by outflows from the accreting supermassive black hole onto the gas in the host galaxy (e.g., Silk & Rees 1998; Springel et al. 2005; Di Matteo et al. 2005; Hopkins et al. 2006). The same AGN outflows have also been suggested to distribute heavy elements into the intergalactic medium (e.g., Scannapieco & Oh 2004; Germain et al. 2009).

Blueshifted UV resonance absorption lines (e.g., C IV λλ 1548, 1550) are often used as signposts of outflows. These lines are classified based on their widths, as follows. Broad absorption lines (BALs), with widths of several thousand km s⁻¹, and intrinsic narrow absorption lines (NALs), with widths less than a few hundred km s⁻¹, are the most commonly studied classes (see, for example, Weymann et al. 1981, 1991; Turnshek 1984; Foltz et al. 1986; Aldcroft et al. 1994; Reichard et al. 2003; Vestergaard 2003; Trump et al. 2006). Absorption lines with intermediate widths, called “mini-BALs,” have not been studied as extensively (e.g., Turnshek 1988; Jannuzi et al. 1996; Hamann et al. 1997; Telfer et al. 1998; Churchill et al. 1999; Ma 2002; Yuan et al. 2002; Narayanan et al. 2004; Misawa et al. 2007; Gibson et al. 2009) and their nature remains poorly understood.

Mini-BALs and BALs could, for example, trace absorbers with different properties (i.e., different densities or ionic column densities that may be attributed to the sizes of the absorbing parcels of gas or their ionization states). Perhaps mini-BALs and BALs probe different regions of the same gas flow where the physical conditions are different, which would mean that both types of lines could be seen in the same type of quasar but along different lines of sight. Yet another possibility is that mini-BALs and BALs represent different stages in the time evolution of a non-steady gas flow. The first of the above scenarios can be tested through a better characterization of the physical properties of mini-BALs and a comparison of these properties with those of BALs. The possibility that BALs and mini-BALs can transform into intrinsic narrow absorption lines (NALs), with widths less than a few hundred km s⁻¹, are the most commonly studied classes.
into each other can be tested through monitoring observations. Variations of the absorption lines caused by changes in the ionization of the gas yield constraints on the gas density via the recombination time. Similarly, variability caused by motion of parcels of gas across the line of sight provide information about the density distribution, hence the “granularity” and phase structure of the gas. Thus, several monitoring campaigns have been carried out aimed at characterizing the variability of BALs (e.g., Barlow 1993; Lundgren et al. 2007; Gibson et al. 2008; Capellupo et al. 2011). Serendipitous discoveries of variability have also contributed to this goal (e.g., Ma 2002; Hamann et al. 2008; Krongold et al. 2010; Vivek et al. 2012). These studies of variability can help us better understand the geometry and location of the absorbing gas, as well as its physical conditions (structure, sizes of gas parcels, variability of the gaseous flow resulting from instabilities, etc.), which could be used to test current theoretical models (e.g., Murray et al. 1995; Proga et al. 2000; Proga & Kallman 2004; Proga et al. 2012).

Here, we present a study of the dramatic variability of the C iv mini-BAL in the radio-quiet quasar J115122.14+020426.3 (hereafter J1151+0204). This quasar was first observed in the Sloan Digital Sky Survey (SDSS), from which its magnitude and redshift were reported to be $z = 1.91$ and $z_{em} = 2.401$, respectively (Schneider et al. 2003). During our systematic study of absorption features in the spectra of the $\sim 2200$ brightest SDSS quasars (P. Rodríguez Hidalgo et al., in preparation), we found a C iv mini-BAL in the spectrum of J1151+0204 at $z_{abs} = 2.296$ with an FWHM of 1220 km s$^{-1}$ and a maximum blueshift velocity of $\sim 9520$ km s$^{-1}$. In an unrelated study of Mg ii absorbers, we came upon an archival spectrum of this quasar taken with the Ultraviolet and Visual Echelle Spectrograph at the Very Large Telescope (VLT/UVES). A comparison of the two spectra shows the transformation of the C iv mini-BAL into a BAL with a maximum blueshift velocity of $\sim 12,240$ km s$^{-1}$; this example is a rare case of such a transformation. We also detect variable absorption lines of other ionic species in the same system and the variability of other absorption systems outflowing at lower velocities. In Section 2, we present the data while in Section 3 we describe the analysis of the spectra (including the normalization of the continuum and the identification of the absorption lines) and we present the measurements. Finally, in Section 4, we consider further the implications of our particular results and discuss what we can learn in general about the properties of quasar outflows from variable absorption systems.

We adopt a redshift for J1151+0204 of $z_{em} = 2.399$, which we determined by measuring the centroid of the peak of the C iii$\lambda:\lambda$1909 emission line in the UVES spectrum. Previous redshift determinations from the SDSS spectrum yielded $z_{em} = 2.401$ (Schneider et al. 2003) and $z_{em} = 2.409$ (Hewett & Wild 2010). The former value is based on multiple emission lines, some of which may be contaminated by associated absorption lines, while the high-ionization lines may be blueshifted relative to the systemic redshift (Shen et al. 2007). The latter value is based on cross-correlation of the C iii$\lambda$ line profile with a template and may be affected by the A I iv$\lambda:\lambda$1857 and S i iv$\lambda:\lambda$1892 lines. Relative velocities computed with our redshift and that of Hewett & Wild (2010) differ by $\sim 900$ km s$^{-1}$, but this fact does not alter any of our conclusions. Throughout this paper, the central wavelengths of the absorption troughs, and thus the absorption redshifts, are determined through the apparent optical depth-weighted mean of the profile, as described in Churchill & Vogt (2001).

