HUBBLE/COS OBSERVATIONS OF THE Lyα FOREST TOWARD THE BL Lac OBJECT 1ES 1553+113*

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ABSTRACT

We present new moderate-resolution, far-ultraviolet spectra from the Hubble Space Telescope/Cosmic Origins Spectrograph (HST/COS) of the BL Lac object 1ES 1553+113 covering the wavelength range 1135 Å < λ < 1795 Å. The data show a smooth continuum with a wealth of narrow (b < 100 km s⁻¹) absorption features arising in the interstellar medium and intergalactic medium. These features include 41 Lyα absorbers at 0 < z_{abs} < 0.43, 14 of which are detected in multiple Lyman lines and 6 of which show absorption in one or more metal lines. We analyze a metal-rich triplet (∆ζ = 1000 km s⁻¹) of Lyα absorbers at z_{abs} ≈ 0.188 in which O vi, N v, and C iii absorption is detected. Silicon ions (Si iii, Si iv) are not detected to fairly strong upper limits and we use the measured Si iii/C iii upper limit to derive an abundance limit (C/Si) ≳ 4 (C/Si)⊙ for the strongest component of the absorber complex. Galaxy redshift surveys show a number of massive galaxies at approximately the same redshift as this absorption complex, suggesting that it arises in a large-scale galaxy filament. As one of the brightest extragalactic X-ray and γ-ray sources, 1ES 1553+113 is of great interest to the high-energy astrophysics community. With no intrinsic emission or absorption features, 1ES 1553+113 has no direct redshift determination. We use intervening Lyα absorbers to place a direct limit on the redshift: z_{em} > 0.395 based on a confirmed Lyα+O vi absorber and z_{em} ≳ 0.433 based on a single-line detection of Lyα. The current COS data are only sensitive to Lyα absorbers at z < 0.47, but we present statistical arguments that z_{em} ≲ 0.58 (at a 1σ confidence limit) based on the non-detection of any Lyβ absorbers at z > 0.4.

Key words: BL Lacertae objects: individual (1ES 1553+113) – galaxies: active – intergalactic medium – quasars: absorption lines – ultraviolet: general

1. INTRODUCTION

The current interpretation of BL Lac objects (Ghisellini et al. 1985) is that they are active galactic nuclei (AGNs) with a strongly relativistic jet pointed toward our line of sight. As such, any line emission or accretion disk features seen in most other types of AGNs could be masked by the bright jet if present in BL Lac objects. Their spectra usually show a featureless power-law continuum extending from radio to X-ray wavelengths. This spectral characteristic makes BL Lac objects ideal for observing absorption features arising in the interstellar medium and intergalactic medium (IGM). Since their continuum is easily defined, they make excellent targets for studying weak metal-line systems and low-contrast, highly thermally broadened Hα features arising in the interstellar medium (ISM) and intergalactic medium. These features include 41 Lyα absorbers at 0 < z_{abs} < 0.43, 14 of which are detected in multiple Lyman lines and 6 of which show absorption in one or more metal lines. We analyze a metal-rich triplet (∆ζ = 1000 km s⁻¹) of Lyα absorbers at z_{abs} ≈ 0.188 in which O vi, N v, and C iii absorption is detected. Silicon ions (Si iii, Si iv) are not detected to fairly strong upper limits and we use the measured Si iii/C iii upper limit to derive an abundance limit (C/Si) ≳ 4 (C/Si)⊙ for the strongest component of the absorber complex. Galaxy redshift surveys show a number of massive galaxies at approximately the same redshift as this absorption complex, suggesting that it arises in a large-scale galaxy filament. As one of the brightest extragalactic X-ray and γ-ray sources, 1ES 1553+113 is of great interest to the high-energy astrophysics community. With no intrinsic emission or absorption features, 1ES 1553+113 has no direct redshift determination. We use intervening Lyα absorbers to place a direct limit on the redshift: z_{em} > 0.395 based on a confirmed Lyα+O vi absorber and z_{em} ≳ 0.433 based on a single-line detection of Lyα. The current COS data are only sensitive to Lyα absorbers at z < 0.47, but we present statistical arguments that z_{em} ≲ 0.58 (at a 1σ confidence limit) based on the non-detection of any Lyβ absorbers at z > 0.4.

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and HST/STIS data (Danforth & Shull 2005, 2008; hereafter DS08). No absorbers are seen from \( z \approx 0.43 \) to \( z \approx 0.47 \), the highest Ly\( \alpha \) redshift covered by our COS observations, and we use the observed Ly\( \alpha \) redshift distribution to place constraints on the emission redshift upper limit.

The observations and data reduction techniques are discussed in Section 2 and we present a catalog of absorption lines in Section 4. We present a detailed analysis of the rich IGM system at \( z \approx 0.188 \) in Section 4.1 and our direct redshift limit on 1ES 1553+113 in Section 4.2. We summarize our findings and detail future work in Section 5.

2. OBSERVATIONS AND DATA ANALYSIS

Far-UV observations of 1ES 1553+113 were carried out on 2009 September 22 by HST/COS as part of the COS Guaranteed Time Observations (PID 11528, PI: Green). Five exposures were made in each of the G130M (1135 < \( \lambda < 1480 \) Å) and G160M (1400 < \( \lambda < 1795 \) Å) medium-resolution gratings (\( R \approx 18,000 \)) totalling 3.1 and 3.8 ks, respectively. Four central wavelength settings at each grating dithered known instrumental features along the spectrum and provided continuous spectral coverage over 1135 < \( \lambda < 1795 \) Å (see J. Green et al. 2010, in preparation; S. Osterman et al. 2010, in preparation). After retrieval from the archive, all 10 exposures were reduced locally using CalCOS v2.11f.

