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EVIDENCE OF A STRONG N V/C IV CORRELATION BETWEEN EMISSION AND ABSORPTION LINES IN ACTIVE GALACTIC NUCLEI

Joanna K. Kuraszkiewicz and Paul J. Green
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138;
jkuraszkiewicz@cfa.harvard.edu, pgreen@cfa.harvard.edu
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ABSTRACT

The narrow absorption lines (NALs) that are seen in the rest-frame ultraviolet near the systemic redshift of active galactic nuclei (AGNs) are not always intrinsic to the near-nuclear region but may originate in the host galaxy or in neighboring galaxies intervening along the line of sight. A variety of criteria have been sought—and several identified—as evidence of an intrinsic origin. We have measured both emission and absorption lines in a *Hubble Space Telescope* Faint Object Spectrograph sample of objects with both C IV and N V NALs within ± 5000 km s^{-1} of the systemic redshift. We find a strong (>99.5% confidence) linear correlation between the N V/C IV ratio in broad emission lines and that in NALs. A control sample of AGNs with NALs separated by larger velocities shows no such correlation. Our finding thus identifies an additional test for the intrinsic nature of NALs in any given object. The correlation shows that the chemical-enrichment histories and/or ionization parameters of the NAL clouds are closely related to those of clouds that produce the broad emission lines.

Subject headings: galaxies: abundances — galaxies: active — quasars: absorption lines — quasars: emission lines

1. INTRODUCTION

Quasar spectra are characterized by strong, broad emission lines (BELs) that are thought to form in a large number of small gas clouds photoionized by the central continuum source (presumably a black hole with an accretion disk). These broad line-emitting clouds lie at distances of 10^{13}–10^{18} cm from the central engine, spanning a range of densities $n_e \sim 10^8$–10^{12} cm^{-3} and covering 10% of the ionizing source. Modeling of the BEL region suggests that although the clouds populating the BEL region span a wide range of distances and densities, only those clouds within an optimum range of density and ionizing flux (different for different lines) dominate the observed line flux. This is the so-called locally optimally emitting clouds model (Baldwin et al. 1995).

Hamann & Ferland (1992) proposed that the N V/C IV ratio can be used as an abundance indicator, affording a probe of galactic nucleosynthesis measurable to high redshifts. This is because studies of high (>0.2 solar) abundance galactic H II regions found that nitrogen goes up roughly as the square of the metallicity as a result of secondary nucleosynthetic processing. At lower metallicities, primary nitrogen is more important (see the work by Izotov & Thuan 1999 on blue compact dwarf galaxies). Many high-redshift/high-luminosity quasars (QSOs) have N V/C IV > 0.1, indicating supersolar abundances (Hamann & Ferland 1993).

QSO spectra often show absorption lines that are adjacent to the emission lines (mostly in the UV; Crenshaw et al. 1999). More than 10% of the optically selected QSOs have highly ionized, broad absorption lines (BALs), which are blueshifted relative to the emission lines by tens of thousands of kilometers per second, with velocity widths of at a least a few thousand kilometers per second. These BALs are undoubtedly intrinsic in origin based on the inferred partial coverage of the continuum source and on the supersolar abundances (e.g., Weymann et al. 1991). However, for the narrow absorption line (NAL) systems, with velocity widths of a few hundred kilometers per second, there is less consensus on the location of absorbing gas. NAL clouds may originate from gas ejected from the nucleus (similar to the BALQSOs), in the host galaxy of the QSO, or from galaxies nearby (e.g., within a galaxy cluster that hosts the QSO). Intervening gas clouds or galaxies at cosmological distances lying along our line of sight may also be responsible.

Adopted from Hamann & Ferland (1999), the following properties are considered strong evidence of intrinsic absorption: the time variability of the absorption lines, the partial coverage of the background light source (implied by multiplet ratios), the high gas densities (inferred from fine-structure lines), and the well-resolved profiles that are smooth and broad (compared with both thermal line widths and the velocity dispersions expected in intervening clouds). Barlow & Hamann (1997) suggested a few other properties that are weaker indicators for intrinsic systems: high metallicity, high ionization, and $z_{\rm abs} \sim z_{\rm em}$. It is often assumed that NAL systems found within 5000 km s^{-1} of the emission redshift are intrinsic to the QSO (however, see Richards et al. 1999 and references therein for examples of intrinsic NALs with velocities >5000 km s^{-1}). This assumption is supported by a statistical excess of such systems over the number expected from cosmologically distributed absorbers and by a correlation between the number of such systems and the QSO's luminosity and radio properties (Foltz et al. 1986, 1988; Aldcroft, Bechtold, & Elvis 1994; Wills et al. 1995; Möller, Jakobsen, & Perryman 1994).