A spectrum of J1151+0204 was first obtained as part of the SDSS on 2001 May 20 with a total exposure time of 3978 s under “excellent conditions.” The spectrum covers the range 3800–9200 Å (in the observer’s frame) at a signal-to-noise ratio (S/N) of 16.4 pixel$^{-1}$ in the i band and 5.5 pixel$^{-1}$ at the shortest wavelengths. The resolving power is $R \sim \lambda/\Delta \lambda \sim 2000$ (corresponding to a velocity resolution of $\sim 150$ km s$^{-1}$; Adelman-McCarthy et al. 2008).

The UVES spectrum was taken on three consecutive nights, on 2008 March 10–12, as part of a program on ultra-strong Mg ii absorbers (VLT/UVES proposal 080.A-0795(A); principal investigators: Nestor, Pettini, & Rao). The total exposure time was 26,297 s, although two different cross-disperser settings were employed (DICHR1 and DICHR2; observations with exposure times of 12,615 and 13,682 s, respectively). The S/N is not constant throughout the spectrum, but it always exceeds 15 pixel$^{-1}$, which is adequate for our purposes. The wavelength range covered is 3595–9466 Å. The resolving power is $R \sim 45,000$ (corresponding to a velocity resolution of 6.7 km s$^{-1}$).

In Figure 1, we display the normalized SDSS and UVES spectra. For the purposes of this illustration, we have normalized both continua to unity (using a power-law fit to those same line-free regions of the SDSS spectrum and a polynomial fit to line-free regions in the UVES spectrum) and have smoothed the UVES spectrum to the resolution of the SDSS spectrum for easier comparison and shifted downward for clarity. There are easily discernible gaps between orders in the UVES spectrum at wavelengths of 4500–4600 Å and 5600–5700 Å.

### 2. OBSERVATIONS, ARCHIVAL SPECTRA, AND BASIC PROPERTIES OF J1151+0204

2.1. OBSERVATIONS, ARCHIVAL SPECTRA, AND BASIC PROPERTIES OF J1151+0204

2.2. VARIABILITY OF C iv MINI-BAL AND ABSORPTION SYSTEMS OUTFLOWING AT LOWER VELOCITIES

2.3. SPECTRAL NORMALIZATION AND CONTINUUM DETECTION

2.4. REALIGNING THE SDSS AND UVES SPECTRA

2.5. NUMERICAL RESULTS

2.6. DISCUSSION

2.7. CONCLUSIONS

### Figure 1. SDSS (upper trace) and UVES (lower trace) spectra of the quasar J1151+0204 taken in 2001 and 2008, respectively. These spectra illustrate the S/N attained and the emission and absorption features present in the spectra. For the purposes of this illustration, we used a polynomial or a power law to normalize the continuum in different segments of each spectrum. The UVES spectrum was then smoothed to the resolution of the SDSS spectrum for easier comparison and shifted downward for clarity. There are easily discernible gaps between orders in the UVES spectrum at wavelengths of 4500–4600 Å and 5600–5700 Å.
In Figure 2, we show an expanded view of the C\textsc{iv} region of the SDSS and UVES spectra from Figure 1, where we mark and label the absorption-line systems discussed in this paper. The absorption trough in the 2001 SDSS spectrum at $\sim$5108 Å has an FWHM = 1220 km s$^{-1}$ and qualifies as a C\textsc{iv} mini-BAL\textsuperscript{7} at $z_{abs}$ = 2.296 (the members of the C\textsc{iv} doublet are blended). Hereafter, we refer to this absorption system as system A. In the rest frame of this system, the SDSS spectrum covers the range 1153–2791 Å while the UVES spectrum covers the range 1091–2871 Å. In the 2008 UVES spectrum, system A has increased substantially in both strength and width. Another absorption system at $\sim$5150 Å ($z_{abs}$ = 2.329; hereafter, system B) also appears to have significantly increased in strength between the two epochs. In the rest frame of system B, the SDSS spectrum covers the range 1142–2763 Å and the UVES spectrum covers the range 1080–2843 Å. A complex system of much narrower, associated C\textsc{iv} absorption lines (hereafter, system C) is also present in the range 5210–5270 Å ($z_{abs}$ = 2.383 for the whole complex, but several subsystems are identified, i.e., $z_{abs}$ = 2.374, $z_{abs}$ = 2.385, and $z_{abs}$ = 2.395). These lines also appear to have varied between the two observations. Other absorption systems (e.g., at 4960 Å, 5050 Å, and 5280 Å) do not appear to have varied and are unlikely to be related to the gas flow we are studying in this paper.

\textsuperscript{7} In the survey of C\textsc{iv} mini-BALs in SDSS spectra (Rodríguez Hidalgo et al. 2007; Rodríguez Hidalgo 2009; P. Rodríguez Hidalgo et al., in preparation), we found this absorption trough and categorized it as a candidate C\textsc{iv} mini-BAL; no other plausible identification was found.

### 3. ANALYSIS

#### 3.1. Continuum Normalization and Line Identification

To carry out measurements of the absorption troughs, we normalized the SDSS and UVES spectra by the effective continuum, which comprises the true continuum and the broad emission lines. To this end, we used cubic splines or low-order Chebyshev polynomials to fit parts of the spectra that were free of absorption troughs. We concentrated on producing a good fit to the effective continuum around the absorption troughs of interest, with the result that some of the undulations elsewhere in the effective continuum are not perfectly reproduced. The complex of associated absorption (system C), which removes a large portion of the C\textsc{iv} emission line (see Figure 2 around 5200–5300 Å), as well as the Ly$\alpha$ forest lines, which appear blueward of 4200 Å, makes the normalization of certain wavelength regions difficult. We have taken a conservative approach, especially in the case of the UVES spectrum where the absorption lines are stronger, by under-fitting the C\textsc{iv} emission line where the choice is uncertain and using low-order polynomials when extrapolating its shape. The effective continua we used are shown in Figure 2 and the normalized spectra around the C\textsc{iv} absorption lines of interest are shown in Figure 3. Our possible under-fitting of the C\textsc{iv} emission line results in lower limits on the rest-frame equivalent widths ($W_{rest}$) measurements for the complex of lines of system C (see Section 3.3). Similarly, we use a low-order polynomial when fitting the continuum regions of interest around other ions. Note that differences in rest-frame equivalent widths resulting from the choice of redshift measurement are considerably

---

**Figure 2.** Enlarged view of the C\textsc{iv} region of the spectra shown in Figure 1. Top panel: the SDSS spectrum is represented by the thin/noisy line and the smoothed UVES spectrum is represented by the thick line. The locations of common emission lines are labeled. The absorption systems discussed in the text are also marked. The middle panel and the bottom panel show the SDSS spectrum and the UVES spectrum, respectively, with the effective continuum we used to normalize each spectrum. Notice how we followed a conservative approach in both cases but even more so in the case of the UVES spectrum, where the C\textsc{iv} emission line might be larger than what we suggest.