Flat-fielding, alignment, and co-addition of the processed exposures were carried out using IDL routines developed by the COS GTO team specifically for COS FUV data.\(^1\) First, the data were corrected for the most egregious instrumental features. While attempts at a true “flat-fielding” of COS data show promise, the technique is not yet robust enough to improve data of moderate signal-to-noise ratio (S/N). However, we are able to correct the narrow \( \sim 15\% \) opaque features arising from ion repeller grid wires in the detector. A one-dimensional map of grid-wire opacity for each detector was shifted from detector coordinates into wavelength space and divided from the flux and error vectors. Exposure time in the location of grid wires was decreased to \( \sim 70\% \), giving these pixels less weight in the final co-addition. We also modify the error and local exposure time at the edges of the detector segments to de-weight flux contributions from these regions. With four different central wavelength settings per grating, any residual instrumental artifacts from grid-wire shadows and detector segment boundaries should have negligible effect on the final spectrum.

The exposures are aligned with each other and interpolated onto a common wavelength scale. One exposure in each grating/detector was picked as a wavelength reference, and the remaining exposures were cross-correlated with it. The wavelength region of cross-correlation for each case was picked to include a strong ISM absorption feature and shifts were typically on the order of a resolution element (\( \sim 0.07 \) Å) or less. The COS wavelength solution has not yet been rigorously characterized, and we see a systematic shift between strong ISM lines and their expected local standard of rest (LSR) velocities. The shift is approximately constant across the COS wavelength range, so we apply a uniform +0.17 Å shift to the wavelength vectors (\( \sim 40 \) km \( s^{-1} \) at \( \sim 1300 \) Å) to bring ISM line centroids to the expected \( v_{\text{LSR}} \approx 0 \) seen in many ISM absorbers.

Next, the aligned exposures were interpolated onto a uniform wavelength grid and co-added. The flux at each position was taken to be the exposure-weighted mean of flux in each exposure. Since exposure time was reduced in certain wavelength locations, as noted above, pixels near detector edges and where grid-wire shadows were removed received less weight than those in less suspect locations. To quantify the quality of the combined data, we identify line-free continuum regions at various wavelengths, smooth the data by the 7 pixel resolution element (\( \sim 0.07 \) Å, \( \sim 17 \) km \( s^{-1} \)), and define S/N \( \equiv \text{mean(flux)}/\text{stddev(flux)} = 15\)–25. This is sufficient to detect narrow absorption features down to \( W_{\lambda} \approx 15 \) mÅ at 4\( \sigma \) significance. Figure 1 shows the entire combined COS/G130M+G160M spectrum. Figure 2 shows a more detailed view of the spectrum with prominent lines marked.

In addition to the COS data, we utilize 45 ks of FUSE observations taken in 2004 April as part of program E526 (PI: B.D. Savage). While FUSE data alone are insufficient to characterize the H\( \text{I} \) absorber systems along a sight line, far-UV coverage is invaluable for confirming Ly\( \alpha \) lines at \( z \lesssim 0.11 \) via Ly\( \beta \) absorption. Additionally, O \( \text{vi} \lambda \lambda \lambda 1032, 1038 \) and C \( \text{iii} \lambda 977 \) absorbers are found only in FUSE data at \( z < 0.10 \) and \( z < 0.16 \), respectively. Thirty-seven FUSE exposures were retrieved from the archive and processed in the usual manner (Danforth & Shull

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1 See http://casa.colorado.edu/~danforth/costools.html for our co-addition and flat-fielding algorithm and additional discussion.
Figure 2. More detailed view of the COS/G130M+G160M dataset smoothed by 7 pixels (approximately one resolution element). Error is shown in gray. Prominent ISM lines are marked with plus signs. IGM Lyα absorbers are marked with large vertical ticks. Smaller ticks denote corresponding Lyβ detections. IGM metal absorbers are marked with open circles. The two question marks denote the ambiguous features discussed in Section 3. See Table 1 for line identifications and measurements.
The final FUSE spectrum covers $\lambda = 905$–1187 Å with S/N $\approx 7$–10 per $\sim 20$ km s$^{-1}$ resolution element.

### 3. ABSORPTION LINES

An analysis of the spectrum reveals a wealth of far-UV absorption features (Figures 1 and 2). Many of these are clearly Galactic ISM lines typical of most sight lines to Galactic and extragalactic sources. We label the remainder as redshifted IGM absorbers. To identify these lines, we follow a procedure similar to that employed in DS08: starting from the long-wavelength end of the spectrum, we interactively mark the strongest absorption features, tentatively identifying them as Ly$\alpha$. Our past experience with far-UV spectra leads us to set a minimum significance level for an absorption line detection without any a priori knowledge of a systemic redshift at $\sim 10\sigma$ (DS08). Once an absorber redshift is established (usually via a $\gtrsim 10\sigma$ Ly$\alpha$ detection), the location of the corresponding Ly$\beta$ absorption is then checked, as are those of prominent metal-ion absorbers (O vi $\lambda\lambda$1032, 1038; C iv $\lambda\lambda$1548, 1550; Si iii $\lambda$1207; C ii $\lambda$977, etc.).

For systems with multiple Lyman-line detections, curves of growth (CoG) were used to find $N_{H1}$, $b_{HI}$ solutions and these are noted in Table 1. For complete details on our methodology, we refer the reader to Danforth et al. (2006). In total, we identify 42 IGM absorbers, 41 of which are detected in at least Ly$\alpha$. Corresponding higher-order Lyman line and/or metal ion absorption is seen in 15 absorbers. Seven systems show metal absorption. The observed Ly$\alpha$ absorber frequency per unit redshift, $dN/dz \approx 87 \pm 15$ down to a limiting equivalent width of 50 mÅ ($\sim 10^{13}$ cm$^{-2}$), is similar to that found for the larger DS08 sample to the same limit ($dN/dz = 95 \pm 5$).