We show here that a comparison of the absorption- and emission-line properties of QSOs—their N V/C IV ratios—yields another useful indicator of intrinsic absorption and adds new insight into the nature and composition of clouds near the nucleus. Early NAL studies using low-quality data noted larger N V/C IV ratios in $z_{\rm abs} \approx z_{\rm em}$ systems compared with $z_{\rm abs} \ll z_{\rm em}$ (Weymann, Carswell, & Smith 1981) and were later confirmed with higher quality data, for which the column densities and abundances could be estimated (e.g., Petitjean, Rauch, & Carswell 1994; Savaglio, D'Odorico, & Möller 1994). It was found that $z_{\rm abs} \approx z_{\rm em}$ systems usually have abundances $Z > Z_{\odot}$, at least an order of magnitude higher than in $z_{\rm abs} \ll z_{\rm em}$ systems, where $Z < 0.1\ Z_{\odot}$.

The N V/C IV ratio can also be used as an abundance indicator in absorption-line systems as long as the effects of saturation and ionization are understood (Hamann et al. 1997b). Since the BALs are mostly heavily saturated and hence only weakly sensitive to the abundances, we exclude them from further analysis. On the other hand, high-resolution studies show that, in general, NALs are not severely saturated. In this Letter, we show that N V/C IV correlates strongly between the BELs and the NALs in active galactic nuclei (AGNs) with $z_{\rm abs} \approx z_{\rm em}$, indicating that either the metallicities or ionization parameters in the NAL and BEL clouds are intimately related.

2. SAMPLE AND SPECTRAL ANALYSIS

Bechtold et al. (2002) present a large database of narrow ultraviolet absorption lines measured from spectra observed with the Faint Object Spectrograph (FOS; Keyes et al. 1995 and references therein) on the *Hubble Space Telescope* (*HST*) and gathered from the Space Telescope Science Institute archives. For each of the 271 QSO spectra, Bechtold et al. present a list of absorption lines (with significance >3.5 σ) together with line identifications and equivalent widths. We searched these absorption-line lists for objects that have both N V and C IV absorption within 5000 km s^{-1} of the emission redshift and for which the velocity difference between the C IV and N V absorbing systems is less than 500 km s^{-1}. All absorption lines with $W_\lambda \geq 0.2$ Å are included. Lines with $W_\lambda < 0.2$ Å were included only if an associated line from the doublet was present with $W_\lambda > 0.2$ Å. We also require that the QSO spectra show complete Lyα and C IV emission lines, to accurately model the N V and C IV emission lines.

The sample of QSOs chosen this way includes 17 objects (two of which have double absorption systems with $\Delta v \leq$ 5000 km s^{-1}: 1351+640 and 1425+267) with redshifts ≤1 and is presented in Table 1. Six of the objects are radio-loud. In 1340+606 and 1631+395, we have refitted the N V absorption lines (using Sherpa) since the partially resolved doublet was fitted in Bechtold et al. (2002) with a single Gaussian, resulting in an underestimate of the N V equivalent width. For the same reasons, we refitted the C IV absorption in 2135−147. In 0050+124, the N V λ1238 absorption line at $z_{\rm abs} = 0.05386$ is contaminated by N V λ1242 from an absorption system with $z_{\rm abs} = 0.05113$. Since it was difficult to resolve the two components in this object, we left the fits unchanged, but the N V equivalent width should be treated with caution since it is slightly overestimated.

