XMM-NEWTON AND FUSE TENTATIVE EVIDENCE FOR A WHIM FILAMENT ALONG THE LINE OF SIGHT TO PKS 0558-504

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ABSTRACT

We present a possible O viii X-ray absorption line at $z = 0.117 \pm 0.001$ which, if confirmed, will be the first one associated with a broad H i Lyβ (BLB: FWHM = 160$^{+50}_{-30}$ km s$^{-1}$) absorber. The absorber lies along the line of sight to the nearby ($z = 0.1372$) Seyfert 1 galaxy PKS 0558-504, consistent with being a WHIM filament. The X-ray absorber is marginally detected in two independent XMM-Newton spectra of PKS 0558-504, a long $\sim 600$ ks guest-observer observation and a shorter, $\sim 300$ ks total, calibration observation, with a combined single line statistical significance of 2.8$\sigma$ (2.7$\sigma$ and 1.2$\sigma$ in the two spectra, respectively). When fitted with our self-consistent hybrid-photoionization WHIM models, the combined XMM-Newton spectrum is consistent with the presence of O viii Ka at $z = (0.117 \pm 0.001)$. This model gives best-fitting temperature and equivalent H column density of the absorber of log $T = 6.56^{+0.19}_{-0.17}$ K, and log $N_H = (21.5 \pm 0.3)(Z/Z_{\odot})^{-1}$ cm$^{-2}$, and predicts the marginal contribution of only two more lines within the XMM-Newton Reflection Grating Spectrometer band pass, Ne ix Ka ($\lambda = 13.45$ Å) and Fe xvii L ($\lambda = 15.02$ Å), both with equivalent widths well within the 1$\sigma$ sensitivity of the combined XMM-Newton spectrum of PKS 0558-504 (EW$< 3$ mÅ). The lack of detection of associated O vi in the archival FUSE spectrum of PKS 0558-504 allows us to infer a tighter lower limit on the temperature, of log $T > 6.52$ K (at 1$\sigma$). The statistical significance of this single X-ray detection is increased by the detection of BLB and complex H i Lyβ absorption in archival FUSE spectra of PKS 0558-504 at redshifts $z = 0.1183 \pm 0.0001$ consistent with the best-fitting redshift of the X-ray absorber. The FUSE spectrum shows a broad (FWHM = 160$^{+50}_{-30}$ km s$^{-1}$) absorption complex, which we identify as H i Lyβ $z_{BLB} = (0.1183 \pm 0.0001)$. The single line statistical significance of this line is 4.1$\sigma$ (3.7$\sigma$ if systematics are considered). A possible H i Lyα is marginally hinted in an archival low-resolution ($\Delta \lambda \sim 6$ Å) International Ultraviolet Explorer (IUE) spectrum of PKS 0558-504, at a redshift of $z = (0.119 \pm 0.001)$ and with single line significance of 1.7$\sigma$. Thus, the combined significance of the three (XMM-Newton, FUSE, and IUE) independent tentative detections, is 5.2$\sigma$ (5.0$\sigma$ if the H i Lyα is not considered, and 4.6$\sigma$ if the systematics in FUSE are considered). The detection of both metal and H lines at a consistent redshift, in this hot absorbing system, allows us to speculate on its metallicity. By associating the bulk of the X-ray absorber with the BLB line detected in the FUSE spectrum at $z_{BLB} = 0.1183 \pm 0.0001$, we obtain a metallicity of 1$\%$–4$\%$ Solar. Although the absorber is only blueshifted by $\sim 6000$ km s$^{-1}$ from the systemic redshift of PKS 0558-504, the identification of the absorbing gas with a high velocity nuclear ionized outflow, is unlikely. The physical, chemical, and dynamical properties of the detected absorber are all quite different from those typically found in the warm absorber (WA) outflows, commonly detected in Seyferts and higher luminosity quasars. WA outflow velocities typically span a range of few hundreds to $\sim 1$–2 thousands km s$^{-1}$; WA metallicities, when measured, are typically found to be at least Solar; high-ionization WAs are virtually always found to coexist with lower-ionization X-ray and UV phases. All this strongly suggests that the absorber, if confirmed, is an intervening WHIM system.