We note two significant absorption features at 1197.25 Å and 1645.9 Å with highly ambiguous identifications. The feature at 1197.25 Å ($W_{obs} \approx 50$ mÅ) cannot be Ly$\alpha$ since it is blueshifted from $\lambda_{rest}$ by $\Delta \lambda \sim 4500$ km s$^{-1}$; nor is it consistent with Ly$\beta$ at $z = 0.1672$, Ly$\gamma$ at $z = 0.2311$, or Ly$\delta$ at $z = 0.2606$. The feature is not identifiable as any metal-ion absorber for any of the known IGM systems. The most plausible identification is that of O vi $\lambda$1032 at $z = 0.1538$ (Figure 3). The stronger $\lambda$1032 line of the O vi doublet is blended with Galactic Si ii $\lambda$1190. No H i absorption is seen at this redshift in Ly$\beta$ and a 4$\sigma$ upper limit on the column-density can be set at $log N_{HI} < 13.81$. Ly$\alpha$ absorption at this redshift is blended with the weaker line of the Galactic Si iv doublet at 1403. However, the Galactic Si iv lines appear in the expected 2:1 ratio, leaving little room for additional blended Ly$\alpha$ $z = 0.1538$ absorption. It appears possible that this is a warm-hot intergalactic medium (WHIM; $T = 10^8$–$10^9$ K) absorber with high enough temperature and metallicity that no neutral gas is seen (see also Savage et al. 2010).

The strong absorption line at 1645.9 Å ($W_{obs} \approx 357$ mÅ) could be identified as Ly$\alpha$ at $z = 0.3539$, but the expected Ly$\beta$ absorber ($W_{obs} \geq 50$ mÅ) is not seen (Figures 4(a) and 4(b)). The line is consistent with being Ly$\beta$ absorption at $z = 0.6046$, and an equivalent Ly$\gamma$ feature is seen at 1560.3 Å at approximately the expected strength (Figures 4(a) and 4(c)). However, the latter feature is consistent with Galactic C i absorption lines seen elsewhere in the data (Figures 4(d)–4(f)). Therefore, we tentatively identify this feature as a multi-component Ly$\alpha$ system at $z = 0.3539$. Two or more Ly$\beta$ features of the required strengths can plausibly be hidden in the noise at the required location.

### 4. RESULTS AND DISCUSSION

#### 4.1. Triple Absorber Complex at $z = 0.188$

The most interesting of the previously undiscovered IGM absorption systems is the triplet of metal-rich absorbers at $z = 0.18640, 0.18773$, and 0.18989 (Figure 5). In Ly$\alpha$, the strong central absorber at $z = 0.18773$ is flanked by two weaker components at $z = 0.18640$ and $z = 0.18989$, or $v = -399$ km s$^{-1}$ and $v = +648$ km s$^{-1}$, respectively, relative to the system at $z = 0.18773$.

The three absorption systems at $z \sim 0.188$ span $\sim 1000$ km s$^{-1}$ in comoving velocity space, typical of the
### Table 1

Intergalactic Line Detections Sorted by Absorber Redshift

| $z_{\text{abs}}$ | Line | $\lambda_{\text{abs}}$ (Å) | $W_I$ (mÅ) | $b$ (km s$^{-1}$) | $\log N$ | Method* | Notes |
|------------------|------|-----------------------------|------------|-----------------|---------|---------|-------|
| 0.00717          | Lyα  | 1224.4                      | 108 ± 12   | 35 ± 4          | 13.37 ± 0.04 | Voigt   | O VI $z = 0.187$ BLEND |
| 0.02386          | Lyα  | 1244.7                      | 54 ± 8     | 19 ± 4          | 13.07 ± 0.05 | Voigt   |       |
| 0.03254          | Lyα  | 1255.2                      | 24 ± 8     | 13 ± 7          | 12.70 ± 0.10 | Voigt   |       |
| 0.04012          | Lyα  | 1264.4                      | 215 ± 9    | 27 ± 3          | 13.86 ± 0.02 | Voigt   |       |
| 0.04281          | Lyα  | 1267.7                      | 135 ± 14   | 73 ± 7          | 13.44 ± 0.04 | Voigt   |       |
| 0.04498          | Lyα  | 1270.3                      | 275 ± 10   | 47 ± 2          | 13.87 ± 0.01 | Voigt   | Asymmetric |
| 0.05094          | Lyα  | 1277.6                      | 84 ± 9     | 17 ± 3          | 13.32 ± 0.04 | Voigt   |       |
| 0.07832          | Lyα  | 1310.9                      | 58 ± 10    | 24 ± 6          | 13.09 ± 0.06 | Voigt   | Weak   |
| 0.09481          | Lyα  | 1330.9                      | 176 ± 9    | 30 ± 2          | 13.67 ± 0.02 | Voigt   |       |
| 0.10230          | Lyα  | 1340.0                      | 360 ± 4    | 52 ± 1          | 14.12 ± 0.03 | AOD     | BLA?   |
| 0.12040          | Lyα  | 1362.0                      | 32 ± 7     | 21 ± 9          | 12.85 ± 0.07 | AOD     |       |
| 0.12325          | H1   | ...                         | 77 ± 17    | 81 ± 16         | 13.18 ± 0.07 | Voigt   | Weak, broad |
| 0.15380          | Si ii 1038 | 1197.2                      | 50 ± 9     | 26 ± 6          | 13.95 ± 0.06 | Voigt   | Tentative |
| 0.16540          | Lyα  | 1416.7                      | 35 ± 9     | 40 ± 11         | 12.83 ± 0.03 | Voigt   |       |
| 0.18640          | Lyα  | 1442.2                      | 139 ± 7    | 32 ± 2          | 13.52 ± 0.02 | Voigt   |       |
| 0.18773          | Lyα  | 1443.8                      | 293 ± 8    | 50 ± 1          | 13.89 ± 0.01 | Voigt   | Double |
| 0.21455          | Lyα  | 1509.3                      | 242 ± 10   | 36 ± 2          | 13.84 ± 0.02 | Voigt   |       |
| 0.21640          | Lyα  | 1478.8                      | 87 ± 14    | 46 ± 7          | 13.25 ± 0.05 | Voigt   |       |
| 0.23559          | Lyα  | 1502.1                      | 20 ± 7     | 12 ± 8          | 12.62 ± 0.12 | Voigt   |       |
| 0.32235          | Lyα  | 1607.4                      | 190 ± 4    | 34 ± 4          | 13.73 ± 0.04 | Voigt   |       |
| 0.35123          | Lyα  | 1356.3                      | 55 ± 9     | 38 ± 7          | 13.92 ± 0.06 | Voigt   |       |

