STUDYING THE WHIM CONTENT OF LARGE-SCALE STRUCTURES ALONG THE LINE OF SIGHT TO H 2356-309

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ABSTRACT

We make use of a 500 ks Chandra HRC-S/LETG spectrum of the blazar H 2356-309, combined with a lower signal-to-noise ratio (S/N; 100 ks) pilot LETG spectrum of the same target, to search for the presence of warm-hot absorbing gas associated with two large-scale structures (LSSs) crossed by this sight line and to constrain its physical state and geometry. Strong (log $N_{\text{O}}$ $\geq$ $10^6$ cm$^{-2}$) O vi absorption associated with a third LSS crossed by this line of sight (the Sculptor Wall (SW)), at $z = 0.03$, has already been detected in a previous work. Here, we focus on two additional prominent filamentary LSSs along the same line of sight, one at $z = 0.062$ (the Pisces-Cetus Supercluster (PCS)) and another at $z = 0.128$ (the “Farther Sculptor Wall” (FSW)). The combined LETG spectrum has an S/N of ~11.6–12.6 per resolution element in the 20–25 Å and an average 3σ sensitivity to intervening O vii Ka absorption line equivalent widths (EWs) of EW$_{\text{O} \text{vii}}$ $\geq$ 14 mÅ in the available redshift range ($z < 0.165$). No statistically significant (i.e., $>3\sigma$) individual absorption is detected from any of the strong He- or H-like transitions of C, O, and Ne (the most abundant metals in gas with solar-like composition) at the redshifts of the PCS and FSW structures and down to the EW thresholds mentioned above. However, we are still able to constrain the physical and geometrical parameters of the putative absorbing gas associated with these structures, by performing a joint spectral fit of various marginal detections and upper limits of the strongest expected lines with our self-consistent hybridization WHIM spectral model. At the redshift of the PCS, we identify a warm phase with log $T = 5.35^{+0.07}_{-0.13}$ K and log $N_{\text{H}} = (19.1 \pm 0.2)$ cm$^{-2}$ possibly co-existing with a much hotter and statistically less significant phase with log $T = 6.9^{+0.1}_{-0.3}$ K and log $N_{\text{H}} = 20.1^{+0.5}_{-1.3}$ cm$^{-2}$ (1σ errors). These two separate physical phases are identified through, and mainly constrained by, C v Ka (warm phase) and O viii Kσ (hot phase) absorption, with single line significances of 1.5σ each. For the second LSS, at $z \simeq 0.128$, only one hot component is hinted in the data, through O viii Kσ (1.6σ) and Ne ix Kσ (1.2σ). For this system, we estimate log $T = 6.6^{+0.1}_{-0.3}$ K and log $N_{\text{H}} = 19.8^{+0.4}_{-0.3}$ cm$^{-2}$. Our column density and temperature constraints on the warm-hot gaseous content of these two LSSs, combined with the measurements obtained for the hot gas permeating the SW, allow us to estimate the cumulative number density per unit redshifts of O vii WHIM absorbers at three different EW thresholds of 0.4 mÅ, 7 mÅ, and 25.8 mÅ. This is consistent with expectations only at the very low end of EW thresholds, but exceeds predictions at 7 mÅ and 25.8 mÅ (by more than 2σ). We also estimate the cosmological mass density of the WHIM based on the four absorbers we tentatively detect along this line of sight, obtaining $\Omega_{\text{WHIM}} = (0.021^{+0.031}_{-0.018} (Z/Z_{\odot})^{-1}$, consistent with the cosmological mass density of the intergalactic “missing baryons” only if we assume high metallicities ($Z \sim Z_{\odot}$). 

Key words: intergalactic medium – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

Cosmological hydrodynamical simulations predict the gradual formation of a local ($z < 1$) web of low density ($n_b = 10^{-6}$–$10^{-5}$ cm$^{-3}$), warm-hot ($T = 10^6$–$10^7$ K) intergalactic gas, connecting virialized halos (i.e., galaxies, galaxy groups, and clusters of galaxies), permeating the large-scale structures (LSSs) of which these systems are constituents, and ultimately providing the necessary fuel for their continuous growth (Cen et al. 1995; Cen & Ostriker 1999; Davé et al. 2001; Cen & Ostriker 2006). This low-redshift intergalactic gas is largely the same primordial gas present at redshifts higher than ~2 in a cool photoionized phase (the so-called Lyα Forest), but in a much hotter and metal-enriched phase, because of efficient shock-heating during the continuous process of LSS assembly and growth in a nonlinear universe and of strong feedback with the same structures for which it provides building blocks. Due to its high temperatures, this intergalactic medium (IGM) phase has been dubbed warm-hot intergalactic medium (WHIM).

Electrons and baryons in the WHIM are shock-heated during their infall in the dark matter LSS potential well and settle in filamentary/sheet-like structures surrounding LSSs. Such matter is predicted to account for a sizable fraction (~50%) of all the baryons in the local ($z < 1$) universe, and it is thus considered the best candidate to host the baryons seen at high redshift and missing from the low-redshift census (Fukugita et al. 1998; Fukugita & Peebles 2004).
Given its high temperature, the WHIM can only emit or absorb in the far-UV and soft X-rays, mainly through Li- to H-like metal transitions and bremsstrahlung continuum emission. However, at WHIM densities both line and continuum emission are highly depressed (due to the dependency of these mechanisms on the square power of the emitters volume densities) and on average well below the sensitivity of current instrumentations. Nonetheless, statistical techniques based on cross correlation of regions with excess diffuse X-ray emission in ROSAT, Chandra, and XMM-Newton deep exposures, with large-scale galaxy distribution, have probably already allowed the marginal detection of the density peak of the WHIM distribution (e.g., Scharf et al. 2000; Zappacosta et al. 2002, 2005; Werner et al. 2008).

A far more promising way to detect the WHIM is through resonance absorption by highly ionized metals. Intervening WHIM filaments should imprint a “forest,” i.e., the so-called X-ray Forest (Hellsten et al. 1998; Perna & Loeb 1998), by analogy with the H I Lyα Forest copiously seen at $z \gtrsim 2$, of metal absorption lines onto the spectra of bright background sources, whose strength depends only linearly on the absorber density, and is therefore less suppressed than the corresponding emission. Predicted equivalent widths (EWs) from the most abundant ions in WHIM range from 1 mÅ to $\lesssim 20$ mÅ for the densest filaments. The detection of even the strongest of such absorption lines (probing only the very high density tail of the WHIM distribution: overdensity $\delta = n_b/(n_h) \gtrsim 300$, compared to the average density of the universe: $n_b = 2 \times 10^{-7}(1+z)^3(\Omega_0 h^2/0.02)$, where $\Omega_0$ is the baryonic density parameter and $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$) is extremely challenging with the limited sensitivity ($A_{\text{eff}} < 60$ cm$^2$) and resolution ($R = E/\Delta E = 400$–800) of the current Chandra and XMM-Newton high-resolution X-ray gratings. A $3\sigma$ detection of an EW = 20 mÅ absorption line requires spectra of the background targets with $S/N \gtrsim 8$ per 50 mÅ resolution element (i.e., $\gtrsim 70$ net counts per bin). These can only be obtained for the brightest ($\sim 10^{-11}$ erg s$^{-1}$ cm$^{-2}$) soft X-ray (0.5–2 keV) targets in the extragalactic sky (preferably blazars, because of their intrinsically featureless spectra), with $\gtrsim 0.5$ Ms exposures, while in quiescence, or $\gtrsim 100$ ks exposures in outburst.