**Figure 3.** Normalized SDSS (thin) and UVES (thick) spectra around the C\textsc{iv} absorption systems of interest. Horizontal lines indicate the studied C\textsc{iv} absorption features; system A at $\sim$5100 Å, system B at $\sim$5150 Å, and system C at $\sim$5240 Å. Typical errors are represented in the bottom left corner. All three systems of study in the SDSS spectrum appear weaker than in the UVES spectrum.
end of each system is always at the same velocity since it represents the maximum blueshift of the blue member of a doublet dictated by C IV, which is also the doublet member used to set the velocity scale. The red end of each system varies because it represents the maximum redshift of the red member of a doublet and the separation of the doublet members is different for different doublets.

None of the lower-ionization lines that are covered (those with rest-frame wavelengths of approximately 1153–2791 Å in the SDSS spectrum and 1091–2871 Å in the UVES spectrum) were detected. In particular, Mg II λ2796, 2803 is not covered in the SDSS spectrum and is not detected in the UVES spectrum. O VI λ1031, 1037 is not covered in either spectrum. In the UVES spectrum shown in Figure 5, the combination of higher S/N, higher resolution, and stronger absorption lines allows us to better discern the troughs in all systems in the N v and Lyα profiles. Both transitions are clearly detected in several of the systems. In Section 3.2, below, we examine the absorption-line profiles seen in the UVES spectrum in more detail, while in Section 3.3 we quantify the variability via measurements of line strengths in both the SDSS and UVES spectra.

In the SDSS spectrum, the Si iv doublet of systems B and C are not detected. The Si iv doublet of system A may be present in the SDSS spectrum but we cannot ascertain this fact for sure because of contamination by an unrelated C IV system at $z_{\text{abs}} = 1.968$, which is marked in Figure 4 (part of a damped

Figure 4. Normalized SDSS spectrum on a velocity scale relative to the quasar emission redshift ($z_{\text{em}} = 2.399$), showing the location of the C iv doublet absorption and other possible transitions at the same velocity. The dashed lines represent the limits of system A in C IV ($v_{\text{max, blue}} = -9520$ km s$^{-1}$), the dotted lines represent the limits of system B ($v_{\text{max, blue}} = -6960$ km s$^{-1}$), and the dashed-dotted lines represent the limits of system C ($v_{\text{max, blue}} = -2670$ km s$^{-1}$). These limits are based on the detected region for C IV absorption, translated to cover the same regions (in velocity space) for both members of the Si iv and N v doublets, and for Lyα. The absorption present in the Si iv region for system A is an unrelated C IV absorber at $z_{\text{abs}} = 1.968$. The region where N v might be present is too contaminated with lines in the Lyα forest to conclude whether N v is present. In the case of Lyα, the region is less contaminated, but it is not possible to assess whether the only absorption clearly present, in the region corresponding to system B at $v \sim 5900$ km s$^{-1}$, is related Lyα or due to an unrelated system.

smaller than the measurement uncertainties derived from the continuum placement.

We searched the SDSS and UVES spectra for other absorption lines commonly observed in the spectra of BAL and mini-BAL quasars at the offset velocities of systems A, B, and C (e.g., O VI λ1031, 1037, H I Lyα, N v λ1238, 1242, O I λ1302, Si ii λλ1304, 1309, C ii λλ1335, Si iv λλ1394, 1403, Si ii λλ1527, 1533, Al iii λλ1855, 1863, Fe ii λ2383, Fe ii λ2600, and Mg ii λλ2796, 2803; see Hamann 1998; Arav et al. 2001; Rodríguez Hidalgo et al. 2011). The absorption lines that we detected are shown on a common velocity scale in Figures 4 and 5 (the Si iv region is missing from the UVES spectrum because of a gap in spectral coverage, therefore the corresponding panel in Figure 5 is blank). The velocity scale in these figures is set according to the wavelength of the blue member of each doublet. We adopt a convention in which negative velocities denote a blueshift relative to the quasar rest frame. For reference, we mark the velocity windows of systems A, B, and C in all the other panels as well, using, respectively, a pair of dashed lines, a pair of dotted lines, and a pair of dashed-dotted lines. The maximum and minimum velocity of each region are defined based on a 3σ detection of the C IV absorption. The blue
Lyα system; see Prochaska et al. 2005). Both the N v and Lyα lines fall in the Lyα forest of the quasar spectrum. The numerous absorption lines in this region and the lower S/N of this part of the SDSS spectrum introduce additional uncertainty in the placement of the effective continuum, as well as the detection and measurement of absorption lines. Thus, we cannot confirm the presence of the N v line of systems A or B in the SDSS spectrum, nor the Lyα line of system A. The Lyα line of system B may be present but the observed absorption trough is more likely due to an intervening system (discussed in Section 3.3). Both Lyα and N v show absorption in system C. Notice that the Lyα of system C overlaps with the N v from systems A and B, as we discuss in Section 3.3.

3.2. Profiles of Absorption Lines in the UVES Spectrum

Figures 6 and 7 show the UVES spectrum of systems A and B, respectively. In each figure, we plot the C iv, N v, and Lyα profiles on a common velocity scale with vertical dashed lines showing the limits of the systems, as in previous figures.