*Notes:
- AOD: Absorption Line Detection
- Voigt: Voigt profile
- Weak: Weak absorption
- Strong, multi-component?: Strong, multi-component absorption
- Tentative: Tentative detection
- OVI: Oxygen VI
- Si: Silicon
- N: Nitrogen
- C: Carbon
- Tentative: See Section 3, Figure 3
Table 1
(Continued)

| \(\zeta_{\text{abs}}\) | Line | \(\lambda_{\text{obs}}\) (Å) | \(W_t\) (mÅ) | \(b\) (km s\(^{-1}\)) | \(\log N\) | Method\(^a\) | Notes |
|---|---|---|---|---|---|---|---|
| 0.35390 | Ly\(\alpha\) | 1645.8 | 235 ± 21 | ~ 79 | 13.73 ± 0.03 | AOD | Tentative; see Section 3, Figure 4 |
| 0.35650 | Ly\(\alpha\) | 1648.9 | 170 ± 14 | 43 ± 4 | 13.60 ± 0.03 | Voigt |
| | Ly\(\beta\) | 1391.4 | 31 ± 9 | 28 ± 9 | 13.66 ± 0.10 | Voigt |
| | H\(\text{I}\) | ... | ... | 28+14/−12 | 13.66+0.06/−0.15 | CoG | Poorly constrained |
| 0.37884 | Ly\(\alpha\) | 1676.1 | 136 ± 19 | 47 ± 6 | 13.47 ± 0.06 | Voigt |
| | Ly\(\beta\) | 1414.3 | 23 ± 5 | 15 ± 5 | 13.55 ± 0.08 | Voigt |
| | H\(\text{I}\) | ... | ... | 27+14/−13 | 13.54 ± 0.12 | CoG | Poorly constrained |
| 0.39505 | Ly\(\alpha\) | 1695.8 | 278 ± 18 | 57 ± 4 | 13.84 ± 0.02 | Voigt | Multiple components |
| | Ly\(\beta\) | 1430.8 | 38 ± 1 | ~ 54 | 13.76+0.05/−0.07 | AOD | Broad, multi-component |
| | O\(\text{vi}\) 1032 | 1439.6 | 57 ± 6 | 31 ± 4 | 13.71 ± 0.04 | Voigt |
| | O\(\text{vi}\) 1038 | 1447.5 | 27 ± 4 | 23 ± 5 | 13.69+0.08/−0.09 | AOD |
| 0.40630 | Ly\(\alpha\) | 1709.6 | 59 ± 5 | 29 ± 2 | 13.13+0.06/−0.11 | AOD | Weak |
| 0.43261 | Ly\(\alpha\) | 1741.5 | 89 ± 6 | 32 ± 2 | 13.31+0.07/−0.05 | AOD | Noisy |

Notes.

\(^a\) Measurement method employed: “AOD,” apparent optical depth; “Voigt,” profile fitting with single or multiple Voigt functions convolved with instrumental line spread function; “CoG,” curve of growth \(b_{\text{HI}}, N_{\text{HI}}\) solution to multiple H\(\text{I}\) Lyman lines.

\(^b\) Measurement based on FUSE data.

Figure 4. Broad feature at 1645.9 Å (panel (a)) is interpreted as Ly\(\alpha\) at \(z = 0.3539\). However, the expected Ly\(\beta\) feature (panel (b)) is not seen in the data. If the 1645.9 Å feature is instead interpreted as Ly\(\beta\) at \(z = 0.6046\), a feature of approximately the correct strength is seen at 1560.3 Å, the location of the expected Ly\(\gamma\) at \(z = 0.6046\) (panel (c)). However, the 1560.3 Å feature is consistent with Galactic C I absorption (dashed profile in panels (d)–(f)). We conclude that the 1645.9 Å feature is most likely a multi-component Ly\(\alpha\) absorber at \(z \approx 0.3539\), but the individual components are too weak to appear in Ly\(\beta\).

velocity dispersion of galaxies in a large-scale filament in the cosmic web. We searched the SDSS Data Release 7 galaxy redshift catalog (Abazajian et al. 2009) for galaxies within 1° of the 1ES 1553+113 sight line and plotted them as a function of
redshift (Figure 6, top panel). While the SDSS is complete only in the brightest galaxies \((L \geq 3 L^*)\) at this redshift, a clear concentration appears at \(z = 0.187 \pm 0.003\). The median redshift of the galaxy sample is \(z = 0.187\) and the 1σ deviation \((\sigma_z = 0.0027)\) is roughly one-third of the redshift range of the search space \((\Delta z = \pm 0.008\), denoted by vertical dotted lines in Figure 6, top panel\). This tight clustering of galaxy redshifts around the IGM absorber redshift, as well as the observed spatial distribution of the brightest galaxies (Figure 6, bottom panel), suggests that the galaxies trace a large-scale filament in the cosmic web and that the absorption in the COS observations arises in the same structure. None of these galaxies is closer than 24' \((\sim 4.5\) Mpc at \(z = 0.188)\) to the line of sight, so it is impossible to claim a specific relationship between the metal-rich absorbers at \(z \sim 0.188\) and a particular galaxy. Deeper galaxy survey work (B. A. Keeney et al. 2010, in preparation) is complete to much lower luminosity \((L \leq 3 L^*)\) and may show a galaxy closer to the line of sight more plausibly linked to the enriched IGM gas.