Key words: cosmology: observations – galaxies: Seyfert – intergalactic medium – line: identification – methods: data analysis

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1. INTRODUCTION

In the present epoch ($z < 1$–2), over half (54%; Fukugita 2004) of the baryons are missing. They are predicted by big bang nucleosynthesis (e.g., Kirkman et al. 2003), inferred by density fluctuations of the cosmic microwave background (e.g., Bennett et al. 2003; Spergel et al. 2007), and seen at $z \sim 3$ in the “Lyα Forest” (e.g., Rauch 1998; Weinberg et al. 1997), but by $z < 2$ they are unaccounted for in detected stars and gas (Fukugita 2004). According to hydrodynamical simulations for the formation of structures in a Λ-CDM universe (e.g., Cen & Ostriker 2006), most, if not all, of these missing baryons should be in a barely visible “warm-hot” phase of the filamentary intergalactic medium (the WHIM). The WHIM was shock-heated to temperatures of $10^5$–$10^7$ K during the continued process of collapse and structure formation, and enriched up to $Z_{WHIM} = 0.1$–1 Z$_\odot$ by galaxy super-winds (GSW; Cen & Ostriker 2006). These GSWs efficiently removed metals from the cool and dense interstellar medium (ISM) phase in galaxies and spread them into the tenuous ($n_e \sim 10^{-6}$ to $10^{-4}$ cm$^{-3}$, i.e., overdensities $\delta \sim 5$–500 compared to the average density of the universe) WHIM phase, enriching the gas to few percent,
and up to tens of percent, of the solar metallicity values (e.g., Cen & Ostriker 2006). WHIM filaments are too tenuous to be detected through their bremsstrahlung and line emission with current X-ray instruments (e.g., Yoshikawa et al. 2003). However, integrated column densities of high-ionization metal ions along a random section of one of these filaments could reach values as high as \(\sim 10^{16} \text{ cm}^{-2}\) (O vii in the soft X-rays) and \(\sim 10^{14} \text{ cm}^{-2}\) (O vi in the far-ultraviolet: FUV), imprinting metal absorption lines in the FUV and soft X-ray spectra of background sources with equivalent width (EW) ranging between EW \(\sim 1–20 \text{ mÅ}\) (the O vii Kα in the X-rays) and EW \(\sim 10–100 \text{ mÅ}\) (the \(\lambda \simeq 1032 \text{ Å}\) transition, in the FUV).

The most intense of these absorption lines is the O vii \(\lambda_{1238},\lambda_{1244}\) doublet in the UV (\(\lambda = 1031.926, 1037.617 \text{ Å}\)), and the C vi \(\lambda\alpha(r) (\lambda = 40.268 \text{ Å}), \text{O vii Kα(r) (}\lambda = 21.602 \text{ Å}), \text{C vi Lyα (}\lambda = 33.74 \text{ Å})\) and \(\text{O viii Lyα (}\lambda = 18.97 \text{ Å})\), in the X-ray band. Which of these lines dominates, depends on the ionization state of the gas, that is mainly on its temperature (and at a second order on the gas volume density). Davé et al. (2001) showed that the baryon temperature distribution in the intergalactic space peaks at \(T \sim 6.6 \text{ K}\) and is strongly skewed toward low temperatures: 50% of the baryon in the WHIM are found between \(T = 5.6 \text{ K}\) and \(T = 6.7 \text{ K}\) at a weighted average temperature of \(T = 5.9 \text{ K}\), while the low (\(T = 5–5.6 \text{ K}\)) and high (\(T = 6.6–7 \text{ K}\)) temperature tails of the WHIM temperature distribution contain 27% and 23% of the gaseous baryons in the universe, respectively, around weighted average temperatures of \(T = 5.4 \text{ K}\) and \(T = 6.7 \text{ K}\) (M. L. Concatoire et al. 2010, in preparation). So, while the vast majority (73%) of the baryons in the WHIM should absorb and emit in the X-rays at the wavelengths of the He-like (50%) and/or H-like (23%) ions of C and O, a substantial fraction of the WHIM (27%) should be detectable in the FUV, through Li-like C and O transitions.