By inspection, we found minima in the complex and asymmetric C iv profiles of systems A and B and used them to identify possible kinematic components. We mark these components with solid tick marks in Figures 6 and 7 (for the C iv and N v doublets, we use pairs of tick marks connected by bridges). In spite of the complexity of the line profiles, the broad, asymmetric trough of system A is clearly seen in Lyα and is also discernible in N v. The Lyα profile of system A is broad ($\Delta v \sim 1700$ km s$^{-1}$), resembling the kinematical structure of the corresponding C iv system. There is also a narrower and deeper component ($\Delta v \sim 200$ km s$^{-1}$) at $v \sim -8000$ km s$^{-1}$ (marked as “?”). This component is unlikely to be related to the C iv outflow of interest: it is black and does not have a counterpart in the C iv profile. The N v profile of system A, although it shows some strong absorption, is severely contaminated by the Lyα forest and partly overlaps with the Lyα profile of system B (N v at $v \sim -11,600$ km s$^{-1}$ corresponds to the same spectral region as Lyα at $v \sim -5900$ km s$^{-1}$) and system C (N v at $v \sim -7800$ km s$^{-1}$ corresponds to the same spectral region as Lyα at $v \sim -2200$ km s$^{-1}$; see Figure 5). As a result, we cannot be very confident that the doublets and kinematic components identified in the C iv and Lyα profiles have counterparts in N v, although some absorption is clearly present.

In the case of system B, the C iv doublets and kinematic components are easier to identify by eye. As in system A, the N v profile of system B is also severely blended, making it difficult for us to verify the troughs that correspond to intrinsic kinematic components seen in the other two transitions. The Lyα profile (bottom panel), as in system A, partially resembles the C iv profile in shape and velocity at the position of the strongest C iv absorption. However, the kinematic component of Lyα at $v \sim -5900$ km s$^{-1}$ (marked as “?”), while it matches a local minima in the C iv absorption in velocity, is black and
smoothed the UVES spectrum to match the SDSS resolution. N\v strongly in systems A and C, but there is almost no variation between the two

A increases by \( \sim 8000 \text{ km s}^{-1} \) (see Section 3.2), the component with an equivalent width of \( W_{\text{rest}} = 0.435 \pm 0.003 \) and, if included in the measurement, the relative increase in \( W_{\text{rest}} \) between the two epochs would be even larger.

Figure 8. Normalized SDSS (thin line) and UVES (thick line) spectra on a velocity scale relative to the quasar emission redshift \( z_{\text{em}} = 2.399 \), showing the location of the N\v doublet and Ly\ alpha. To facilitate the comparison, we have smoothed the UVES spectrum to match the SDSS resolution. N\v has become stronger in systems A and C, but there is almost no variation between the two observations in system B. In the UVES spectrum, Ly\ alpha is clearly present in system A at \( v \sim 9500 \text{ km s}^{-1} \), and a new component might have appeared at \( v \sim 8000 \text{ km s}^{-1} \) (see the text), while in system B we observe new absorption (at \( v \sim 6500 \text{ km s}^{-1} \)) and stronger previously-observed narrow absorption (at \( v \sim 5900 \text{ km s}^{-1} \)), which might be due to an unrelated Ly\alpha system. System C seems to vary only in the region around \( v \sim -3000 \text{ km s}^{-1} \), which is most likely due to N\v at \( v \sim -8500 \text{ km s}^{-1} \) (see the text).

obviously saturated, unlike any of the other components of Ly\alpha or other transitions in this system. We discuss the nature of the Ly\alpha and N\v absorption further when exploring their variability in Section 3.3 and elaborate on the issue of saturation in Section 4.2.

3.3. Variability and Line Measurements

It is clear from a visual inspection of Figures 3–5 that the C\iv lines of systems A and B have become considerably stronger between the 2001 and 2008 observations. The C\iv absorption profile becomes stronger over a velocity window \( \sim 12,520 \text{ km s}^{-1} \) wide. The absorption troughs do not shift in velocity and (1) the strongest parts of the troughs in the SDSS spectrum remain at approximately the same velocity in the UVES spectrum, and (2) regions of the SDSS spectrum that appear unabsorbed are part of the absorption trough seen in the UVES spectrum. The maximum blueshift velocity of system A increases by \( \sim 2720 \text{ km s}^{-1} \), creating an asymmetric profile. This appearance of additional absorption troughs in the same system without a change in the velocity of existing troughs is characteristic of the variable absorbers we have observed in our monitoring program and those noted by other authors (Narayanan et al. 2004; Misawa et al. 2005; Hamann et al. 2008; Rodríguez Hidalgo et al. 2011; Vivek et al. 2012; P. Rodríguez Hidalgo et al., in preparation). The variability pattern described above suggests that the region of the outflow responsible for the C\iv absorption is not experiencing changes in velocity.

Comparing the N\v and Ly\alpha profiles between the two epochs is complicated due to the multiple lines in the Ly\alpha forest. To aid in this comparison, we overplot the SDSS and UVES spectra in Figure 8, after smoothing the latter to the resolution of the former, as we did in the top panel of Figure 2. We note that the strength of the absorption troughs of both Ly\alpha and N\v in system A (between the dashed lines, particularly at \( v \sim 9500 \text{ km s}^{-1} \)) appear stronger and wider in the UVES spectrum and so do the troughs of system B in Ly\alpha (between the dotted lines, particularly at \( v \sim 6500 \text{ km s}^{-1} \)) and system C in N\v. The N\v trough of system B, if present, does not appear to have changed significantly. We can also see that the sharp and black absorption trough in the Ly\alpha profile in the UVES spectrum at \( v \sim 8000 \text{ km s}^{-1} \) (system A; discussed in Section 3.2) does not appear to be present in the older SDSS spectrum. On the other hand, the system at \( v \sim -5900 \text{ km s}^{-1} \) does not seem to have varied by more than the \( 3\sigma \) error, which indicates that this system might be due to an unrelated Ly\alpha system. Similarly, the Ly\alpha trough of system C does not present significant variations between the two spectra. There is a partial overlap between the regions corresponding to N\v and Ly\alpha, and the small variation at \( v \sim -3000 \text{ km s}^{-1} \) in Ly\alpha (bottom panel) is most likely attributable to N\v at \( v \sim -8500 \text{ km s}^{-1} \) (top panel).