The emission-line measurements for the spectra obtained before the installation of the Corrective Optics Telescope Axial Replacement (COSTAR; 1993 December) were taken from Kuraszkiewicz et al. (2002). The calibrated and dereddened spectra obtained after the COSTAR installation were retrieved from Bechtold et al. (2002). To obtain emission-line measurements consistent with the pre-COSTAR data, we modeled (and in some cases merged) post-COSTAR spectra just as described in Kuraszkiewicz et al. (2002).[1]

TABLE 1

LIST OF OBJECTS

Designation	Systemic Redshift	N V/C IV Emission	N V/C IV Absorption[a]	Reference[b]
Program Sample: $\Delta v < 5000$ km s^{-1}				
0050+124 ……	0.061	$0.30^{+0.06}_{-0.06}$	1.03 ± 0.09	1
0350−073 ……	0.962	$0.13^{+0.05}_{-0.04}$	0.56 ± 0.04	2
0955+326 ……	0.533	$0.31^{+0.05}_{-0.05}$	1.41 ± 0.33	2
1114+444 ……	0.144	$0.06^{+0.02}_{-0.02}$	0.71 ± 0.02	1
1130+111 ……	0.510	$0.11^{+0.02}_{-0.02}$	0.72 ± 0.08	1
1309+355 ……	0.184	$0.20^{+0.09}_{-0.03}$	1.38 ± 0.11	1
1340+606 ……	0.961	$<0.01^{+0.01}_{-0.01}$	0.80 ± 0.07	2
1351+640 ……	0.088	$0.26^{+0.04}_{-0.04}$	1.39 ± 0.21	1
		$0.26^{+0.04}_{-0.04}$	0.72 ± 0.04	1
1404+226 ……	0.098	$0.03^{+0.12}_{-0.03}$	0.23 ± 0.06	1
1425+267 ……	0.366	$0.08^{+0.02}_{-0.02}$	1.19 ± 0.39	1
		$0.08^{+0.02}_{-0.02}$	0.96 ± 0.15	1
1538+478 ……	0.770	$0.22^{+0.11}_{-0.01}$	0.66 ± 0.03	1
1631+395 ……	1.023	$0.41^{+0.08}_{-0.07}$	1.36 ± 0.19	2
1704+608 ……	0.371	$0.15^{+0.04}_{-0.03}$	1.03 ± 0.14	2
2041−109 ……	0.035	$0.11^{+0.01}_{-0.01}$	1.11 ± 0.11	2
2135−147 ……	0.200	$0.04^{+0.02}_{-0.01}$	0.49 ± 0.05	2
2251−178 ……	0.068	$0.07^{+0.00}_{-0.04}$	1.04 ± 0.05	1
2251+113 ……	0.323	$0.03^{+0.15}_{-0.02}$	0.28 ± 0.05	2
Control Sample: $\Delta v > 5000$ km s^{-1}				
0414−060 ……	0.781	$0.34^{+0.17}_{-0.02}$	0.74 ± 0.09	2
0454−220 ……	0.534	$0.02^{+0.01}_{-0.01}$	0.05 ± 0.02	2
		$0.02^{+0.01}_{-0.01}$	0.24 ± 0.04	2
0710+118 ……	0.768	$0.20^{+0.12}_{-0.03}$	0.19 ± 0.05	1
0916+513 ……	0.553	$0.40^{+0.06}_{-0.05}$	0.40 ± 0.10	2
1229−021 ……	1.045	$0.03^{+0.01}_{-0.01}$	0.19 ± 0.03	1
		$0.03^{+0.01}_{-0.01}$	0.14 ± 0.03	1
1248+401 ……	1.030	$0.23^{+0.04}_{-0.04}$	0.14 ± 0.03	1
		$0.23^{+0.04}_{-0.04}$	0.36 ± 0.03	1
1544+489 ……	0.400	$0.08^{+0.02}_{-0.01}$	0.27 ± 0.07	1
1611+343 ……	1.401	$0.32^{+0.05}_{-0.04}$	0.98 ± 0.31	2
2128−126 ……	0.501	$0.13^{+0.07}_{-0.01}$	0.74 ± 0.28	2
2145+067 ……	0.999	$0.14^{+0.02}_{-0.02}$	0.11 ± 0.02	2

[a] Ratio calculated using Bechtold et al. 2002 data, except for 1340+606, 1631+395, and 2135−147, which we refitted (details in text).

[b] Emission-line ratio from (1) this Letter and (2) Kuraszkiewicz et al. 2002.