O\(\text{VI}\) absorption is seen in all three systems \((\log N_{\text{OVI}} = 13.4 \pm 0.3, 14.1 \pm 0.1,\) and \(13.5 \pm 0.1\), respectively). Strong N\(\text{V}\) absorption is seen in the central component \((\log N_{\text{NV}} = 13.7 \pm 0.1)\). DS08 measure \((\log N_{\text{NV}}/N_{\text{OVI}}) = 0.24^{+0.22}_{-0.12}\) in 11 O\(\text{VI}+\text{NV}\) low-\(z\) IGM absorbers, so the ratio observed at \(z = 0.18773\) toward 1ES 1553+113 \((N_{\text{NV}}/N_{\text{OVI}} = 0.4)\) is high but within the observed range. Because the DS08 sample is biased toward higher \(N_{\text{NV}}\) values, the observed ratio suggests an elevated N/O abundance in this absorber.

C\(\text{III}\) is detected in the central and blue components \((\log N_{\text{CIII}} = 13.25^{+0.06}_{-0.04}\) and \(12.64 \pm 0.15\), respectively), but 4σ upper limits of \(\log N_{\text{SiIV}} < 11.64\) and \(\log N_{\text{SiIII}} < 12.29\) can be placed on Si-ion absorption in all three systems. Si\(\text{II}\) \(\lambda 1260\) is tentatively detected at \(z = 0.1877\) as a pair of weak, narrow components with a total column density \(\log N_{\text{SiII}} \sim 12.1\). However, we do not detect other Si\(\text{II}\) lines, nor equivalent absorption in C\(\text{II}\) \(\lambda 1334.5\) or C\(\text{II}\) \(\lambda 1036.3\) \((\log N_{\text{CII}} \leq 12.82)\) and other singly ionized species.

It is likely that the gas in the central \(z = 0.1877\) Ly\(\alpha\) system is multi-phase in nature, with a WHIM component traced by O\(\text{VI}\) and N\(\text{V}\) and a cooler, photoionized component traced by H\(\text{I}\) and C\(\text{II}\). The “multiphase ratios” for these absorbers (Danforth & Shull 2005, 2008) are \(N_{\text{HII}}/N_{\text{OVI}} \sim 1.3\), \(\sim 0.6\), and \(\sim 0.5\) for the three main components. Typical values for absorbers with similar \(N_{\text{HII}}\) are \(\sim 0.6,\) \(\sim 2.5,\) and \(\sim 0.8\), respectively (Danforth & Shull 2005). We can use the Ly\(\alpha\) and low-ionization metal detections and upper limits to constrain metallicity and relative abundances in the photoionized gas. In particular, C\(\text{II}\) and Si\(\text{III}\) have similar ionization potentials and are often detected in the same systems. At solar abundance ratios (Asplund et al. 2009), carbon is 8.3 times more abundant than silicon, but Si\(\text{III}\) is detectable to much lower column densities than C\(\text{III}\) owing to the very strong f-value of the 1206.5 Å transition (Shull et al.)
Thus, the two ions are often seen together in photoionized IGM absorbers (DS08).

We measure $N_{\text{C}^\text{iii}}/N_{\text{Si}^\text{iii}} > 40$ in the $z = 0.1877$ absorber, an unusually high lower limit. DS08 report C iii and Si iii detections in 22 low-$z$ IGM systems with a median distribution of $N_{\text{C}^\text{iii}}/N_{\text{Si}^\text{iii}} = 8.5^{+5.5}_{-2.0}$ (1σ). In Galactic High Velocity Clouds (Fox et al. 2006; Shull et al. 2009) the ratio, $N_{\text{C}^\text{iii}}/N_{\text{Si}^\text{iii}}$, typically ranges from 5 to 20. Thus, the abnormally high ratio $\sim$40 found in these IGM absorbers is well outside the usual range. We compare our measurements with a grid of simple CLOUDY photoionization models (detailed in Danforth et al. 2006); a 400 kpc cloud is illuminated with an AGN SED. Free parameters in the model are gas density ($n_H = 10^{-6}$–$10^{-4}$ cm$^{-3}$) and metallicity ($Z/Z_\odot = 0.01$–0.3) and the intensity (photoionization parameter $U \equiv N_\gamma/n_H = 10^{-5}$–1) and spectral index ($\alpha = 1.0$–3.0) of the SED. Relative column densities of C iii and Si iii are fairly insensitive to photoionization parameter. Typical model ratios are $(N_{\text{C}^\text{iii}}/N_{\text{Si}^\text{iii}}) \sim 10$ in the expected range of IGM photoionization parameters ($U \sim 10^{-2}$) and are largely insensitive to assumptions about metallicity, photon continuum, and gas density.