In Table 1, we include the \( W_{\text{rest}} \) measurements of C\iv in all systems and Ly\alpha lines in systems A and B in the SDSS and UVES spectra. For the reasons we explained in Section 3.2, we do not attempt to measure the N\v lines in either system or Ly\alpha in system C. We also give our best estimates of the central wavelengths and maximum blueshift velocities of the absorption troughs. We estimated the uncertainties in the equivalent width measurements by repeating the continuum fits and looking for the highest and lowest plausible placement of the continuum level. These continuum adjustments are guided by the amount of noise around the absorption troughs of interest and do not modify the shape of the pseudo-continuum across the absorption profiles. The measurements in Table 1 reflect the increase in the strength of the absorption lines described earlier. The equivalent width of the C\iv line in system A has increased by a factor of approximately 8, while that of the C\iv line in system B has increased by a factor of approximately 2.5. While both measurements for system C are included as lower limits due to the uncertain strength of the C\iv emission line, they also reflect the strength increase seen in the spectra.

We have also used the “baldicity” index (BI) and the absorption index (AI) to quantify the increase in the strength of the C\iv absorption (Weymann et al. 1991; Hall et al. 2002; Trump et al. 2006). We obtain BI = 0 km s\(^{-1}\) and AI = 850 km s\(^{-1}\) for the SDSS spectrum, and BI = 590 km s\(^{-1}\) and AI = 2350 km s\(^{-1}\) for the UVES spectrum. The increase in each measurement is a

| Spectrum | Line | System | \( v_{\text{max,blue}} \) (km s\(^{-1}\)) | \( \lambda_{\text{central}} \) (Å) | \( W_{\text{rest}} \) (Å) |
|----------|------|--------|-----------------------------------|-------------------------------|---------------------|
| SDSS     | C\iv | A      | -9, 520                           | 5107.5                        | 1.1 ± 0.4           |
|          |      | B      | -6, 960                           | 5153.5                        | 1.4 ± 0.3           |
|          | C    | -2, 670 | 5240.3                            | >7.2                          | 0.53 ± 0.09         |
| Ly\alpha | A    | -9, 520 | ...                               | 0.35 ± 0.09                   | 0.25±0.09           |
|          | B    | -6, 960 | ...                               | >10.2                         | 1.41 ± 0.02         |
| UVES     | C\iv | A      | -12, 240                          | 5098.0                        | 8.6±0.5             |
|          |      | B      | -7, 000                           | 5155.4                        | 3.5±0.5             |
|          | C    | -2, 870 | 5240.1                            | >10.2                         | 1.41 ± 0.02         |
| Ly\alpha | A    | -12, 240 | ...                               | 1.41 ± 0.02                   | 1.82 ± 0.09         |
|          | B    | -7, 000 | ...                               |                                |                    |

Note. This value does not include the new narrow system at \( v \sim -8000 \text{ km s}^{-1} \) (see Section 3.2). This component has an equivalent width of \( W_{\text{rest}} = 0.435 ± 0.003 \) and, if included in the measurement, the relative increase in \( W_{\text{rest}} \) between the two epochs would be even larger.
result of the higher-velocity mini-BAL becoming broad enough to satisfy the formal definition of a BAL, with contiguous absorption deeper than 10% below the continuum level across a window of at least 1000 km s\(^{-1}\). We have also used a modified version of the AI that integrates the absorption trough from \(v = -3000\) km s\(^{-1}\) to \(-25,000\) km s\(^{-1}\), rather than from \(v = 0\) km s\(^{-1}\) as Trump et al. (2006) did to avoid the inclusion of the low-velocity, associated absorption of system C (see a discussion of the issues associated with this convention in Knigge et al. 2008). In this case, we obtain a value of \(\Delta v = 30\) km s\(^{-1}\) for the SDSS spectrum and \(\Delta v = 1140\) km s\(^{-1}\) for the UVES spectrum. We note that J1151+0204 was previously classified as a Hi-BALQSO by Trump et al. (2006) based on a measurement of \(\Delta v = 1483\) km s\(^{-1}\) (integrating from \(v = 0\) km s\(^{-1}\)). This measurement differs from ours because of a different continuum placement between our analysis and that of Trump et al. (2006).

4. DISCUSSION

4.1. J1151+0204 in the Context of Previous BAL Variability Studies

In the preceding sections, we described the transition from a C\(_{\text{IV}}\) mini-BAL to a strong BAL in J1151+0204 on a rest-frame timescale of \(\lesssim 2.86\) yr.\(^8\) The appearance of BALs in quasar spectra that did not previously show them is a rare occurrence with only a handful of such reports available in the literature, both in radio-quiet and radio-loud quasars. High-velocity C\(_{\text{IV}}\) BALs (with maximum velocities between \(-25,000\) and \(-50,000\) km s\(^{-1}\)) have been reported to appear in a few quasars that did not previously exhibit them, namely J105400.40+034801.2, Ton 34, and PG0935+417 (Hamann et al. 2008; Narayanan et al. 2004; Kronogol et al. 2010). Upper limits on the timescale for these transitions range from 1.5 to 8.3 yr; in the case of PG0935+417, subsequent monitoring showed that the variability continued on timescales of years (Rodríguez Hidalgo et al. 2011). An equally small number of cases of low-velocity C\(_{\text{IV}}\), Si\(_{\text{IV}}\), and/or Mg\(_{\text{II}}\) BALs (maximum velocities between \(-6000\) and \(-12,000\) km s\(^{-1}\)) have also been reported, specifically in the quasars TEX 1726+344 and J133356.02+001229.1 (Ma 2002; Vivek et al. 2012). Upper limits on the timescales for these transitions are 3.5 and 5.3 yr, respectively. In an analogous event, BALs appeared in the far-UV resonance lines of the Seyfert 1 galaxy WPVS 007, which previously possessed only mini-BALs, on a rest-frame timescale of \(\lesssim 7\) yr (Leighly et al. 2009). All of the above discoveries have been fortuitous since there is no way to systematically select candidates for this type of variability. Moreover, these discoveries often rely on the comparison of new and archival spectra, which yields only large upper limits on the variability timescale. Another consequence of the sparse time sampling is that when the new BALs are discovered, they are already fully formed, i.e., the intermediate steps of the transition are not observed.