3. CORRELATION BETWEEN N V/C IV EMISSION AND ABSORPTION

The N V/C IV emission- and absorption-line equivalent width ratios (from both lines of the doublet) are presented in Table 1 with 1 σ errors (which do not include errors from the uncertainty of the continuum placement that we estimate to be ~10%). In Figure 1*a*, we show the dependence between the N V/C IV absorption-line ratio (N V/C IV)$_{\rm abs}$ and the N V/C IV emission-line ratio (N V/C IV)$_{\rm em}$. QSOs that had more than one associated absorption system have their data points either circled (1351+640) or surrounded by an open square (1425+267).[2] Figure 1*a* shows a strong correlation between (N V/C IV)$_{\rm abs}$ and (N V/C IV)$_{\rm em}$ in QSOs, with the probability of a correlation occurring by chance $P = 0.5\%$ in the generalized Kendall rank test and $P = 0.8\%$ in the Spearman rank test (using the survival analysis package of Lavalley, Isobe, & Feigelson 1992 to allow for the presence of a lower limit in 1340+606). The best-fit linear regression yields a slope $\alpha = 1.06 \pm 0.33$ consistent with unity. Lines with ± 1 σ are shown as dotted lines in Figures 1*a* and 1*b*.

We also studied a control sample selected with identical criteria to the program sample except that we now require $\Delta v > 5000$ km s^{-1} for both N V and C IV absorption. Based on this change, these NAL systems are more likely to be intervening. The control sample includes objects with a range of redshifts $0.4 < z < 2.4$ and is presented in Table 1 and Figure 1*b*. As is immediately

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[1] We fitted each spectrum with a power-law continuum, modeled blended iron emission, included Galactic and intrinsic absorption lines, and performed multicomponent fits to the emission-line profiles. For detailed spectral modeling and emission- and absorption-line measurements, we refer the reader to our Web site http://hea-www.harvard.edu/~pgreen/HRCULES.html.

[2] In these objects, the absorption systems with higher abundances have a larger velocity difference relative to the systemic redshift (Δv).