Such dense WHIM filaments are rare. According to hydrodynamical simulations, at $z \approx 0$ one expects $\lesssim 0.05$ WHIM filaments with EW(O vii Ka) $\geq 20$ mÅ, per unit redshift. The probability of having one of such filaments along a random line of sight up to $z = 0.3$ is therefore only 1.5% (Gehrels 1986), and only few filaments are found with quiescent F(0.5–2 keV) $\gtrsim 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ available (e.g., M. L. Concatoire et al. 2009, private communication). The number density of O vii WHIM absorbers per unit redshift increases by almost 2 orders of magnitude by lowering the EW(O vii Ka) detection threshold down to 2 mÅ so dramatically increasing the probability of randomly detecting one of such filaments to $P(z = 0.3) = 97.5\%$. In theory this observational strategy has the advantage of probing the bulk of the WHIM mass distribution, but requires incredibly high signal-to-noise ratio ($S/N$) spectra ($\gtrsim 75$ per resolution element with the Chandra LETG and $\gtrsim 180$ per resolution element with the XMM-Newton RGS, for a $3\sigma$ detection), obtainable only with several Ms exposures on the brightest possible $z \gtrsim 0.3$ targets in their quiescent states. Moreover, even when such high $S/N$ spectra are obtained (for example by observing background target during exceptionally high outburst; Nicastro et al. 2005a, 2005b), the clear assessment of the statistical significance of such weak 2–3 mÅ absorption lines is hampered by our limited knowledge of the instrument systematics, which is comparable to the statistical uncertainties on the line EWs (Kaastra et al. 2003; Rasmussen et al. 2007; Nicastro et al. 2008).

An alternative observational strategy is to select lines of sight where the probability of crossing dense WHIM filament is enhanced (e.g., Zappacosta 2005, 2006). WHIM gas density and metallicity is predicted (and possibly in the UV observed; Stocke et al. 2006) to correlate with LSS galaxy overdensity (Viel et al. 2005). Thus, chances of intercepting a dense WHIM filament may be improved by carefully selecting bright sources in the background of extreme filamentary LSS concentrations (Figure 1). This observational strategy has been successfully exploited recently in Buote et al. (2009), who detected a strong (EW $\sim 30$ mÅ) absorption line in two XMM-Newton RGS and Chandra LETG spectra of the blazar H 2356-309 ($z = 0.165$), and tentatively identified it with O vii Ka at a redshift consistent with that spanned by the intervening Sculptor Wall (SW; da Costa et al. 1988).

Here and in our companion paper (Fang et al. 2010), we report on the successful extension of this observational program. H 2356-309 has been recently re-observed with the Chandra LETG for 500 ks, as part of an approved cycle 10 GO observational program. The main goal of this deep observation was to confirm, at higher significance, the SW O vii detection (Fang et al. 2010). Secondary objectives were to confirm the presence of other (lower significance) lines from the same absorber (D. A. Buote et al. 2010, in preparation). Here, instead we focus on constraining the physical parameters of the putative WHIM gas content of two additional galaxy LSSs present along this line of sight, at $z = 0.062$ (the Pisces-Cetus Supercluster (PCS)) and $z = 0.128$ (a farther wall which we will call the Farther Sculptor Wall (FSW)). In this paper, we use all the existing Chandra LETG data of H 2356-309 to characterize the physical properties of the WHIM permeating these additional structures, and conclude by estimating the contribution of such dense gaseous component of LSSs to the WHIM cosmological mass density. In Section 2, we describe the richness of LSSs along the line of sight to H 2356-309. In Sections 3 and 4, we present the data and describe their reduction and analysis. Section 5 is devoted to a critical discussion of our findings. In Section 6, we summarize our conclusions. Throughout the paper we adopt a Λ-CDM cosmology, with $h = 0.71$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$.

2. THE LSS RICHNESS OF THE LINE OF SIGHT TO H 2356-309

Figure 1 shows the wedge diagram of the line of sight to H 2356-309 in the declination range $-33 < \delta < -29$. Galaxies (black point), clusters, and groups of galaxies (magenta circles) shown in the diagrams of Figure 1 are extracted from a number of different and non-homogeneous catalogs and galaxy surveys (including the 2dF Galaxy Redshift Survey (2dF GRS); Colless et al. 2003 and 6dF Galaxy Redshift Survey (6dF GRS); Jones et al. 2004) and are the results of a general query to the NASA/IPAC Extragalactic Database (NED).9 As such, these diagrams do not represent the complete flux-limited sample of the actual galaxy distribution along this line of sight.

Several strong LSS concentrations are clearly visible and cross the line of sight to H 2356-309 at, at least, three different

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9 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
average redshifts: $\langle z_1 \rangle = 0.03$ (the SW), $\langle z_2 \rangle = 0.062$ (the PCS), and $\langle z_3 \rangle = 0.128$ (the FSW). Both the PCS and the FSW LSSs are significantly larger than the SW and are delimited in the wedge diagram of Figure 1 by cyan dashed arcs. The two two-dimensional sky map projections on the right of the wedge diagram of Figure 1 show the R.A. versus decl. extent of these two LSSs.

The PCS (Burns & Batuski 1984; Tully et al. 1992) is one of the richest nearby ($z < 0.1$) superclusters. It is clearly visible in the Sloan Digital Sky Survey and 2dF redshift surveys as a remarkable filament of galaxies (Porter & Raychaudhury 2005). The structure intercepted by the line of sight to H2356-309 is a long filament of galaxies located on the plane of the sky at $z = 0.06–0.063$ within <1 Mpc from the projected blazar position.

The FSW is a conspicuous wall of galaxies, which originates from the Sculptor supercluster at $z = 0.11$ and stretches out to redshift $z \sim 0.135$ crossing the blazar sight line at $\Delta z = 0.127–0.129$.

### 3. OBSERVATIONS AND DATA REDUCTION

The blazar H2356-309 has been observed twice with the Chandra LETG, as part of two different observational programs. A first 100 ks LETG observation was performed in 2007 October and has been already analyzed in Buote et al. (2009). A second deeper LETG observation was carried out over the 2008 September–December period, through 10 different pointings with exposures ranging from 15 ks to 100 ks, for a total of 496.4 ks. The aim of this observation was to secure, with a conservative flux of $1.0 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ (0.5–2.0 keV), a 5$\sigma$ significant detection of an absorber with a column density of at least $9 \times 10^{15}$ cm$^{-2}$ (this is the 90% lower limit found by Buote et al. 2009) by means of a long 0.5 Ms non-ToO observation. Table 1 shows the log of the observations.