The unusually high C iii/Si iii ratio suggests that the C/Si abundance in this system may have a strongly non-solar abundance pattern. If $N_{\text{Si}^\text{iii}}$ is typically $\sim 10\%$ of $N_{\text{C}^\text{iii}}$, as seen in the CLOUDY models (where solar abundance ratios are assumed) as well as other IGM observations, [C/Si] $> 0.6$, or greater than four times the solar value. Comparing the observed $N_{\text{C}^\text{iii}}/N_{\text{H}^\text{i}}$ ratio with the models, we expect log $(N_{\text{C}^\text{iii}}/N_{\text{H}^\text{i}}) \lesssim -1.7$ for $Z = 0.1 Z_\odot$. However, the observed column density ratio is an order of magnitude higher, suggesting that (C/H) is close to solar values in this system. Without additional low-ionization species detected, we cannot determine whether carbon is over-abundant or silicon is underabundant relative to the solar ratio. The C iii detection at $z = 0.1864$ is factor of 4 weaker than in the main absorber, while the upper limit on $N_{\text{Si}^\text{iii}}$ is the same. Therefore, this system puts weak constraints on the metallicity and abundances in this absorber.

Although $N_{\text{C}^\text{iii}}$ = 8.3 ± 1.2 in the Sun (Asplund et al. 2009), variations in this abundance ratio can occur, depending on the youth of the stellar population and its initial mass function (IMF). Carbon is produced primarily by helium burning in intermediate-mass stars (red giants, horizontal branch), whereas silicon arises from more advanced α-process nucleosynthesis in massive stars. The usual abundance trends show enhanced (Si/C) and reduced (N/O) in low-metallicity stellar populations (McWilliam 1997; Cayrel et al. 2004). Theoretical predictions (Woosley & Weaver 1995) show that $[\alpha/\text{Fe}]$ increases with increasing progenitor mass (here, α includes O, Mg, Si, S, Ca, Ti). Thus, a low Si and O abundance compared to C and N suggests an IMF skewed toward low-mass stars.

Comparing H i or C iii to high ions O iv and N v requires them to be in the same thermal phase for a meaningful analysis. Hybrid ionization modeling (CIE plus photoionization) of the high ions in this system is reported by Yao et al. (2010), in which the $z = 0.1877$ system is used as a test case for a physical parameter-based absorption-line modeling exercise.

4.2. Constraining the Redshift of 1ES 1553+113

The redshift of 1ES 1553+113 is crucial to determining the intrinsic properties of the source. Indirect methods of constraining the redshift of 1ES 1553+113 fall into two categories. First, the ratio of AGNs to host galaxy optical luminosity in BL Lacs is thought to cover a fairly small range (Wurtz et al. 1996; Sbarufatti et al. 2005). Various deep ground-based (Hutchings & Neff 1992; Scarpa et al. 2000) and space-based (Urry et al. 2000; Carangelo et al. 2003; Sbarufatti et al. 2006; Treves et al. 2007) optical studies have failed to detect a host galaxy beneath the glare of the AGN. From these non-detections, redshift limits from $z > 0.09$ to $z > 0.78$ have been set by various groups. Treves et al. (2007) refined this to $z = 0.3$–0.4 using a more sophisticated analysis of the same optical data. However, the validity of the assumption of host/nuclear luminosity relationship has been called into question by O’Dowd & Urry (2005).

A complementary technique uses the observed VHE spectrum (0.1–10 GeV) to place limits on the redshift of BL Lacs. This method assumes that the VHE SED of an object will be modified, as TeV photons interact with photons in the ambient extragalactic background and produce $e^+e^-$ pairs (e.g., Younger & Hopkins 2010; Persic & De Angelis 2008). The longer the
pathlength, the steeper the VHE SED becomes. Uncertainties in the extragalactic IR background and the intrinsic SED of the AGN render this method uncertain, but the redshift of 1ES 1553+113 has variously been constrained to $z < 0.74$ (Aharonian et al. 2006; Albert et al. 2007) or $z < 0.80$ or $z < 0.42$ (Mazin & Goebel 2007) based on HESS and MAGIC observations. Abdo et al. (2010) use data from the first 6 months of Fermi γ-ray observations in conjunction with observations from radio wavelengths to 1 TeV to model the intrinsic SED of 1ES 1553+113. Based on these models, they determine a redshift $z = 0.75_{-0.04}^{+0.05}$. The error bars on this estimate appear to be much smaller than justified by this method.

From Figures 1 and 2, it is clear that there are Hα systems throughout the redshift range from $z \approx 0$ to near the end of the COS spectral coverage ($z = 0.47$). A strong line at 1695 Å is identified as Lyα at $z = 0.395$ and confirmed by detection of O VI at the same redshift in both lines of the doublet. This sets a firm lower limit on $z_{\text{em}} > 0.395$. Two weaker features at 1709.5 Å and 1741.5 Å appear in the data, which we identify as Lyα at $z = 0.4063$ and $z = 0.4326$, respectively. Though we do not detect higher-order Lyman or metal-ion lines at these redshifts, the two $z > 0.4$ Lyα absorbers are weak enough that we do not expect confirmation in other lines. The continuum of the BL Lac object remains smooth across the entire COS band (Figures 1 and 2), and no intrinsic emission or absorption is seen.

Thus, we can confidently constrain the emission redshift of 1ES 1553+113 to $z_{\text{em}} > 0.400$ and it may be as high as $z_{\text{em}} = 0.433$. Additional COS observations may detect corresponding Lyβ absorption to these two $z > 0.4$ absorbers ($W_{\text{Ly}\beta} \sim 12$ mÅ is expected). The confirmed and unconfirmed direct redshift limits from the HST/COS observations are compatible with both the lower limits set by the non-detection of an optical host galaxy ($z_{\text{em}} \gtrsim 0.1$–0.4; Urry et al. 2000; Sharufatti et al. 2006; Treves et al. 2007) and the VHE SED upper limits ($z_{\text{em}} \lesssim 0.8$; Aharonian et al. 2006; Albert et al. 2007; Mazin & Goebel 2007).