The case we have presented here is a transition from a mini-BAL to a BAL in the same quasar. Because the absorption profiles appear at similar velocities and show similar kinematic structure in some of the systems, we interpret this transition as being most likely an intermediate phase of the appearance of a BAL in a quasar without previous broad absorption lines. In fact, the timescale for the transition is very similar to the timescales reported in the few previously known cases.

Similarly, the velocity of the BAL that has just emerged in J1151+0204 is comparable to those of the low-velocity BALs cited in the previous paragraph. Our present case is reminiscent of WPVS 007 (Leighly et al. 2009), where the first set of observations revealed mini-BALs in the near-UV resonance lines and followup observations seven years later showed the appearance of BALs. Similarly, monitoring of the BALQSO HB89 1303+308 shows a separate C\(_{\text{IV}}\) mini-BAL feature that increased in strength and width to become a BAL (Capellupo et al. 2012). Moreover, it is possible that the emergence of the Mg\(_{\text{II}}\) BAL in J133356.02+001229.1, monitored by Vivek et al. (2012), represents an event similar to the one we have observed here, even though an intermediate mini-BAL phase was not observed. Taken together, all the cases summarized above also suggest that mini-BALs and BALs are connected to each other; some mini-BALs may be the intermediate phases of the appearance or disappearance of BALs (see the next paragraph), which would imply that quasars with mini-BALs and BALs might not be intrinsically different. Dramatically varying mini-BALs, such as those reported by Misawa et al. (2005), Hamann et al. (2008, 2011), and Rodríguez Hidalgo et al. (2011) could be related to this phenomenon, corresponding to more prolonged and complex intermediate phases, or cases where the final profile never satisfies the definition of a BAL. Monitoring of similar cases at high spectral resolution will help discern whether the physical properties of the absorbers that produce mini-BALs are similar to those producing BALs.

In contrast to studies of the abrupt appearance of BALs, studies of variability of existing BALs, including BAL disappearance, can be very systematic. A recent, extensive, and systematic study of this type was carried out by Filiz Ak et al. (2012), who re-observed several hundred BAL quasars discovered in the SDSS-I/II survey during SDSS-III (probing rest-frame time intervals of approximately 1–4 yr). These authors find that a few percent of the C\(_{\text{IV}}\) BAL troughs in their sample disappear in the interval between the two observations and they conclude that C\(_{\text{IV}}\) absorbers are detectable along their line of sight for time intervals of order a century. The disappearing troughs tend to be those with moderate equivalent widths and shallow depths. Filiz Ak et al. (2012) also observe that some of the troughs do not completely disappear but weaken into an intermediate mini-BAL phase, as in the case of J1151+0204. This effect is also seen in other quasars with multiple BAL troughs (i.e., Hall et al. 2011), where some troughs are observed to weaken while others disappear, reminiscent of the behavior observed in J133356.02+001229.1 by Vivek et al. (2012).

4.2. Inferring Some of the Properties of the Absorber in J1151+0204

The optical depths of the resolved C\(_{\text{IV}}\) doublets in system B appear to depart from the 2:1 ratio expected for unsaturated profiles (see the relative depths at \(v \approx -6500\) and \(-6000\) km s\(^{-1}\) in Figure 7). The depths of the lines approach a ratio of 1:1, suggesting that the lines are saturated but that the absorber does not cover the background source completely (a signature of “partial coverage”; see Barlow & Sargent 1997; Hamann & Ferland 1999; Ganguly et al. 1999). For fully resolved, unblended profiles, one can use the relative depths of the doublet to derive the coverage fraction as a function of velocity, \(C_r(v)\), defined as the fraction of photons from the background source that pass through the absorber. This derivation relies on the assumption that the absorber is homogeneous, (i.e., the optical

\(^8\) All timescales in this section are converted to the rest-frame timescales of each quasar.
depth as a function of position across the face of the background source is uniform.\footnote{This might not be the case in practice as measurements of different coverage fractions in different lines suggest that the absorber may not be homogeneous (see, for example, Arav et al. 2008). Nonetheless, we are not able to constrain the relevant properties of the absorber here; therefore we make this simplifying assumption and examine the consequences (see also the discussion in Hamann et al. 2011).} In the special case we are considering here, where the lines are fully saturated but not black, the coverage fraction, as a function of velocity across the profile, is given by $C_f(v) = 1 - I(v)$, where $I(v)$ is the normalized intensity in the observed absorption troughs. Thus, we arrive at $C_f(v) \approx 0.65$ as a plausible estimate in the velocity range from $-6700$ to $-6300$ km s$^{-1}$ in system B. This estimate is subject to the caveat that the C IV troughs probably comprise multiple blended kinematic components, as indicated in Figure 7. Assuming that the C IV line in system A is also saturated, we then infer the same value of $C_f(v)$ as for system B, based on the fact that the C IV line depth in system A is approximately the same as that of system B (see Figures 3 and 6).