We mention that H2356-309 has also been observed with XMM-Newton for 130 ks and this observation has been analyzed in Buote et al. (2009). We will not use this observation in our analysis since (1) it adds only 70 counts in 0.06 Å (the XMM-Newton-RGS FWHM) which are $\sim 1/4$ the net counts

![Figure 1. Sky map and wedge diagram of the region of the SW where the blazar H2356-309 is located. The upper sky map refers to the FSW and the lower to the PCS. Galaxies (black point), clusters, and groups of galaxies (magenta circles) in the wall are taken from NED. The wedge diagram shows galaxies inside the dashed blue box drawn in the sky map and reports the sight line to the blazar as red dashed line. The galaxy and cluster catalogs contain objects belonging to different parent catalogs. Hence, we point out that some holes in the projected galaxy distribution are artificially caused by this non-homogeneity like the hole at northeast of the blazar position visible at R.A. = 0.1 hr and decl. = −29.5 in the PCS sky map.](Image)
all the Chandra data provide in 0.05 Å; (2) it does not reach the wavelengths of the C v transition which, as we will see in Section 4.2, characterizes the most important intervening system; and (3) it makes the analysis in Section 4.2 very complicated due to the presence of several instrumental features very close to the lines we are investigating.

3.1. Chandra Reduction

Each Chandra observation was reduced with the latest version of the Chandra Interactive Analysis of Observation software (CIAO v. 4.1.2, CALDB v. 4.1.2), following the standard processing procedures outlined in the High Resolution Camera for Spectroscopy (HRC-S)/LETG grating analysis thread and applying a recently implemented filtering procedure on the level 1 event files. This allowed us to greatly reduce the number of background counts, compared to the standard pipeline procedure, while losing only a negligible percentage of source counts, and so greatly increasing the S/N of the background subtracted source spectrum.

For each observation, we produced background light curves and inspected them visually to filter out periods of background flares. Only few observations were affected by short and mild flaring periods and their screening removed a total of just 30 ks, leaving a cleaned total 562 ks exposure.

To maximize the throughput, we used the Chandra LETG in combination with the Chandra HRC-S dispersion detector. This has virtually no spectral resolution which prevents the separation of the different spectral orders dispersed by the LETG. We extracted “all-order” negative and positive source and background spectra with the CIAO tool tg_extract. Due to the impossibility of separating HRC-LETG spectral orders, the spectral modeling of these spectra can only be performed by pre-folding the fitting models with the sum of the convolution products of the redistribution matrices (RMFs) and ancillary response files (ARFs) belonging to the first N positive and negative orders, respectively. Here, N is a number that depends on the intensity of the source, its spectral energy distribution, and the possible presence of strong spectral absorption or emission features, and has to be carefully chosen on an observation by observation base. For our LETG observations of H 2356-309, we verified that in no case high-energy photons from orders higher than 3% (0.06% at the O vii wavelength). We decided to conservatively build our final “all-order” response matrix by adding up N = 10. For each order, we used the ftools task MARFRMF to “multiply” the RMF by its corresponding ARF. This produced 10 positive and 10 negative normalized RMFs, which we then co-added with the ftools task ADDRMF.

Finally, to maximize the S/N of our spectra, for each observation we co-added negative and positive order source and background spectra (add_grating_orders task) and response files (ADDRMF).

Because of our co-adding procedure, particular care must be devoted to account for the wavelength calibration inaccuracy. An updated version of the degap polynomial coefficients based on empirical wavelength corrections from multiple HRC-S/LETG observations of Capella has been released since CALDB 3.2. This update allows the correction of the nonlinearities in the HRC-S dispersion relation improving the uncertainties across the detector from 0.014 Å to 0.010 Å (rms deviation). This uncertainty is lower at shorter wavelengths and higher at longer wavelengths. Since we have co-added positive and negative orders, we should consider a larger uncertainty. The propagation of the rms deviations gives an uncertainty of 0.014 Å. However to be conservative, we adopt 20 mÅ of uncertainty since the updated wavelength corrections have been applied to the rest-frame position of the strongest soft X-ray metal electronic transitions and the interpolation of the correction may not be strictly valid to the position of blueshifted and redshifted lines.

4. SPECTRAL ANALYSIS

We performed all our spectral analysis with the fitting package Sherpa of CIAO (v. 4.1.2). The statistics we used for our fits is the data weighted χ² with the Gehrels variance function (Gehrels 1986), the default in Sherpa. We first checked for variability of the broadband 10–50 Å continuum (flux and spectral shape) of H 2356-309 between the 11 Chandra observations. We grouped each spectrum at a minimum of 20 counts per bin and modeled each data set independently with a power law attenuated by the sight line Galactic column of neutral gas (NH = 1.44 × 10²² cm⁻²; Kalberla et al. 2005). We found that both the source spectral shape and flux varied only moderately (12% and 20%, respectively) between the ten 2008 observations: the 0.3–1 keV flux ranges within the 1.25–1.5 × 10⁻¹¹ erg s⁻¹ cm⁻² interval, while the power-law best-fitting spectral indices vary between Γ = 1.96–2.20. The 0.3–1 keV source flux during the 2007 observations is 50%–80% lower than during the 2009 observations, but the best-fitting power-law spectral index of Γ = 2.19 ± 0.06 is still in the range measured during the 2008 observations. Since both the 10–50 Å flux and spectral shape of the target varied only moderately between the different observations, and because we are interested in the search of narrow spectral features, which are not affected by broadband spectral-shape variability, we decided to co-add the HRC-S/LETG spectra of all the observations to increase the final S/N per resolution element. The resulting spectrum has ≃290 net source Counts per 50 mÅ Resolution Element (CPRE) and ∼120–160 background CPRE at 22 Å, and so an S/N ≃ 11.6–12.6 at 22 Å. This gives a theoretical 3σ sensitivity to absorption lines with EW > 12–13 mÅ at 22 Å. We grouped the data to half the nominal FWHM of LETG spectra with 25 mÅ per bin for all the subsequent analysis.

4.1. Search for Intervening Absorption Lines

Our main goal is to constrain the warm-hot gaseous content of the two filamentary galaxy structures here identified as PCS and FSW. At the expected WHIM temperatures, the most intense absorption lines are the Kα resonant transitions from He- and H-like C, O, and Ne. Table 2 lists the rest-frame wavelengths and oscillator strengths of these transitions.

A crucial condition for the search for unresolved absorption lines in intrinsically featureless spectra is the accurate subtraction of the local continuum. A visual inspection of the broad band, 10–50 Å, residuals of the co-added LETG spectrum of H 2356-309, after subtracting the best-fitting absorbed power

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10 http://cxc.harvard.edu/ciao/guides/gspec_hrcsletg.html
11 http://cxc.harvard.edu/cal/Letg/Hrc_bg/
12 http://cxc.harvard.edu/ciao/threads/hrcsletg_orders/
13 http://heasarc.gsfc.nasa.gov/lheasoft/ftools/caldb/marfrmf.html
14 http://heasarc.gsfc.nasa.gov/lheasoft/ftools/caldb/addrmf.html
15 http://cxc.harvard.edu/cal/Letg/Hrc_disp/dgap.html
law, clearly showed the presence of 1–3 Å broad systematics, particularly near or at the wavelength of the main instrumental edges of CI and OI. In general, the residuals deviated significantly from zero, in both directions, in several spectral regions. This makes the assessment of the actual significance of a possible absorption line at such wavelengths difficult. For each of the two redshifted systems (the PCS and the FSW), we therefore decided to isolate four 3–6 Å broad spectral regions, around the absorption lines of interest (Table 1), at the following rest-frame intervals: 11–14 Å (Ne x, Ne ix), 18.5–25.0 Å (O vii, O viii), 31.5–34.5 Å (C vii), and 39–42 Å (C v). We fitted each of these spectral intervals with continuum models including third-order polynomial. We then inspected visually the residuals to look for possible relatively broad 0.5–1 Å deviations (due to instrumental effects) and, when needed, added to the best-fit polynomial 0.5–1 Å broad emission or absorption Gaussian, to improve the modeling of the local continua. We iterated this procedure until we obtained a satisfactory description of all the local continua, and a visual inspection of the residuals revealed no further deviations.