These theoretical predictions have been confirmed by FUV observations (e.g., Danforth & Shull 2005, 2008; Tripp et al. 2008; Richter 2006). Danforth & Shull (2005) analyzed Far-Ultraviolet Spectroscopic Explorer (FUSE) data of 31 active galactic nuclei (AGNs) with \(\zeta < 0.15\) to search for O vi absorption counterparts to 129 known Lyα absorbers. They found 40 such systems, deriving a \(dN_{\text{O vi}}/d\zeta(\geq\text{EW}_{\text{thresh}})\) that agrees strikingly with the latest predictions by Cen & Fang (2006, see their Figure 2). However, as pointed out recently by Tripp et al. (2008), the vast majority of the associated H I Lyα absorption lines are too narrow to be produced in gas with typical WHIM temperatures. Danforth & Shull (2008) proposed that low-ionization metals and narrow H I Lyα trace mildly photoionized medium (the low-\(\zeta\) Lyα forest: \(\sim 30\%\) of the baryons), while narrow H I/O vii/N v absorptions trace a multiphase intergalactic medium, with a photoionized portion of the intervening filament imprinting the narrow-H I absorption and a shock-heated part (WHIM) imprinting the O vii/N v on the UV spectra (\(\sim 10\%\) of the baryons). Danforth & Shull (2008) estimate \(\Omega_{\text{O vii}}^{\text{WHIM}} = 0.34\%\) (down to log \(N_{\text{O vii}} > 13.4 \text{ cm}^{-2}\)). This is \(\sim 15\%\) of the “missing mass” (strictly speaking, only a lower limit, given the large uncertainties in the ionization correction for the O vii-bearing gas), in good agreement with the WHIM baryon fraction predicted to reside in the low-temperature tail of the WHIM mass–temperature distribution.

Detecting the bulk of the “Missing Baryons” in the “X-ray Forest,” instead, has proven to be extremely difficult. This is because of the unfortunate combination of (1) the still limited resolution (\(R \sim 400\) at \(\lambda = 21.6 \text{ Å}\)) and the low through-put (\(\sigma_{\text{eff}} \sim 20–40\text{ cm}^{2}\)) of the current high-resolution X-ray spectrometers (the \textit{XMM-Newton} Reflection Grating Spectrometer (RGS; den Herder et al. 2001) and the \textit{Chandra} Low Energy Transmission Grating (LETG; Brinkman et al. 2000)); (2) the lack of bright (\(\varepsilon_{6,5–2\text{ keV}} \geq 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\)) extragalactic point-like targets (e.g., M. L. Concatoire et al. 2010, in preparation); and, (3) the dramatic steepening (\(\Delta \sigma \gtrsim 1.5\)) of the predicted number density of metal WHIM filaments per unit redshift at ion column densities \(\gtrsim 10^{13} \text{ cm}^{-2}\).

Current evidence is still limited and highly controversial: in 2005, Nicastro et al. (2005a, 2005b) reported the first two \(\geq 3\sigma\) detections of absorption systems identifiable with WHIM filaments, at \(z = 0.011\) and \(z = 0.027\), toward the blazar Mkn 421, which was in outburst. One of these two systems is at a redshift consistent with that of a known intervening H I Lyα absorber (Shull et al. 1996) that line, however, is too narrow, and so the absorbing gas is too cold, to be physically associated with the X-ray metal filament. This claim has been questioned in two subsequent papers by Kastra et al. (2006) and Rasmussen et al. (2007), based on (1) apparent wavelength inconsistencies for some of the lines, which called into question their association with a given WHIM system; (2) statistical arguments for a significantly lower detection significance for the WHIM identifications than originally reported by Nicastro et al. (2005a, 2005b); and (3) the lack of detection of these two systems in \textit{XMM-Newton} RGS calibration spectra of Mkn 421 (but see also Nicastro et al. 2008, for rebuttal arguments). Fang et al. (2007) proposed the detection of an O vii WHIM filament along the line of sight to the blazar PKS 2155-304, once again near the redshift of a known narrow H I Lyα absorber not due to the same gas as the putative X-ray filament because of the line width. The above reported pieces of evidence for the existence of an “X-ray Forest” at low redshift have been gathered by exploiting the technique of observing random lines of sight toward the brightest possible X-ray sources, with exposures long enough to reach extremely high signal-to-noise ratio (S/N) spectra. This technique has the advantage of not being biased toward the strongest WHIM systems and so allows probes of the bulk of the WHIM mass distribution. However, the WHIM is predicted, and in the FUV has most likely been found (e.g., Stocke et al. 2006), to correlate strongly with galaxy concentrations in the universe: the densest of such concentrations are also supposed to host the nodes, and so the densest and hottest parts, of the WHIM network.