Since the C IV absorption troughs of systems A and B are superposed on the continuum and not on the C IV emission lines, we can adopt a simple picture in which the absorber covers only the UV continuum source. Thus, we can constrain the transverse size of the absorber by comparing it with the size of the continuum source, under the assumption that the absorber has a uniform optical depth and sharp edges (i.e., partial coverage is a simple geometrical effect). To this end, we first estimate the mass of the central black hole following the three different prescriptions of Warner et al. (2003), Vestergaard & Peterson (2006), and Shen & Liu (2012). We make use of the FWHM of the C IV emission line (none of the other preferred estimators, such as Mg II and H β, are covered in our spectra) and the continuum luminosities at rest wavelengths of 1350 Å and 1450 Å, assuming a cosmological model with \( H_0 = 71 \) km s$^{-1}$ Mpc$^{-1}$, \( \Omega_m = 0.27 \), and \( \Omega_\Lambda = 0.73 \). The method employing the FWHM of the C IV emission lines is subject to the caveat that the blue wing of the line is contaminated by the associated absorption complex discussed in earlier sections. We arrive at $M_\ast \approx 3 \times 10^8 M_\odot$. Although the C III] emission line is also present, it is contaminated by the Si iii λ1892 and Al iii λ1857 emission lines and the black hole masses derived from this method can deviate significantly from those derived using the FWHM of the H β line. To determine the effective size of the continuum source at a rest wavelength of 1510 Å, we follow the method described in Rodríguez Hidalgo et al. (2011), based on Peterson (1997). This method relies on the Shakura & Sunyaev (1973) model of the disk (assuming a radiative efficiency of $\eta = 0.1$) and makes use of a bolometric luminosity of $L_{bol} = 1.1 \times 10^{47}$ erg s$^{-1}$ (obtained from $L_{bol} \approx 4.36 \lambda L_\lambda (1450 \text{ Å});$ see Warner et al. 2004). The final result was boosted by a factor of four to account for the fact that quasar microlensing studies systematically yield a larger continuum source size than what the Shakura & Sunyaev (1973) model predicts (see Morgan et al. 2010). We arrive at a continuum source diameter of $d_{cont} \approx 8 \times 10^{16}$ cm. To assess the sensitivity of this result to the uncertainty in the black hole mass, we varied the black hole mass by an order of magnitude in either direction and found a corresponding change in the diameter of the continuum source of a factor of two. Assuming that the projected area of the absorber is smaller than that of the continuum source and that the coverage fraction inferred earlier represents the fraction of the area of the continuum source covered by the absorber, we obtain a characteristic transverse dimension of the absorbing gas at $-6700$ to $-6300$ km s$^{-1}$ of, at least, $\sim 6 \times 10^{16}$ cm.

In contrast, the narrower absorption-line complex (system C) at lower velocities is saturated and black, at least in the UVES spectrum,\footnote{There seems to be no significant change in the C IV emission line profile between the two epochs, as shown in Figure 2 where both spectra are over-plotted after a “normalization” that did not include the emission lines.} suggesting that, if no other broad, shallow absorption component is present, the absorber covers completely the broad emission line region and the continuum. This system also increases in strength between the two observations, suggesting that these lines are intrinsic to the quasar environment. The lines also show larger widths compared with other associated lines (for example, those at $\sim 5050$ Å; see Figure 3), which is characteristic of intrinsic absorption (Vestergaard 2003). Moreover, systems A, B, and C are all varying in concert, which suggests that they are part of the same outflow and subject to the same influences (e.g., the same ionizing continuum). While we can affirm that this absorber is more extended in size than the system discussed in the previous paragraph (due to the larger coverage fraction), the spatial relation between this complex system and the outflowing gas of system A and B is unknown.

The gas responsible for the Ly α absorption in systems A and B may also cover the background source partially since the Ly α profile is similar to the C IV profile (see Figure 6). In this case, however, we cannot make a robust estimate of the coverage fraction but instead we can obtain upper and lower bounds of $0.42 < C_f(v) < 1$ based on the depth of the trough in system A. If the black, saturated trough at $v = -5900$ km s$^{-1}$ in system B is part of the Ly α profile, then the $C_f(v)$ likely spans a range of values across the Ly α profile. We would obtain a lower limit on the hydrogen column density of $N$(Ly α) > $4.8 \times 10^{14}$ cm$^{-2}$ by assuming that the Ly α trough in system A is not saturated and that it fully covers the background source (i.e., $C_f = 1$). However, Ly α saturates at approximately $10^{14}$ cm$^{-2}$ and it would be very difficult to obtain an unsaturated Ly α profile with the corresponding amount of observed C IV. Thus, using the value of $C_f = 0.42$, we obtain a better estimate of $N$(Ly α) > $1.6 \times 10^{15}$ cm$^{-2}$. No lines from lower ionization species such as Mg II, Fe II, and Al III were detected in either epoch. It is not surprising to detect saturated Ly α in the same phase as C IV and N V (see, for example, Wu et al. 2010) and the absence of other low ionization species supports the idea that these three lines originate in the same ionization phase.

### 4.3. Possible Causes of the Observed Variability

The observed variability can be a result of at least one of the following effects: variations caused by changes in the ionization state of the absorber and variations caused by motion of the absorber across the cylinder of sight; a combination of the two is also possible. The changes in the line profiles expected from each of these two extreme scenarios are illustrated in Misawa et al. (2005). The fact that we do not observe any substantial change in the apparent outflow speeds of the absorption troughs is consistent with both of these interpretations. Therefore, we examine each of these two possibilities in turn.