Table 2

| Ion     | Wavelength (Å) | Oscillator Strength |
|---------|----------------|--------------------|
| C v Kα  | 40.2678        | 0.648              |
| O vii Kα| 33.7360        | 0.416              |
| O viii Kα| 21.6019       | 0.696              |
| Ne ix Kα| 18.9689        | 0.416              |
| Ne x Kα | 13.4471        | 0.724              |
| N v     | 12.1339        | 0.416              |

For each of the transitions listed in Table 2, we then added to the local best-fitting continuum a negative-only Gaussian (i.e., with flux allowed to be only negative in the fit), with wavelength allowed to vary within the redshift intervals of the PCS and the FSW and FWHM frozen to 10 mÅ (unresolved in the LETG), and re-fitted the data. For each line, we estimate a single line significance in standard deviations, as the ratio between its best-fitting flux and its 1σ error (computed with the Sherpa routine projection,16 by leaving both the continua and Gaussian normalizations free to vary). Four and three of the transitions listed in Table 2 were preliminarily and tentatively identified at a single line significance >1σ, for the PCS (C v, O vii, O viii, and Ne ix) and the FSW (C vi, O viii, and Ne ix), respectively. For the remaining transitions, we list their 3σ EW upper limits. For comparison and completeness, Table 3 also lists the result of our fitting procedure for the lines listed in Table 2, at z ≃ 0. Five of these transitions are detected at >1σ at z ≃ 0 (C v, O vii, O viii, Ne ix, and Ne x). What we discussed above provides only a preliminary attempt to check for the presence of the expected absorption lines at the redshifts of the large-scale galaxy structures present along the lines of sight. The presence (or absence) of a given line (at the quoted significance level; Table 3) is only used as a guidance for the detailed global fitting procedure presented in the next section and that makes use of our self-consistent WHIM collisional ionization plus photoionization model.

Figure 2 shows two spectral portions of the total Chandra LETG spectrum of H 2356-309, containing the three lines tentatively identified at the redshifts of the PCS and the FSW.

Table 3

| Wavelength (Å) | EW (mÅ) | Significance σ | Identification | Redshift z
|----------------|---------|----------------|----------------|-------------|
| PCS            |         |                |                |             |
| 42.770 ± 0.015| 19.6 ± 13.1| 1.5            | C v Kα         | 0.0621 ± 0.0004 |
| 35.76 − 35.86 | <5.5    | NA             | C v Kα         | 0.060 − 0.063  |
| 22.970 ± 0.015| 6.2 ± 5.5 | 1.1            | O vii Kα       | 0.0633 ± 0.0008 |
| 20.160 ± 0.015| 7.3 ± 4.8 | 1.5            | O viii Kα      | 0.0628 ± 0.0007 |
| 14.280 ± 0.015| 5.0 ± 3.3 | 1.5            | Ne ix Kα       | 0.062 ± 0.001  |
| 12.86 − 12.90 | <3.2    | NA             | Ne xNeX Kα     | 0.060 − 0.063  |
| FSW            |         |                |                |             |
| 45.38 − 45.46 | <6.1    | NA             | C v Kα         | 0.127 − 0.129  |
| 38.042 ± 0.015| 10.4 ± 8.5| 1.2            | C v Kα         | 0.1278 ± 0.0004 |
| 24.32 − 24.39 | < 5.8   | NA             | O vii Kα       | 0.126−0.129    |
| 21.396 ± 0.015| 7.7 ± 4.9 | 1.6            | O viii Kα      | 0.1279 ± 0.0008 |
| 15.161 ± 0.015| 4.0 ± 3.3 | 1.2            | Ne ix Kα       | 0.127 ± 0.001  |
| 12.46 − 12.47 | <3.1    | NA             | Ne x Kα        | 0.127−0.129    |
| z ≃ 0          |         |                |                |             |
| 40.274 ± 0.015| 38.5 ± 12.3| 3.1            | C v Kα         | 0.0002 ± 0.0005 |
| 33.72 − 33.75 | < 7.1   | NA             | C v Kα         | ±0.0004       |
| 21.561 ± 0.015| 8.1 ± 5.0 | 1.6            | O vii Kα       | −0.0019 ± 0.0007 |
| 18.952 ± 0.015| 4.6 ± 3.6 | 1.3            | O viii Kα      | −0.0009 ± 0.0008 |
| 13.449 ± 0.015| 7.6 ± 3.3 | 2.3            | Ne ix Kα       | ±0.001        |
| 12.131 ± 0.015| 7.7 ± 2.9 | 2.7            | Ne x Kα        | ±0.001        |

Notes.

a Single line significance in standard deviations evaluated as the ratio between the best-fitting EW and its 1σ error (see the text for details).

b The error is derived from the systematic 1σ wavelength uncertainty of ±15 mÅ due to the nonlinearity of the HRC-S LETG dispersion relationship.

16 http://cxc.harvard.edu/sherpa/ahelp/projection.py.html
4.2. Constraining the Physics of the Putative PCS and FSW Absorbers with a Self-consistent WHIM Model

In Section 4.1, we generally searched for the presence of the strongest absorption metal lines expected from highly ionized gas with temperatures in the broad interval $T = 10^5$–$10^7$ K. However, these transitions belong to ions with quite different ionization potential (e.g., C v and Ne x) and whose relative abundances critically depend on the ionization mechanisms at work and on the actual gas temperature. For example, in collisionally ionized gas, O vii, being H-like and so quite stable, is virtually the only abundant ion of O within a broad interval of temperatures, within log $T$ (K) = 5.5–6.2. In the same temperature interval, the lower ionization ions C v and C vi are relatively abundant, with C v decreasing monotonically from ∼75% down to ∼5% and C vi raising from ∼25% up to ∼50% at its log $T$ (K) = 6 peak temperature and then decreasing again down to ∼20%. On the contrary, the higher ionization ions O viii, Ne ix, and Ne x are only important at the high-temperature extreme of this interval, with relative abundances steeply raising from very low values up to 23% (O viii), 96% (Ne ix), and 3% (Ne x). Modeling the spectra of extragalactic sources crossing regions of the universe with large galaxy overdensities (expected to trace WHIM filaments) with self-consistent ionized absorber models may therefore provide useful constraints on the ionization state and column density of the putative absorbers embedded in these LSSs, even if the spectral signature of the gas is individually marginally detected (and/or upper limits are obtained) as long as they are modeled jointly.