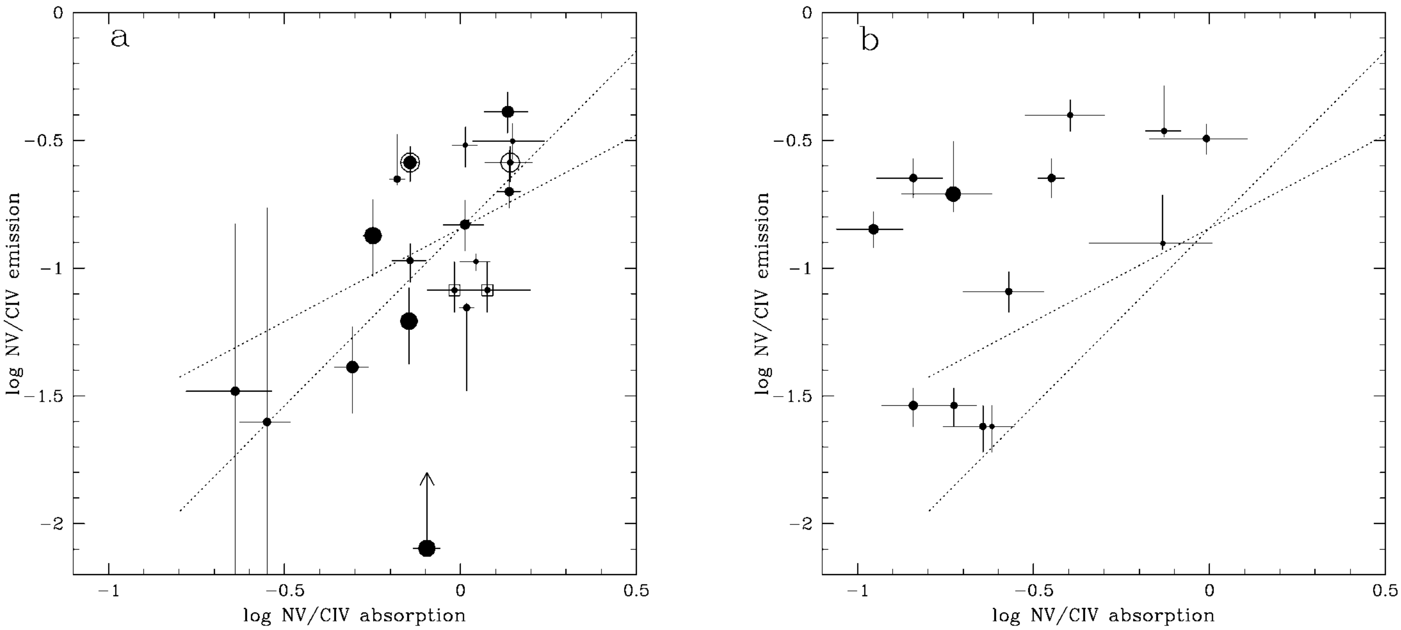

FIG. 1.—(*a*) N V/C IV emission-line ratio vs. N V/C IV absorption-line ratio with 1 σ errors for QSOs with NALs within ±5000 km s^{-1} of the emission-line redshift. QSOs 1351+640 and 1425+267, which have two intrinsic absorption-line systems, are indicated by an open circle and an open square, respectively. The sizes of the data points are proportional to the C IV NAL equivalent width. The dotted lines show the ±1 σ best-fit regressions, which include all measurements plotted. (*b*) Control sample ($\Delta v > 5000$ km s^{-1}).

evident, the control sample shows no correlation ($P \geq 16\%$) between $(\mathrm{N\ V/C\ IV})_{\mathrm{em}}$ and $(\mathrm{N\ V/C\ IV})_{\mathrm{abs}}$.

We also tested the above correlations using N V/C IV flux ratios. While flux ratios may be more strongly affected by continuum placement, they also show a strong correlation ($P \leq 0.01\%$ in the Kendall rank test and $P \leq 0.04\%$ in the Spearman rank test) and an identical regression slope (1.07 ± 0.15) in the program sample and no correlation in the control sample ($P > 30\%$).

4. DISCUSSION

The *HST*/FOS spectra that we use here have only moderate resolution, which can lead to an underestimate of the optical depths, and hence column densities, of the absorption-line systems. Many objects in the program sample have absorption-line doublet ratios N V λ1238/N V λ1242 and C IV λ1548/C IV λ1550 close to 2, implying that the lines are not saturated; however, higher resolution spectra are needed to confirm this. The conversion of measured columns to metal abundances depends directly on the ionization fractions of those species measured, whereas without further (e.g., X-ray absorption) measurements, we have little information available on the ionization state of the absorbers. Finally, our measurements are likely to compound the absorption from an ensemble of clouds along the line of sight with a range of columns, thermal and bulk velocities, and ionization levels. However, the correlation in Figure 1*a* shows that, whatever its quality as an abundance indicator in these data, N V/C IV correlates strongly between the BEL gas and the NAL gas. If ionization or other effects differed between the NAL and BEL clouds, this would merely add scatter to the correlation. The fact that a strong correlation persists suggests that the metallicity and/or ionization parameters in BEL and NAL clouds are related. Otherwise the differences in these properties must conspire to cancel each other so that the observed correlation might persist. However, we now also consider possible selection effects in our measurements.

The emission lines in both the control and program samples are easy to detect and are measured consistently using the same, semiautomatic measuring technique. However, the presence of underlying emission lines could affect the measurement of the absorption lines in the program sample differently. In general, the N V NAL is the more difficult to detect and measure. If stronger emission lines yielded preferentially better detection and measurement of N V absorption, the observed correlation in Figure 1*a* could be spuriously enhanced. If so, we might expect that (1) the minimum absorption line W_λ of the program sample would be larger than for the control sample and (2) some dependence of the absorption-line measurements on the emission-line strengths. We find that the minimum absorption line W_λ for the program sample is 0.14 ± 0.02, similar to the 0.16 ± 0.03 found for the control sample. We also find that objects with different C IV (and, as we found, N V) equivalent widths (W_λ proportional to the data point size in Fig. 1*a*) are evenly distributed along the $(\mathrm{N\ V/C\ IV})_{\mathrm{em}}$ versus $(\mathrm{N\ V/C\ IV})_{\mathrm{abs}}$ correlation. Hence, the underlying continuum+emission-line model does not significantly affect the absorption-line measurement or detection.