An alternative technique, therefore, is to target the WHIM in the X-rays along those lines of sight toward bright background X-ray sources that intercept large-scale structure concentrations. By exploiting this technique, Buote et al. (2009) reported a \(\sim 3\sigma\) detection of a high column density (\(N_{\text{O viii}} > 10^{16} \text{ cm}^{-2}\)) O vii Kα absorption line, along the line of sight to the blazar H 2356-309, at the redshift of a very large concentration of galaxies in the Sculptor Wall. This technique has the disadvantage of probing only the extreme high-temperature/density and low-mass fraction ends (\(\sim 23\%\)) of the WHIM distribution.

All the above proposed WHIM detections so far suffer the serious handicap of lacking the detection of a clearly associated H I counterpart. The detection of broad H I Lyman lines (mostly Lyα at \(\lambda = 1215.67 \text{ Å}\), BLA; Lyβ at \(\lambda = 1025.72 \text{ Å}\), BLB) is vital for a proper assessment of the WHIM metallicity and mass, and require the use of both X-ray and FUV facilities. Without H I, metallicity cannot be determined and so a cosmological mass density \(\Omega_{\text{H I}}^{\text{WHIM}}\) cannot be derived.
The expected thermal FWHM of an absorption line imprinted from a gas of particles of mass $m$ at the equilibrium temperature $T$ is given by $2 \sqrt{2 \ln 2 \times KT/m}$. For H\textsc{i}, this implies a broadening of FWHM $\sim 380$ km s$^{-1}$ at log $T = 6.5$.

The H\textsc{i} fraction, relative to the total H, in gas with temperatures in the $log T = (5.8–6.3)$ range (where 50% of the WHIM should be; e.g., Davé et al. 2001), spans the interval $10^{4.2} \sim 10^{7.2}$. Thus, only very shallow (EW(\Halpha) $\sim 8–80$ mÅ) and broad H\textsc{i} absorption lines are expected to be imprinted onto FUV spectra by WHIM filaments, requiring spectra with S/N $\sim 10–100$ per resolution element to make them detectable.

Here we present the first tentative detection of a hot (X-ray) WHIM filament along the line of sight to the $z = 0.1372$ Seyfert galaxy PKS 0558-504, that is physically associated with a BLA H\textsc{i} absorber. A full band analysis of the XMM-\textit{Newton} RGS spectrum of PKS 0558-504 is deferred to a companion paper (Papadakis et al. 2010). In Section 2, we present the XMM-\textit{Newton}, FUSE, and International Ultraviolet Explorer (IUE) data that we use in our analysis. Sections 3 and 4 are dedicated to the analysis of the longer and much higher S/N RGS spectra extracted from both data sets. We focus mostly on the GO spectrum. More recently, in 2008 September, PKS 0558-504 was re-observed by the XMM-\textit{Newton} satellite twice: on 1999 December 10 and 2001 November 7, with net exposure times of 47.2 ks and 48.3 ks, respectively. In our analysis, we co-added the two spectra from the Lif2A channel (with the highest efficiency in the 1100–1200 Å interval) to maximize the S/N and perform our search for intervening BLAs and BLBs in this co-added FUSE spectrum.

Finally, PKS 0558-504 has been observed 3 times with the “Short-Wavelength” spectrometer of the IUE satellites (the only one covering the wavelength range of interest), on 1987 September 22 and 1989 November 14–15. In our analysis, we use the highest S/N of the three spectra (with a net exposure time of 16.2 ks), the one taken on 1989 November 15 and check the other two spectra for consistency.

Table 1 lists the journal of the XMM-\textit{Newton, FUSE,} and IUE observations used in this work. For all our spectral fitting we use the fitting package Sherpa, of the Chandra Interactive Analysis of Observation (Ciao) software (ver. 4.1.2; Freeman et al. 2001).