Figure 7 shows the observed and predicted distribution of IGM absorbers as a function of redshift. We calculate the expected number of IGM systems as $N_{\text{abs}} \propto (1+z)^7$, the expected number of IGM systems rises by $\sim 20$–$50\%$ at higher redshifts (dotted curve). At $z > 0.47$ (shaded region), Lyα absorbers can no longer be detected in the COS far-UV band and we must rely on much less sensitive Lyβ detections. As discussed in the text, no $z > 0.4$ Lyβ absorbers are detected.

We now assess the validity of the most recent VHE SED redshift estimate ($z_{\text{em}} = 0.75_{-0.04}^{+0.05}$) from Abdo et al. (2010). Our current COS far-UV spectra (G130M and G160M) are only sensitive to Lyα absorbers at $z < 0.47$. However, higher redshift absorbers can be detected using the less sensitive higher-order Lyman lines or O VI doublet. COS far-UV data cover the wavelength range 1135 Å < $\lambda < 1795$ Å corresponding to Lyβ redshifts $0.11 < z < 0.75$ and O VI redshifts $0.10 < z < 0.74$. Lyβ and O VI systems at $z > 0.47$ will appear at $\lambda \gtrsim 1508$ Å. We find empirically (DS08) that the detection threshold for absorption lines with no prior “signposts” (such as known absorber redshifts) is $\sim 10\sigma$. The COS/G160M data in this region are of sufficiently high quality that we would expect to detect lines of $W_{\text{obs}} \gtrsim 50$ mÅ at a $\sim 10\sigma$ significance level. This corresponds to rest-frame $W_r \gtrsim 30$ mÅ ($\log N_{\text{HI}} \gtrsim 13.6$) for Lyβ absorbers at $z \sim 0.5$.

Figure 7 shows the observed and predicted distribution of IGM absorbers as a function of redshift. We calculate the expected number of absorbers $N_{\text{abs}}$ per $dz = 0.025$ bin (alternately, $dN/dz$) based on the S/N-determined minimum equivalent width in each bin and the sample of $\sim 650$ H1 absorbers from DS08. The dashed curve in the figure represents no $dN/dz$ evolution with redshift. The evolution of low-$z$ H1 absorbers is somewhat uncertain. However, if we assume that the H1 absorber frequency evolves as $(dN/dz)_{H1} \propto (1+z)^{\gamma}$ (Penton et al. 2004) and adopt $\gamma \approx 0.7$ for a modest evolution between $z = 0$ and $z \sim 1$, the expected number of H1 detections (dotted curve in Figure 7) rises at higher redshift by $\sim 20$–$50\%$. The sharp drop in expected detections at $z > 0.47$ coincides with the switch from Lyα to Lyβ as an IGM tracer (shaded area) and the resulting loss of sensitivity discussed above. Summing the expected number of Lyβ absorbers ($N_{\text{abs,exp}}$) from Figure 7 over the range $0.47 < z_{\text{obs}} < 0.75$, we find $N_{\text{abs,exp}} \approx 7$ and $N_{\text{abs,exp}} \approx 9$ in the constant and evolved H1 models, respectively. Thus, we should expect $\sim 8$ high-$z$ Lyβ absorbers in the 1ES 1553+113 data if $z_{\text{em}} \gtrsim 0.75$. 

![Figure 7](image_url)
Are the predicted high-\(z\) Ly\(\beta\) absorbers seen? As discussed in Section 3, the strong feature at 1645.9 Å can be ruled out as Ly\(\beta\) at \(z = 0.6046\) since the corresponding Ly\(\gamma\) line is consistent with Galactic C\(\text{ii}\) (Figure 4). Thirteen other absorption features longward of 1508 Å have been identified as Ly\(\alpha\) lines and eight of these identifications are not confirmed with higher-order Lyman or metal-ion lines. If these eight single-line detections are instead interpreted as potential high-\(z\) Ly\(\beta\) systems, six have inconsistent Ly\(\gamma\) non-detections and a seventh has Ly\(\gamma\) blended with another line. The only possible high-\(z\) Ly\(\beta\) absorber is a marginal line detected at 1584.3 Å and identified as Ly\(\alpha\) at \(z = 0.30328\). If this line is instead identified as Ly\(\beta\) at \(z = 0.54463\), the corresponding Ly\(\gamma\) absorber should be at 1502.2 Å, nearly coincident with a weak feature identified as Ly\(\alpha\) at \(z = 0.23559\). The relative strengths of the two features are consistent with H\(\text{I}\) absorbers at \(z = 0.54463\), but both line detections are of relatively low significance. Additional COS observations may improve the significance of the line detections. However, we find none of the other predicted high-\(z\) H\(\text{I}\) or O\(\text{vi}\) absorbers in the data, so the \(z_{\text{em}} > 0.545\) redshift limit from the possible Ly\(\beta\) detection for IES 1553+113 is very speculative.

We constrain the source redshift of IES 1553+113 statistically by truncating the \(N_{\text{abs}}\) expected model curves in Figure 7 at a range of \(0.4 < z_{\text{em}} < 0.75\). Applying a Kolmogorov–Smirnov test to the different models, we set a \(1\sigma\) constraint of \(z_{\text{em}} \leq 0.58\) for the non-evolved model (and \(z_{\text{em}} \leq 0.49\) for the evolved H\(\text{I}\) distribution). An emission redshift of \(<0.75\) is ruled out for both models at a 90% or greater level of confidence. Thus, we constrain the redshift of IES 1553+113 to the range \(0.43 < z_{\text{em}} \leq 0.58\).

5. CONCLUSIONS AND FUTURE WORK

The BL Lac object IES 1553+113 is one of the brightest objects in the sky in \(\gamma\)-rays, as well as being a notable UV and X-ray source. However, the AGN emission is that of a relativistic jet aligned closely with our line of sight and, like most such objects, has no intrinsic emission or absorption features at any wavelength. This featureless, power-law continuum is ideal for measuring intervening IGM features that are weak and broad, such as thermally broadened Ly\(\alpha\) systems. However, the lack of intrinsic features makes constraining the redshift of the object difficult.