Here, we make use of an adaptation of the Photoionized Absorber Spectral Engine (Krongold et al. 2003) code for WHIM gas (e.g., Nicastro et al. 2010). The code includes more than 3000 electronic resonant transitions (including metal inner shell) from all elements lighter than Ni and computes, for a given H equivalent column density, temperature, and turbulence velocity of the absorber, the Voigt profile folded opacity of each transition. The ionization balance in the gas is computed by perturbing the equilibrium collisional ionization balance at a given temperature $T$ with photoionization by the meta-galactic UV and X-ray background at a given redshift (the redshift of the absorber). Such second-order photoionization contribution depends uniquely on the baryon density $n_b$ in the gas (the lower the density the higher the contribution of photoionization) and it starts to be effective at $n_b \lesssim 10^{-5}$ cm$^{-3}$.

In our fitting procedure, we use the same initial methodology as adopted in Section 4.1. For each of the two superstructures, the PCS and the FSW, we fit the four different narrowband portions of the continuum where the main transitions lie independently. For each spectral interval, our fitting model includes the best-fitting continuum determined in Section 4.1 attenuated by our hybrid-ionization absorption WHIM model. For each spectral interval, we leave free to vary in the fit the continuum normalization and two out of the five parameters of the WHIM model, namely, the equivalent H column density $N_H$ and the temperature $T$ of the gas. Both $N_H$ and $T$ are linked to their same respective values in the four independently fitted spectral regions. The remaining parameters of our WHIM model are the turbulence velocity $v$ (summed in quadrature to the thermal Doppler parameter of a given transition), the redshift $z$, and the baryon density $n_b$ of the absorbers. The baryon density $n_b$ is highly degenerate with the electron temperature (which is set mainly by collisions in shock-heated WHIM gas) and modifies only slightly the ionization balance of the gas, compared with pure collisional equilibrium at a given temperature. Consequently, $n_b$ can be constrained independently of temperature only with data where several transitions from different ions of the same element are clearly detected. In our fit of the putative absorbers at the redshifts of the PCS and the FSW, we therefore freeze the gas baryon density to a typical WHIM value of $n_b = 10^{-5}$ cm$^{-3}$. Analogously, the turbulent velocity of the absorber (degenerate with the ion column density for saturated lines) can only be properly constrained when the single absorption lines are resolved and their profile clearly detected at high significance. We freeze this parameter to $v = 100$ km s$^{-1}$, comparable to typical values of Doppler velocities inferred by hydrodynamical simulations (e.g., Cen & Fang 2006). Finally, for each of the four spectral regions, we first leave the redshift of the absorbers to vary independently over the entire redshift extent of the two superstructures ($z = 0.060$–0.063 for the PCS and $z = 0.127$–0.129 for the FSW) and then refine the fitting by freezing the redshift of the absorber in the spectral region where the most significant absorption line is detected to its best-fitting
value, and leaving the redshifts of the other absorbers in the three remaining spectral regions, free to vary between ±20 mÅ from the frozen redshift of the most significant absorption line, to account for the 90% systematic wavelength uncertainties in the HRC-S LETG.

Table 4 summarizes the results of our fit. Errors are quoted at a 68% confidence limit. For each parameter listed in Table 4, we compute errors by allowing the continuum normalization to vary within its 1σ uncertainty and allowing the other free WHIM model parameters free to vary except in the case of the estimation of log \( N_H \) and log T errors where we fixed the redshifts to their best-fit value.

### 4.2.1. The PCS Filament

For this structure, we found the possible coexistence of two distinct WHIM phases (Figure 3): a warm phase, traced by CV absorption (Figure 4), with log \( T = 5.35 \pm 0.13 \) K and log \( N_H = (19.1 \pm 0.2) \times (Z/Z_\odot)^{-1} \text{ cm}^{-2} \) and a much hotter and less constrained phase, traced by O viii absorption (Figure 5), with log \( T = 6.9^{+0.1}_{-0.8} \) K and log \( N_H = 20.1^{+0.3}_{-0.8} \times (Z/Z_\odot)^{-1} \text{ cm}^{-2} \).

The redshift interval traced by the distribution of galaxies of the PCS, along the line of sight to H 2356-309, is \( 0.060 < z < 0.063 \). The two WHIM phases tentatively identified here have best-fitting redshifts consistent with each other and with the PCS redshift interval, namely, \( z_{\text{warm}} = 0.0623 \pm 0.0005 \) and \( z_{\text{hot}} = 0.063 \pm 0.001 \).

We note that the physical parameters of the putative warm component of the PCS are constrained much better than those of the hot component (Figure 3). This is because the opacity of absorbing gas to light metal transitions decreases with increasing temperatures. At the best-fitting temperature of the hot component of the PCS, only residual opacity from highly ionized O, Ne, and Fe is present (Figure 5), and the two free model parameters, temperature and \( N_H \), become highly correlated (Figure 3, red, dotted lines) and therefore only poorly constrained. At the temperatures of the warm-PCS phase, instead, several strong transitions from a number of abundant ions can still produce enough opacity in the data, which make \( T \) and \( N_H \) virtually uncorrelated (Figure 3, cyan solid lines).

![Figure 3](image_url)

**Figure 3.** 68%, 90%, and 95% temperature and equivalent H column density confidence contours for the two putative WHIM phases (warm: solid cyan; hot: dotted red) permeating the PCS.

| log \( T \) (in K) | log \( N_H \) (in \((Z/Z_\odot)^{-1} \text{ cm}^{-2}\)) | Redshift |
|-----------------|---------------------|---------|
| 5.35^{+0.07}_{-0.13} | 19.1 ± 0.2 | 0.0623 ± 0.0005 |
| 6.9^{+0.1}_{-0.8} | 20.1^{+0.3}_{-1.7} | 0.063 ± 0.001 |

| log \( T \) (in K) | log \( N_H \) (in \((Z/Z_\odot)^{-1} \text{ cm}^{-2}\)) | Redshift |
|-----------------|---------------------|---------|
| 6.9^{+0.1}_{-0.2} | 19.8^{+0.4}_{-0.8} | 0.126 ± 0.001 |

17 We caution that the opening of the contours at low temperatures is mostly likely a numerical artifact, due to the hitting of the low-temperature end of the model grid, during the error-estimate procedure.

![Figure 4](image_url)

**Figure 4.** Portions of the LETG spectrum of H 2356-309 showing the strongest absorption lines from the warm component of the PCS. The best-fitting continuum model is shown in solid thick red, while absorption lines from the warm WHIM component are shown in solid thin blue. The C v Kr absorption line at a redshifted wavelength of \( \lambda = 42.776 \) Å is the strongest line of the best-fitting warm component of the PCS (right panel). The other strong lines predicted by the model are the outer shell O viii Kr absorption line at \( \lambda = 22.95 \) Å (superimposed on the O i instrumental edge) and the two inner shell Kr transitions from O v at \( \lambda = 23.74 \) Å (\( \lambda = 22.35 \) Å rest frame) and O iv at \( \lambda = 24.17 \) Å (\( \lambda = 22.75 \) Å rest frame; left panel). Also shown in the left panel are the \( z \simeq 0 \) O vii Kr and the atomic and molecular O i Kr lines.
can also be seen in Figure 4, where we show two portions of the LETG spectrum of H 2356-309 with the strongest absorption lines from the warm component of the PCS, superimposed to the best-fitting continuum (red line) plus warm WHIM model component (blue line). The right panel of Figure 4 shows the strongest line of the best-fitting warm component of the PCS, the C IV Kα at a redshifted wavelength of \( \lambda = 42.776 \) Å. However, several other, moderately strong, lines are predicted by this model at shorter wavelengths and are shown in the left panel of Figure 4, namely, the outer shell O vii Kα absorption line at \( \lambda = 22.95 \) Å (superimposed on the O I instrumental edge) and the two inner shell Kα transitions from O v at \( \lambda = 23.74 \) Å (\( \lambda = 22.35 \) Å rest frame) and O iv at \( \lambda = 24.17 \) Å (\( \lambda = 22.75 \) Å rest frame). The data are consistent with the presence of these lines, which tightly constrain the temperature and column density of the warm component of the PCS.