The ionization state of the absorbing gas can change as a result of fluctuations in the ionizing continuum that illuminates it. In this context, we can obtain a lower limit on the electron density in the absorbing gas by requiring that the recombination...
time of the C iv ion is shorter than the interval between observations (see Hamann et al. 1997). This assumption yields \( n_e \gtrsim (\alpha \Delta \text{rest})^{-1} \approx 4000 \text{ cm}^{-3} \), where \( \alpha \) is the recombination coefficient with values of \( 5.3 \times 10^{-12} \) and \( 2.8 \times 10^{-12} \text{ cm}^{-3} \text{ s}^{-1} \) for C iii \( \rightarrow \) C iv and C v \( \rightarrow \) C iv, respectively. These values are taken from Arnaud & Rothenflug (1985) assuming a temperature of 20,000 K; we use the value for C v \( \rightarrow \) C iv since it results in the strongest limit. Moreover, because we observe N v and Ly\(\alpha\) increasing as well as C iv, in a scenario where these changes are due to ionization variations it is more likely that the ionization parameter is decreasing (see Appendix A in Hamann et al. 2011). This scenario relies on the dominant ionization state of C changing from C v to C iv on a time interval shorter than 2.86 yr, hence the intensity of the ionizing continuum must change by at least an order of magnitude on this timescale.\(^{11}\) We consider this possibility unlikely for such a luminous quasar, which should vary quite slowly. In the sample of luminous quasars monitored by Kaspi et al. (2007), for example, the most extreme variation observed is the brightening of SBS 1116+5603 by 40% in a rest-frame time interval of 3 yr. Even the moderate-luminosity Palomar Green quasars monitored by Ghez et al. (1999) do not vary by more than 60% over rest-frame time intervals of about 5 yr. However, it is possible that the flux illuminating the absorber can change by large factors as a result of variable transmission through a porous or patchy “screen” between the absorber and the continuum source. This possibility was suggested by Misawa et al. (2007) and it is supported by observations of rapid, high-amplitude X-ray variability in mini-BAL quasars (e.g., Giustini et al. 2011). Such a scenario is also compatible with the observation that multiple absorption systems (A, B, and C) at different velocities and with different trough shapes vary in concert.

If, instead, we suppose that the variations in the absorption troughs are the result of a parcel or filament of gas entering the cylinder of sight, then the transverse speed of the parcel can be estimated by assuming that the parcel has traversed the diameter of the continuum source in the interval between our two observations, i.e., \( v_{\text{trans}} \gtrsim d_{\text{cont}}/\Delta \text{rest} \approx 8900 \) km s\(^{-1}\). If we further assume that the parcel is moving at the local dynamical speed (either because it is in Keplerian rotation or because it has been launched at the local escape speed; this assumption is further justified by the similarity of the transverse speed to the apparent outflow speed), then we obtain the following constraint on its distance from the black hole: \( \alpha \lesssim G M_*/v_{\text{trans}}^2 \approx 5 \times 10^{17} \) cm \( \approx 1100 \) \( r_g \) (where \( r_g = G M_*/c^2 \) is the gravitational radius). This distance places the absorber in the vicinity of the broad emission-line region (hereafter BELR; cf. Kaspi et al. 2005, 2007) and suggests a connection between the emission- and absorption-line gas.

Future monitoring at high resolution of the multiple ions present in the outflow is necessary to better characterize the variability and, thus, find its cause. The simulations of these processes presented in Wise et al. (2004) and Misawa et al. (2007) can form the basis for the observational tests.

5. SUMMARY AND CONCLUSIONS

We present the discovery of dramatic variability in the C iv \( \lambda \lambda 1548, 1550 \) mini-BAL of the radio-quiet quasar J115122+020426 (\( z_{\text{em}} = 2.399 \)). Our results are based on the comparison of an older SDSS spectrum and a newer VLT/UVES spectrum. The original mini-BAL profile had a FWHM of 1220 km s\(^{-1}\) and a maximum blueshift velocity of 9520 km s\(^{-1}\). Over a rest-frame time interval of 2.86 yr, the equivalent width increased by a factor of eight and the maximum blueshift velocity became 12,240 km s\(^{-1}\). There is no clear evidence for changes in the centroid velocity of the absorption troughs. Instead, the absorption lines in the earlier spectrum became stronger and regions of the spectrum that appeared unabsorbed in the earlier spectrum are clearly absorbed in the later spectrum. The properties of the new absorption trough satisfy the definition of a BAL. Thus, we have caught a rare transition of a mini-BAL to a BAL. Two other absorption systems at somewhat smaller blueshift velocities (one of them a cluster of narrow absorption troughs) also became substantially stronger in the same time interval. We observe a similar variability pattern in the N v and Ly\(\alpha\) absorption lines.

From the residual depths of the lines in the C iv mini-BAL (system B), we infer that the absorber covers a fraction \( C_f = 0.65 \) of the area of the background continuum source. In contrast, the absorber responsible for the cluster of narrow C iv lines appears to cover the background continuum source completely during the later observation. If we ascribe the variability to changes in the coverage fraction due to motion of the absorber at the dynamical speed, we conclude that the absorber is located at a distance from the continuum source that is comparable to the size of the BELR. If, on the other hand, the variability is a result of changes in the ionization state of the absorber, the short variability timescale suggests that the ionizing flux incident on the absorber is modulated by a screen with rapidly variable transmission.

Future monitoring is necessary to better characterize the cause of this variability, in particular to determine whether the variability is caused by the motion of the absorber across the cylinder of sight or changes in its ionization state. The simulations of these processes presented in Wise et al. (2004) and Misawa et al. (2007) can form the basis for the observational tests.

We thank the anonymous referee for thoughtful comments. This research was funded by NASA under grant NAG5-6399 NNG04GE73G and by the National Science Foundation (NSF) under grants AST-0407138 and AST-0807993 and through the REU program. P.R.H. would like to thank Pat Hall for fruitful discussions and comments on the manuscript. P.R.H. is currently supported by an Ontario Early Researcher Award to P.B.H. M.T.M. thanks the Australian Research Council for a QEII Research Fellowship (DP0877998).

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the

---

\(^{11}\) A more sophisticated approach to inferring the density from the variability timescale is given in Arav et al. (2012, see their Equation (10)). However, that approach can only be applied when more detailed information about the variations of the ionizing continuum is available.