It could also be argued that the lack of points in the upper left-hand corner of Figure 1*a* could be caused by objects that have measurable C IV absorption but undetectable N V absorption. However, in the control sample, we find many objects in that region, which additionally provides evidence for the generally lower column of intervening absorbers. Similarly, the lack of objects in the lower right-hand corner of Figure 1*a* might be suggested as a selection effect caused by objects that have measurable N V absorption but undetectable C IV absorption. We found two such objects in the Bechtold et al. (2002) sample: 1118+1252 (with $\Delta v = -790$ km s^{-1}), for which C IV absorption by pure accident coincides with strong Galactic Fe II absorption and hence has not been identified, and 1111+4053 (with $\Delta v = -1027$ km s^{-1}), for which C IV absorption is visible in the spectrum but is too weak to be detected. We have modeled the emission lines in the latter object and found that log (N V/

C IV)$_{\rm em}$ > -0.6, which, together with the possibly large (N V/C IV)$_{\rm abs}$ ratio, would place 1111+4053 in the upper right-hand corner of Figure 1*a* without effecting the overall correlation.

A few objects from the control sample extend into the region occupied by the program sample in Figure 1*b*. Since some absorbers are known to extend beyond the $\Delta v = 5000$ km s^{-1} criterion (e.g., BALQSOs), it is possible that NALs among the control sample objects that lie near the program sample correlation may be intrinsic. There is mounting evidence that some QSO absorption systems with velocities 5000 km s^{-1} $< v <$ 75,000 km s^{-1} are, if not intrinsic, at least affected by the illuminating QSO. For example, Richards et al. (1999) show that the distribution in velocity space of such systems is dependent on the QSOs' radio properties (luminosity, radio spectral index, and radio morphology; see also Borgeest & Mehlert 1993, Petitjean et al. 1994, and Hamann et al. 1997a). Based on the evidence here, we consider ratios lying in the region of the program sample correlation to provide corroborative evidence for an intrinsic nature, which may extend to absorbing systems at these higher velocities.

5. SUMMARY

One reasonable interpretation of the (N V/C IV)$_{\rm em}$ versus (N V/C IV)$_{\rm abs}$ correlation we report here is that the NAL and BEL clouds share related chemical-enrichment histories and/or ionization parameters. In Elvis (2000), the NALs and BELs are cospatial, situated in gas outflowing from the disk, where NAL gas is the warm highly ionized medium that confines the BEL clouds. In Sabra, Hamann, & Shields (2002), NALs originate from the narrow line-emitting region when the observer is looking down through the line-emitting gas toward the continuum source. It may also be possible that the NAL gas is enriched in the vicinity of the QSO nucleus and then ejected into the host galaxy of the QSO or farther out into the intergalactic medium. But high abundance does not guarantee an intrinsic origin.[3] Conversely, lower abundance in NAL gas does not *exclude* an intrinsic origin. In the lower left region of Figure 1*a*, there are NALs in the program sample that lie directly along the correlation, but with ratios indicating lower abundances, similar to those in the control sample.

The wide velocity range of clouds contributing to BELs makes it likely that BELs are produced by clouds spanning a wide range of physical conditions, with an ionization level and a density of principal interest to line production (Baldwin et al. 1995). BEL or BAL measurements are thus likely to integrate over thousands of clouds or perhaps over a wind structure (e.g., de Kool & Begelman 1995; Murray & Chiang 1995; Proga, Stone, & Kallman 2000) covering wide ranges of density and ionizing flux (Korista et al. 1997; Baldwin et al. 1995). By contrast, the velocity width of NALs is lower. The NAL clouds may probe fewer lines of sight, which facilitates a simpler and perhaps partially independent physical interpretation of absorption-line measurements. We thus suggest that even using spectra of moderate resolution and signal-to-noise ratio (S/N), the strong correlation that we report is supportive evidence for the validity of BEL ratios as either ionization or abundance indicators. Investigations at higher resolution and S/N are clearly warranted.

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[3] Tripp, Lu, & Savage (1996) studied an associated absorption system in a $z = 3$ QSO with a high metal abundance ($>1\ Z_\odot$) NAL, which at first suggested that the absorbing gas could originate near the nucleus of the QSO. However, a lack of the excited-state absorption in C II* λ1336 (compared with detected C II λ1335) in this system indicates a very low (<7 cm^{-3}) density absorber suggesting >300 kpc distances from this QSO.

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