4.2.2. The FSW

For the FSW, the LETG data are consistent with the presence of one hot WHIM component (Figure 6), traced mainly by Kα O viii and Ne ix absorption (Figure 7). The best-fitting WHIM parameters of this component are log \( T = 6.6^{+0.1}_{-0.2} \) K and log \( N_H = 19.8^{+0.4}_{-0.8} \) cm\(^{-2} \), and, as for the hot component of the PCS, they are only poorly constrained, due to the high best-fitting temperature of the gas. The tight lower limit on the temperature, compared to that of the hot phase of the PCS, is due to the inconsistency of the data with any O vii Kα absorption stronger than EW \( \geq 5.8 \) mA (3σ limit; Figure 7, third panel).18

The redshift interval traced by the distribution of galaxies of the PCS, along the line of sight to H 2356-309, is 0.127 < \( z < 0.129 \). The WHIM phase tentatively identified here has best-fitting redshifts consistent at 1σ with the low-redshift end of the FSW interval, namely, \( z_{FSW-WHIM} = 0.126 \pm 0.001 \).

5. DISCUSSION

The line of sight to the blazar H 2356-309 is extremely rich in galaxy large-scale filamentary structures (Figure 1). Other than the SW at least two distinct filaments of galaxies cross this line of sight at average redshifts \( \langle z_1 \rangle = 0.0615 \) (the PCS structure) and \( \langle z_2 \rangle = 0.128 \) (the FSW structure). These very rich structures have line-of-sight extensions of \( D_1 = 12.4 \) Mpc and \( D_2 = 8 \) Mpc, respectively, implying Hubble-flow velocity ranges of \( \Delta v_H = 890 \) km s\(^{-1} \) and \( \Delta v_H = 580 \) km s\(^{-1} \).

The thermal broadening of C or O lines in gas with \( T < 10^7 \) K is \( b < 85 \) km s\(^{-1} \) (C) or \( b < 74 \) km s\(^{-1} \) (O), negligible compared to turbulence induced by peculiar motion of the structures. In simulations (e.g., Cen & Ostriker 2006), WHIM intrinsic (i.e., excluding Hubble-flow broadening) turbulence is observed to be of order \( \sim 100 \) km s\(^{-1} \). If the PCS and the FSW galaxy structures were homogeneously embedded by WHIM, therefore, the Hubble-flow broadening would be by far the dominant broadening mechanism, and the gas would imprint metal absorption lines with FWHM \( \sim 890 \) km s\(^{-1} \) and FWHM \( \sim 580 \) km s\(^{-1} \), for the PCS and the FSW, respectively, easily resolved by the HRC-S/LETG (FWHM = 750 km s\(^{-1} \) at 20 Å and FWHM = 375 km s\(^{-1} \) at 40 Å).

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18 At the redshift of the putative FSW WHIM component, the O vii Kα falls at \( \lambda = 24.25 \) Å, a region of the detector free of instrumental features, unlike the PCS case, where the O vii Kα falls at the exact wavelength of the instrumental O I edge.
In the third panel, we also show the region where the O \textsuperscript{vii} strong predicted line is the Ne \textsuperscript{x} with the presence of such a line. (A color version of this figure is available in the online journal.)

On the contrary, unresolved O absorption lines in the HRC-LETG must imply that the gas is homogeneously spread over a limited portion of these two galaxy structures, extending not more than 4 Mpc along the line of sight (corresponding to Hubble-flow broadening of 0.021 Å at 20 Å, i.e., 1σ of the LETG line-spread function).

5.1. On the O \textsuperscript{vii} Bearing WHIM or Galaxy Halo Gas

Our total \textit{Chandra} LETG spectrum of H 2356-309 is sensitive to absorption line EW ⩾ 14 mA at 22 Å, at ⩾3σ confidence level. For unsaturated lines (b ⩾ 200 km s\(^{-1}\)), this corresponds to O \textsuperscript{vii} column densities \(N_{\text{O vii}} \geq 3.4 \times 10^{13}(1+z)^{-2} \text{ cm}^{-2}\). At overdensities \(\delta \approx 50(1+z)^{-2}\) and temperature \(T \approx 10^6 \text{ K}\), typical of the bulk (~50%) of the WHIM density–temperature distribution (e.g., Cen & Ostriker 2006), and assuming homogeneity, these columns correspond to line-of-sight extensions of the filament of \(D \geq N_b/n_b = [N_{\text{O vii}}/(A_{\text{O vii}}f_{\text{O vii}})]/n_\odot (Z/Z_\odot)^{-1} \approx 1.4(Z/Z_\odot)^{-1} \text{ Mpc}\) (where we assumed \(A_{\text{O}} = 8.5 \times 10^{-4}\), Grevesse & Anders 1989, and a relative fraction of O \textsuperscript{vii} \(f_{\text{O vii}} = 0.9\)). The extensions of the PCS and FSW galaxy structures, if entirely permeated by WHIM gas representative of the bulk of its density-temperature distribution, should then guarantee the high-significance detection of strong O \textsuperscript{vii} absorbers. This has proven to be true only for the SW (Fang et al. 2010) which is the most extended structure along the line of sight with \(D = 16.6 \text{ Mpc}\).

We did not detect strong (i.e., \(N_{\text{O vii}} \geq 3.4 \times 10^{15}(1+z)^{-1} \text{ cm}^{-2}\) at ⩾3σ), unresolved (i.e., \(b \leq 285 \text{ km s}^{-1}\) at 1σ) O \textsuperscript{vii} absorption along either of the other two LSSs crossing the line of sight to H 2356-309, the PCS and the FSW. These non-detections tell us that any ionized gas at typical WHIM temperatures (\(T \sim 10^6 \text{ K}\)) embedded in the 4 Mpc cores (i.e., imprinting unresolved O lines; see Section 5) of the line-of-sight extent of the PCS and FSW structures must have overdensities \(\delta \lesssim 18(Z/Z_\odot)^{-1}(1+z)^{-4}\) (where the additional \((1+z)^{-3}\) term comes from the \((1+z)^3\) redshift dependency of \((n_b)\)). For both the PCS (\(\delta \lesssim 14(Z/Z_\odot)^{-1}\) at ⩾3σ) and the FSW (\(\delta \leq 11(Z/Z_\odot)^{-1}\) at ⩾3σ), these overdensities lie on the lower end of the predicted overdensity interval for the bulk of the WHIM, ranging between \(\delta \approx 5–50\). This is the opposite of what intuitively expected (though with a large scatter, e.g., Viel et al. 2005), that richer galaxy LSSs potentially harbor denser WHIM filaments.