### Table 1

| Data Set       | Date of Obs. | Obs. ID    | Exposure $^a$ |
|----------------|--------------|------------|---------------|
| XMM-RGS CAL    | 2000 Feb 7   | 0116700301b | 19.0          |
|                | 2000 Feb 10  | 0117500201  | 40.8          |
|                | 2000 Feb 12  | 0117710701  | 49.9          |
|                | 2000 Feb 13  | 0117710601  | 56.9          |
|                | 2000 Feb 14  | 0117710501  | 6.8           |
|                | 2000 Mar 7   | 0120030501   | 6.5           |
|                | 2000 Mar 17  | 0120030601   | 7.0           |
|                | 2000 Mar 17  | 0120030801   | 39.7          |
|                | 2000 May 24  | 0125110101   | 30.0          |
|                | 2000 Oct 10  | 0129360201   | 26.4          |
|                | 2001 Jun 26  | 0137550201   | 14.8          |
|                | 2001 Oct 19  | 0137550601   | 14.6          |
| XMM-RGS GO     | 2008 Sep 7   | 0555170201   | 121.4         |
|                | 2008 Sep 9   | 0555170301   | 127.8         |
|                | 2008 Sep 11  | 0555170401   | 126.2         |
|                | 2008 Sep 13  | 0555170501   | 126.6         |
|                | 2008 Sep 13  | 0555170601   | 115.8         |
| FUSE-LWRS      | 1999 Dec 10  | P1011504000  | 46.2          |
|                | 2002 Nov 7   | C1490601000  | 48.3          |
| IUE-SWP LR     | 1987 Sep 22  | SWP31899     | 13.8          |
|                | 1989 Nov 14  | SWP37589     | 13.8          |
|                | 1989 Nov 15  | SWP37604     | 16.2          |

Notes.

$^a$ Net in ks.

$^b$ RGS1 only.

3. THE RGS SPECTRUM OF PKS 0558-504

3.1. RGS Data Reduction and Analysis

The 2008 GO RGS data of PKS 0558-504 were reduced as in Papadakis et al. (2010), and the same standard reduction procedure was applied to the 2000–2001 calibration observations of this target. The data were cleaned for periods of high background activity, by excluding events taken within time intervals where the background deviated positively by its average level by more than 2$\sigma$. Finally, RGS1 and RGS2 spectra and responses of the single observations of the two data sets (CAL and GO) were co-added and averaged by using the $rgscombine$ tool. This produced total net exposures of 480 ks (RGS1) and 466 ks (RGS2), for the GO data set, and 309 ks (RGS1) and 283 ks (RGS2) for the CAL data set. Despite a 30% higher average flux level of PKS 0558-504 during the CAL observations, compared to the GO observations, and a relatively small difference of only 65% in the net exposure times of the two data sets, the S/N of the GO spectra is significantly (factor of $\sim 2$) higher than that of the CAL spectra. In half RGS resolution element (30 mA), at 0.5 keV the co-added RGS1 CAL spectrum has S/N = 9, compared with S/N = 16 for the GO spectrum. This difference in S/N is due to the much higher (more than an order of magnitude) level of the average background during all individual CAL observations, compared with the GO observations. This is clearly seen in Figure 1, where we plot the combined GO RGS1 $20–24$ Å background-subtracted source (green filled circles and

8 For heavier elements, the width scales with the inverse of the root square of the atomic weight. So, for example, for O, Ne, and Fe, at log $T = 6.5$, FWHM $= 95$, 85, and 51 km s$^{-1}$.  
9 We also reduced and analyzed the sum of the two spectra from the Lif2B channel, which is sensitive (though with about half of the effective area of the Lif2A channel) in a wavelength interval similar to that of the Lif2A channel. However, the Lif2B channel is unreliable at $\gtrsim 1100$ Å (The FUSE Data Handbook, Chapter 7, Section 7.3.2, http://archive.stsci.edu/fuse/DH_Final/Factors_Affecting_FUSE_Data.html), which is the region of interest for our analysis. Therefore, we decided to consider only the Lif2A channel in our analysis (but see also footnote 16, Section 4).
In our companion paper (Papadakis et al. 2010), we present the broadband 0.4–2 keV spectral analysis of the 2008 RGS spectra of PKS 0558-504 and show that the soft X-ray continuum of PKS 0558-504 is well modeled by a broken power law with a break energy of $E_{\text{br}} \sim 1.5$ keV, attenuated by Galactic ISM absorption. More importantly we exclude the presence of a warm absorber (WA) with typical column densities and ionization parameters (Papadakis et al. 2010). This is consistent with the absence of associated, intrinsic, narrow absorption lines (NALs) in the far-ultraviolet spectrum of PKS 0558-504 (Dunn et al. 2007). However, Papadakis et al. (2010) also note that weak absorption line-like features are detected in the spectrum of PKS 0558-504, in the narrow 20–24 Å spectral interval. These three lines, and in particular the line at $\lambda = 21.18$ Å, are the subject of this study.