We present unprecedented high-quality far-UV \(HST/\)COS spectra of IES 1553+113 at spectral resolution 15–20 km s\(^{-1}\). These data show 42 intervening IGM absorbers, 41 of which are detected in Ly\(\alpha\), and 15 in Ly\(\beta\) and/or metal lines. The richest absorption system in the line of sight is a trio of Ly\(\alpha\) absorbers at \(z \approx 0.188\) covering \(\sim 1000\) km s\(^{-1}\) of velocity space. Several metal ions are also detected in these systems, including O\(\text{v}\), N\(\text{v}\), and C\(\text{iii}\). However, neither Si\(\text{iv}\) nor Si\(\text{ii}\) is detected in any of the systems. The C\(\text{iii}/\)Si\(\text{ii}\) ratio implies a (C/Si) abundance at least four times the solar value, while a high N\(\text{v}/\)O\(\text{v}\) value suggests an overabundance of N as well. A detailed analysis of the physical conditions in this system can be found in Yao et al. (2010).

The redshift of IES 1553+113 has never been determined directly, and the only limits placed on it come from indirect means such as the shape of the \(\gamma\)-ray spectrum and the lack of an AGN host galaxy in deep optical images. A strong Ly\(\alpha\)+O\(\text{vi}\) absorber at \(z = 0.3951\) gives the first direct lower limit to the redshift of the object. Two weaker Ly\(\alpha\) absorbers at \(z = 0.4063\) and \(z = 0.4326\) give slightly higher estimates of the redshift, but these weak Ly\(\alpha\) lines are not confirmed by additional line detections.

These lower limits are consistent with most previous measurements via optical non-detections of host galaxies and \(\gamma\)-ray SED constraints. Abdo et al. (2010) derive \(z_{\text{em}} = 0.75^{+0.04}_{-0.05}\) based on the latest \(Fermi\) \(\gamma\)-ray SED measurements, considerably higher than our intervening absorber upper limits. COS far-UV spectra are not sensitive to Ly\(\alpha\) absorbers at \(z > 0.47\), but the G160M grating has some sensitivity to intervening Ly\(\beta\) and O\(\text{vi}\) absorbers out to \(z \sim 0.75\). If the Abdo et al. (2010) redshift estimate were accurate, we would expect to find \(<8\) Ly\(\beta\) absorbers at \(0.47 < z < 0.75\). We find no evidence for any higher redshift absorption systems, and only a few absorption features at \(\lambda > 1500\) Å with ambiguous line identifications that could potentially be Ly\(\beta\) systems at \(z > 0.47\). While these systems are individually suggestive, we find nowhere near the number of absorbers predicted statistically. We conclude that the redshift of IES 1553+113 is not much higher than \(z \approx 0.45\).

These observations showcase the powerful new tool available to astronomers for probing the low-redshift IGM. In the far-UV, COS is 10–20 times more sensitive to point sources than previous instruments on \(HST\). An additional six orbits of COS observations are planned for \(HST\) Cycle 18 (2010/11), which should improve the S/N of the combined dataset by a factor of \(\sim 1.7\). Improved S/N, as well as our evolving understanding of the COS instrumental effects, will enable us to reliably measure low-contrast absorbers such as broad (\(b > 40\) km s\(^{-1}\)) Ly\(\alpha\) systems and weak metal lines, and place further constraints on [C/Si] and [N/O] in the \(z = 0.188\) system. Improved S/N will lower the minimum detectable line strength for potential Ly\(\beta\) absorbers at \(z > 0.47\) by a similar factor and improve the estimates of \(z_{\text{em}}\).

Extending the spectral coverage to 1800 Å \(\lambda < \lambda < 2100\) Å (0.47 \(\leq z_{\text{abs}} \leq 0.73\) in Ly\(\alpha\)) with the COS/G185M grating would be more efficient at detecting \(z > 0.47\) IGM absorbers. Despite the relatively lower efficiency of the COS near-UV gratings and detectors compared with their far-UV counterparts, the Ly\(\alpha\) lines will be \(\sim 3–7\) times stronger than Ly\(\beta\) and should easily be detected or ruled out with only a few kiloseconds of observations.

Finally, IES 1553+113 is one of the brightest X-ray sources on the sky and has been proposed as a sight line that could be efficiently probed for WHIM absorption in O\(\text{vii}\). The combined O\(\text{v}\) volume column density in the three absorbers at \(z \approx 0.19\) is \(\sim 2 \times 10^{14}\) cm\(^{-2}\). Spectrographs on modern X-ray observatories are sensitive to log \(N_{\text{Ovii}} < 15.5\) (Yao et al. 2009). If the temperature of any of these O\(\text{vii}\) systems is high enough, sufficiently long \(Chandra\) and/or \(XMM/\)Newton observations may reveal a O\(\text{vii}\) counterpart that could constrain the long-sought X-ray WHIM (Bregman 2007). However, at the observed Li-like (O\(\text{v}\)) oxygen column density, log \(N_{\text{Ov}} \approx 14.3\) in the trio of absorbers, the expected column densities of He-like (O\(\text{vii}\)) and H-like (O\(\text{viii}\)) oxygen are probably just below the detectability levels of \(Chandra\) and \(XMM\). Recent analysis of stacked X-ray absorption data (Yao et al. 2009) at the known IGM redshifts of O\(\text{v}\) absorbers finds no evidence for O\(\text{vii}\) or O\(\text{viii}\) absorbers to a limit \(N_{\text{Ovii}}/N_{\text{Ov}} < 10\). Therefore, the \(z \approx 0.19\) absorbers might have X-ray column densities log \(N_{\text{Ov}} \approx 15.3\), just below the limits of current X-ray observatories.

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