Alternatively, the O \textsuperscript{vii} bearing gas in these structures could spread over the large extent of the galaxy superstructure along the line of sight and so produce broader and resolved shallow (hence more difficult to detect) lines in the LETG (see Section 5) or could have metallicity lower than 10% solar, in either case relaxing the above limits on the gas overdensities. However, any denser WHIM gas at the typical \(T \sim 10^6 \text{ K}\) temperature and with line-of-sight turbulence velocity lower than a few hundreds km s\(^{-1}\) should have been detected at high significance in the LETG spectrum of H 2356-309.

An alternative interpretation of the O \textsuperscript{vii} absorption is that it could be associated with the hot extended halo of a single galaxy with small line-of-sight impact parameter. In this scenario, if \(r\) is the galaxy spherical halo radius, the impact parameter \(d\) must be smaller than \(r\), and the line of sight can only cross a section of the halo \(D = 2r \sin(\alpha)\), where \(0 \leq \alpha \leq \pi/2\) is the angle between the direction of the galaxy line-of-sight impact parameter \(d\) and the halo radius \(r\) in the direction of the interception of the halo external boundary with the line of sight. By averaging over \(0 \leq \alpha \leq \pi/2\), we get \(<D> \approx 4r/\pi\). With this assumption, the baryon density of the galaxy halo is given by \(n_b = N_b/D \approx \langle[N_{\text{O vii}}/(A_{\text{O vii}} f_{\text{O vii}})]/(4d/\pi)\rangle (Z/Z_\odot)^{-1}\).

The non-detection of O \textsuperscript{vii} bearing gas up to the \(N_{\text{O vii}} \geq 3.4 \times 10^{15}(1+z)^{-1} \text{ cm}^{-2}\) limit allows us to estimate stringent upper limits on the densities of putative galaxy halo gas with \(T \sim 10^6 \text{ K}\) intercepting the line of sight to H 2356-309 at the redshifts of the PCS and FSW structures. By using an impact parameters \(200 \lesssim d \lesssim 300 \text{ kpc}\) (Stocke et al. 2006), we obtain \(n_b \approx (3–5) \times 10^{-5}(Z/Z_\odot)^{-1} \text{ cm}^{-3}\) for both the PCS and the FSW which is lower than the values derived for our Galaxy halo or extended Local Group gas (e.g., Rasmussen et al. 2003; Williams et al. 2005). These values would be raised at most by a factor of 2 by accounting for non constant gas density profile.\(^{19}\)

5.2. The Ionized Gas Content of the PCS and FSW Galaxy Structures

As discussed in the previous section, we do not detect significant amount of O \textsuperscript{vii}-bearing (i.e., typical of the bulk WHIM temperature-density distribution) gas in either the PCS or the FSW galaxy superstructures. However, at the redshift of these structures, we do marginally detect a number of (individually low significance) metal absorption lines, from either low-ionization (O \textsuperscript{vi}, O \textsuperscript{v}, C \textsuperscript{v}, and C \textsuperscript{v}) or high-ionization (O \textsuperscript{viii}, Ne \textsuperscript{x}) ions. Such ions populate gas with temperatures in the low or high end of the WHIM temperature distribution, containing roughly 27% and 23% of the predicted WHIM mass, respectively. The absorption lines hinted in the LETG spectrum

\(^{19}\) We assumed a β-model (Cavaliere & Fusco-Femiano 1976) gas density distribution with β parameter ranging between 0.6 and 0.9 and assumed core radius ranging from 1 kpc to an unrealistically high 400 kpc value.
of H 2356-309 at the redshifts of the PCS and the FSW are all unresolved, which imply line-of-sight extensions of the absorber $D \lesssim 4$ Mpc.

Despite the low statistical significance of each of these individual absorption lines, we were still able to constrain the main physical parameters of the absorbing gas, namely, its equivalent H column density and temperature, by modeling the broadband LETG data with our hybridly ionized WHIM gas model. We identify two different absorbing WHIM phases at the redshift of the PCS, with log $T = 5.35^{+0.07}_{-0.13}$ K, log $N_H = 19.1 \pm 0.2(Z/Z_\odot)^{-1}$ cm$^{-2}$ and log $T = 6.9^{+0.1}_{-0.8}$ K, log $N_H = 20.1^{+0.3}_{-1.7}(Z/Z_\odot)^{-1}$ cm$^{-2}$, for the warm and the hot phases, respectively. For the FSW, instead, only one hot phase is tentatively detected, with log $T = 6.6^{+0.5}_{-0.2}$ K and log $N_H = 19.8^{+0.4}_{-0.8}(Z/Z_\odot)^{-1}$ cm$^{-2}$.

We can infer baryon densities lower limits for these systems, by assuming that the absorbers are embedded in their galaxy superstructures and have dense cores extending <4 Mpc along the line of sight (we note that for the two phases in the PCS, assuming that they are physically separated, the total extent can be close to the entire line-of-sight extension of the PCS galaxy filament). By conservatively assuming the $\pm 1\sigma$ $N_H$ value as $N_b$, for the two WHIM phases, we get $n_b(\text{warm}) = N_b(\text{warm})/D > 6.4 \times 10^{-7}(Z/Z_\odot)^{-1}$ cm$^{-3}$ ($\delta > 2.7(Z/Z_\odot)^{-1}$) and $n_b(\text{hot}) = N_b(\text{hot})/D > 2.0 \times 10^{-7}(Z/Z_\odot)^{-1}$ ($\delta > 0.9(Z/Z_\odot)^{-1}$), while for the hot phase of the FSW we obtain $n_b = N_b/D > 8.1 \times 10^{-7}(Z/Z_\odot)^{-1}$ ($\delta > 2.8(Z/Z_\odot)^{-1}$), all consistent with predicted WHIM overdensities.

5.3. Number Density of O vii Absorbers Along the Line of Sight to H 2356-309

From our best-fitting WHIM model temperatures for the three putative WHIM absorbers at the redshifts of the PCS and the FSW, we can infer the relative fraction of O vii in each phase. These are $f_{O \text{vii}} = 0.15$, $f_{O \text{vii}}^{\text{W-PCS}} = 9 \times 10^{-4}$, and $f_{O \text{vii}}^{\text{FSW}} = 0.028$. These ion fractions correspond to columns of $N^{O \text{vii}}_{\text{W-PCS}} = 1.6^{+1.8}_{-0.6} \times 10^{15}$ cm$^{-2}$, $N^{O \text{vii}}_{\text{H-PCS}} = 9.6^{+9.5}_{-9.5} \times 10^{13}$ cm$^{-2}$, and $M_{\text{FSW}} = 1.5^{+2.3}_{-1.3} \times 10^{15}$ cm$^{-2}$, or to unsaturated O vii EWs of $7^{+8}_{-4}$ mÅ, $0.42^{+0.42}_{-0.42}$ mÅ, and $7^{+11}_{-11}$ mÅ, respectively.