We first explored the 20–24 Å region of the GO and CAL RGS1 spectra of PKS 0558-504 (the RGS2 is blind in this wavelength range, due to the lack of a readout CCD chip). We fitted the data simultaneously, with two local continuum models, each including a power law attenuated by neutral absorption with the metallicity set to Anders & Grevesse (1989). While such a model gives a statistically acceptable fit for the GO spectrum of PKS 0558-504, it leaves broad and systematic residuals in the CAL spectrum. This is because the rgscombine-averaged CAL response matrix fails to properly reproduce the depth of the several effective area features present in this portion of the RGS1 spectrum. We therefore added a number of FWHM $\sim 0.5–1$ Å broad emission and absorption Gaussians to the best-fitting continuum model of the CAL spectrum of PKS 0558-504, until we reached a statistically acceptable fit. Three narrow regions with a deficit of counts are left in the GO and CAL residuals to the best-fitting continuum models, at $\lambda \sim 23.5$ Å, $\lambda \sim 21.6$ Å, and $\lambda \sim 21.2$ Å. To model these residuals we added three Gaussians to our best-fitting continuum models and refitted the data leaving all Gaussian parameters free to vary independently in the fit to the GO spectrum, but linking the line energies and Gaussian widths in fitting the CAL spectrum to those of the corresponding parameters of the fitting model of the GO spectrum. The first three rows of Table 2 show the best-fitting parameters of these three absorption lines. Errors on wavelengths and redshifts are assumed to be equal to 1 bin size, 30 mA, if unresolved by the fitting routine). Figure 2 shows the 20–24 Å RGS1 CAL and GO data of PKS 0558-504, with their best-fitting models superimposed. The first two of these lines, at $\lambda = 23.52 \pm 0.03$ Å and $\lambda = 21.61 \pm 0.03$ Å, are easily identified with the KZ inner shell transition from atomic O I in the ISM of the Galaxy, and the KZ He-like transition from O VII either in our Galaxy halo or in the Local group (e.g., Bregman & Lloyd-Davies 2007, and references therein). The third line, at $\lambda = 21.17 \pm 0.04$ Å, appears marginally resolved (but still consistent with an unresolved Gaussian at a 1σ confidence level) in the RGS1 ($\text{FWHM} \lesssim 1200$ km s$^{-1}$, Table 2) and has no obvious identification with transitions at $z = 0$. If redshifted to the systemic redshift of PKS 0558-504 ($z = 0.1372$, REFs), this line would have a rest-frame wavelength of $\lambda = 18.62$ Å, close to the rest-frame wavelength of the O VII Kβ transition. However, in this case, a much stronger (factor $\sim 6.4$) O VII Kα line$^{11}$ with EW $\sim 60$ mA should be visible at $\lambda = 24.55$ Å. Such a line is not seen in the data (see also Papadakis et al. 2010).

$^{10}$ The projection routine in Sherpa, which we use here to compute uncertainties and upper limits, finds only an upper limit for the line FWHM, at a 1σ confidence level. This is because of the high non-Gaussianity of the RGS line spread function (e.g., Williams et al. 2005), which makes the effective LSF FWHM significantly broader than the nominal Gaussian equivalent LSF FWHM of 60 mA (corresponding to $\sim 900$ km s$^{-1}$ at 21.2 Å).

$^{11}$ Together with several other strong lines from He- and H-like ions of C, N, and Ne.
2010) at a 3σ limit of EW < 18 mA. Moreover, the absence of intrinsic O vi absorption in the FUSE data of PKS 0558-504 (Dunn et al. 2007) makes this interpretation less likely.

The next possible identification is with an intervening absorber, between the redshift of PKS 0558-504 and us. This imposes the condition that the line has a rest-frame wavelength in the 18.6–21.2 Å spectral interval. The strongest resonant absorption line expected in this spectral range is the O viii Lyα transition, with an unresolved doublet at an oscillator-strength-weighted average wavelength (λ) = 18.97 Å. This would give a redshift of z = 0.116 ± 0.002 for the intervening absorber.

3.3. Consistency Test with a Self-consistent WHIM Spectral Model

To check whether the presence of an O viiiKα WHIM filament at z = 0.116 ± 0.002 along the line of sight to PKS 0558-504, is consistent with the full band XMM-Newton RGS spectra of this target, we used our hybrid ionization (collisional + photoionization by the meta-galactic UV and X-ray background at a given redshift) WHIM spectral models (an evolution of our PHotoinized Absorber Spectral Engine: “PHASE”; Krongold et al. 2003), to simultaneously fit the RGS1 and RGS2 Cal and GO data of PKS 0558-504. The fitting model includes our best-fitting continuum model (a combination of power laws and broad Gaussians to cure residual calibration uncertainties), two negative Gaussians to model the O Kα and O viiiKα absorptions at z ≈ 0, and a WHIM model. In the X-ray band alone one cannot constrain the absolute metallicity of the absorber (for which detection of H i is needed), since the ionization balance of an hydrogen ionized cloud of gas (i.e., the fractional ion abundances), parameterized by the temperature of the absorber, at equilibrium, is virtually independent on metallicity (see also Section 5.2). Thus, for fitting purposes only, we froze the WHIM metallicity to Solar. The turbulent velocity of the absorber was frozen to 400 km s^{-1} (about 1/2 of the RGS FWHM resolution at 22 Å). In a hybrid-ionization WHIM model, photoionization by the meta-galactic UV and X-ray photon field is only a secondary ionization mechanism, and its relative importance, compared to the collisional shock mechanism, depends only on the volume density of the WHIM filament: the lower the density the more important is the photoionization contribution. In such models, the absorber density is thus highly degenerate with the absorber temperature and equivalent H column density, and so is difficult to constrain. We therefore froze the density of the absorbing gas to a typical expected WHIM value of n_b = 10^{-5} cm^{-3} (overdensity δ ≈ 50 compared to the average baryon density in the universe), corresponding to an ionization parameter (the ratio between the photon density at the surface of the absorbing cloud and the baryon density in the cloud) of log U = −1.9 at z = 0.1. At such densities (and higher), the photoionization contribution is essentially negligible, and the model reduces to a pure collisional ionization model. The remaining WHIM parameters, namely the gas temperature and equivalent hydrogen column density, and the redshift of the WHIM filament, were left free to vary in the fit. The best-fitting WHIM model (Figure 3, black curve) has log T = 6.56^{+0.19}_{-0.10}, log N_H = 19.5 ± 0.3 (for Z = Z_t) and z = 0.117 ± 0.001. This model fits the most prominent O viiiKα line at z = 0.117 and predicts only two additional weak absorption lines (EW < 1 mA): the Ne x Kα, at λ = 15.02 Å (WHIM filament frame) and a strong (oscillator strength 2.95) Fe xvii L line at λ = 16.77 Å (Figure 3, black curve).

Figures 4, 5, and 6 show the two portions of the RGS Cal and GO spectra of PKS 0558-504, in which the lines predicted by the best-fitting WHIM model lie. The superimposed red curve is the best-fitting WHIM model convolved with the instrumental responses. The O viiiKα line is detected both in the CAL and GO spectra (Figure 4). The position of the predicted Ne ix Kα and Fe xvii L lines is marked in Figure 5 (RGS1 and RGS2 GO spectra of PKS 0558-504) and Figure 6 (RGS1 and RGS2 CAL spectra of PKS 0558-504); the strength of these lines is <1/3 the minimum detectable 1σ EW in the combined CAL+GO spectrum (Table 2). We note the hint of the presence of the Fe xvii L line at 16.77 Å in both the RGS1 GO (Figure 5, top panel) and RGS2 CAL (Figure 6, bottom panel) spectra of PKS 0558-504.