Assuming the best-fitting temperature and $N_H$ values as face values, the lowest O vii EW that we are indirectly probing through our hybrid-ionization WHIM code, along the line of sight to H 2356-309, is therefore EW(O vii) $\gtrsim 0.4$ mÅ, corresponding to the hot phase of the PCS. Combining our three tentative WHIM detections with the WHIM detection associated with the SW leaves us with four distinct WHIM systems with EW(O vii) $\gtrsim 0.4$ mÅ, along a $\Delta z = 0.165$ path length, or a number density of EW(O vii) $\gtrsim 0.4$ mÅ filaments of $dN/(EW > 0.4)/dz \approx 24.3^{+19.2}_{-11.6}$ (allowing for the large $\sigma$ uncertainties due to the small number statistics, i.e., Gehrels 1986). This is fully consistent with hydrodynamical simulation predictions (e.g., Cen & Fang 2006).

We can, in principle, also compute the cumulative number density of O vii filaments per unit redshift, with EW larger than a given threshold, for two additional EW thresholds: $\geq 7$ mÅ (three absorbers) and $\geq 25.8$ mÅ (one absorber; Fang et al. 2010). We get $dN/(EW > 7)/dz = 18.2^{+17.7}_{-9.0}$ and $dN/(EW > 25.8)/dz = 6.1^{+13.9}_{-5.1}$. We plot such derived number density per unit redshift, in Figure 8, superimposed to the theoretical cumulative $dN(> EW_{\text{threshold}})/dz$ curve from Cen & Fang (2006).

The data point at 25.8 mÅ exceeds the predictions by more than $2\sigma$. This could be due to a line-of-sight selection bias or may reflect the possibility that one or more of the detected absorption do not actually arise in tenuous WHIM filaments, but in much denser galaxy halos of one (or more) components of the LSSs with line-of-sight impact parameter of $\approx 200–300$ kpc. It may finally be that the most marginally detected systems, the hot-PCS and the FSW, given their large uncertainties in temperature and column density may just be explained as occasional statistical fluctuation. In this case, considering only the SW and warm-PCS systems, the number density of EW(O vii) $\gtrsim 7$ mÅ filaments would be $dN/(EW > 7)/dz = 12.1^{+16.0}_{-11.2}$, which within the large uncertainties is consistent with the predictions (see Figure 8, dashed data point).

5.4. Cosmological Mass Density of the WHIM from the H 2356-309 Line-of-Sight Absorbers

Finally, we derive the cosmological mass density of the WHIM as measured along the line of sight to H 2356-309, by assuming that all four different phases seen at the redshifts of the three SW, PCS, and FSW galaxy superstructures are intervening WHIM filaments. By propagating in quadrature the large errors associated with the equivalent H column density measurements of the absorbers and those intrinsic with cosmic variance low-number statistics, we obtain $\Omega_{b\text{WHIM}} = (0.021^{+0.031}_{-0.018})(Z/Z_\odot)^{-1}$. This is consistent with the cosmological mass density of intergalactic missing baryons ($\Omega_{b\text{missing-IGM}}$ $\approx 0.016 \pm 0.005$, e.g., Fukugita & Peebles 2004) in the local universe, but assumes solar metallicities. Metallicities of $\lesssim 10$% solar would give an $\Omega_{b\text{WHIM}}$ in excess by $\gtrsim 1\sigma$ compared to $\Omega_{b\text{missing-IGM}}$, again probably indicating an intrinsic line-of-sight selection bias or simply reflecting the possibility that one or more of the detected absorptions are not imprinted by tenuous WHIM filaments. Again as in the previous section, we excluded from the analysis the most uncertain systems hot-PCS and FSW and estimated an $\Omega_{b\text{WHIM}} = (0.0026^{+0.005}_{-0.0018})(Z/Z_\odot)^{-1}$ which is consistent with the predicted missing baryons by assuming 10% solar metallicity.
6. CONCLUSIONS

We have analyzed a long integration (600 ks) Chandra HRC-S/LETG spectrum of the blazar H 2356-309 to search and characterize the WHIM in two large-scale galaxy structures along this line of sight and, more specifically, the “PCS” at $z = 0.03$ and the “FSW” at $z = 0.128$. These are structures more prominent and more distant with respect to the “SW” at $z = 0.03$, where WHIM was identified in previous works through the detection of the O vi absorption line.

Although we do not detect significant individual absorption lines in the PCS nor in the FSW, the joint analysis of the marginally detected lines (as well as of stringent upper limits) through a self-consistent hybrid-ionization spectral model allows us to constrain the physics of the WHIM in the two farther superstructures. The main results are summarized as follows.

1. At the redshift of the PCS, we identify two distinct phases: a warm phase, with $\log T = 5.35^{+0.10}_{-0.13}$ K and $\log N_H = (19.1 \pm 0.2)$ cm$^{-2}$, and a much hotter less significant phase, with $\log T = 6.9^{+0.8}_{-0.9}$ K and $\log N_H = 20.1^{+0.9}_{-1.1}$ cm$^{-2}$ ($1\sigma$ errors).

2. At the redshift of the FSW, only one hot component is hinted in the data, with $\log T = 6.6^{+0.1}_{-0.2}$ K and $\log N_H = 19.8^{+0.8}_{-1.4}$ cm$^{-2}$.

3. Under the assumption that the absorbers are embedded in their galaxy superstructures having baryonic column densities $N_b$ equal to the $-1\sigma$ $N_H$ value and have dense cores extending <4 Mpc along the line of sight, we can infer conservative lower limits on the baryons densities in the two systems for the three absorbers. More specifically, for the two PCS WHIM phases we get $\delta > 2.7(Z/Z_\odot)^{-1}$ and $\delta > 0.9(Z/Z_\odot)^{-1}$, while for the hot FSW phase we obtain $\delta > 2.8(Z/Z_\odot)^{-1}$, all consistent with predicted WHIM overdensities.

4. By combining the constraints on the O vi absorbers in the PCS and in the FSW, with the previous detection in the SW (Fang et al. 2010), we derive the cumulative number density of O vi absorbers per unit redshift, as a function of the EW(O vi). While at low EWs (EW(O vi) $> 0.4$ mÅ), the absorbers number density is fully consistent with the predictions of hydrodynamical simulations, at EW(O vi) $> 10$ mÅ the inferred absorbers number density exceeds significantly the theoretical predictions. The latter finding may result from a line-of-sight selection bias or may reflect the possibility that one or more of the detected absorptions do not arise in WHIM filaments but in galaxy halos. We also considered the possibility that the two most marginally detected systems (hot-PCS and FSW) may be just statistical fluctuations and not absorbers. In this case, the number density of O vi absorbers per unit redshift would agree with the predictions within the large uncertainties.

5. Finally, by combining the measurements in all absorbers we derive a cosmological mass density of the WHIM of $\Omega_{\text{WHIM}}^p = (0.021^{+0.031}_{-0.018})(Z/Z_\odot)^{-1}$, consistent with the cosmological mass density of intergalactic missing baryons in the local universe. Yet, if the WHIM metallicities are $<10\%$ solar, then the resulting $\Omega_{\text{WHIM}}^p$ is significantly in excess of the missing baryon density, again possibly indicating a line-of-sight selection bias or reflecting the possibility that one or more absorbers are not associated with WHIM. The exclusion of the two most marginally detected systems may bring in agreement the $\Omega_{\text{WHIM}}^p$ value if we assume 0.1 $Z_\odot$.

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