In Figure 3, we plot the best-fitting WHIM model (central, black curve) together with its negative (lower, red curve) and positive (upper, green curve) limits, respectively. The blue curve is the spectrum of our fiducial gas model with n_b = 10^{-5} cm^{-3}, log T = 6.56, and z = 0.117. The redshift of this model is consistent within 1σ of the measured value of z = 0.116 ± 0.002. The high C O viiiL/R ratio and the Ne x Kα line are consistent with these values. The lower-density model (green curve) is consistent with the absence of O vi absorption, but only consistent within the 1σ limit of EW < 18 mA. The high-density model (blue curve) is consistent with the presence of O vi absorption, but only consistent within the 1σ limit of EW < 18 mA. The central, best-fitting model (black curve) is consistent with the absence of O vi absorption and the presence of O viii absorption.

### Table 2

Absorption Lines (and Upper Limits) in the XMM-Newton RGS, FUSE, and IUE Spectra of PKS 0558-504

| Wavelength (Å) | Width (FWHM km s^{-1}) | EW (mA) | Significance (σ) | Id | Redshift in km s^{-1} if z < 10^{-3} |
|----------------|-------------------------|---------|-----------------|----|-------------------------------------|
| XMM-Newton RGS |                         |         |                 |    |                                     |
| 23.52 ± 0.03   | <900                    | 23.7_{-5.0}^{+5.0} | 6.4 | O viiiKα                         | ±380 km s^{-1}   |
| 21.61 ± 0.03   | <900                    | 12.9_{-5.2}^{+1.5} | 2.5 | O viiiKα                         | 138 ± 380 km s^{-1} |
| 21.17 ± 0.03   | <120                    | 9.1_{-3.3}^{+3.3} | 2.8 | O viiiKα                         | 0.116 ± 0.002    |
| 15.00–15.03    | <900 (fixed)           | <3.0    | 1^{b}           | Ne ixKα                         | 0.117 ± 0.001    |
| 16.76–16.79    | <900 (fixed)           | <5.0    | 1^{b}           | Fe xviiL                        | 0.117 ± 0.001    |
| FUSE-LWRS      |                         |         |                 |    |                                     |
| 1147.1 ± 0.1   | 160^{+50}_{-30}         | 66 ± 16 | 4.1 | H iγθ                          | 0.1183 ± 0.0001  |
| 1152.7–1154.7  | 50 (fixed)             | <12     | 1^{b}           | O vi(λ = 1031.9)                | 0.118 ± 0.001    |
| IUE-SWP LR     |                         |         |                 |    |                                     |
| 1360 ± 1       | <1300                   | 1000 ± 600 | 1.7 | H iγα                           | 0.119 ± 0.001    |

Notes:

^{a} Wavelength interval over which the 1σ EW upper limit is computed, corresponding to z = 0.117 ± 0.001 for the X-ray lines, and z = 0.118 ± 0.001 for the UV line.

^{b} 1σ upper limit.
positive (upper, blue curve) $1\sigma$ temperatures. Both lower and upper limits on the temperature are weak. The strongest X-ray lower limit diagnostics in the model is the increasing strength of O\textsc{vii} K series absorption lines. However, the sensitivity of the RGS1 GO and CAL spectra of PKS 0558-504 at the wavelength of the strongest line of this series (the O\textsc{vii} K$\alpha$ line) is dramatically reduced by the presence of an instrumental feature due to a bad pixel in the readout dispersion detectors. On the other end, at higher temperature, the limit is set by the decrease of opacity at the wavelengths of the O\textsc{viii} K$\alpha$ transitions, which is only detected at a combined single-line significance level of $2.8\sigma$ in the data. This can be also seen in Figure 7, where we show the 68%, 90%, and 95% log $T$–log $N_H$ contours of the best-fitting WHIM model. The parameters are clearly correlated and the temperature poorly constrained both at low and high temperatures. However, low temperatures and high column densities are excluded at high confidence levels.

4. THE FUSE AND IUE SPECTRA OF PKS 0558-504

We searched The Multimission Archive at STScI (MAST) archive\textsuperscript{13} for far-UV data of PKS 0558-504 and found several

\textsuperscript{13} http://archive.stsci.edu/index.html
data sets, taken with FUSE, Hubble Space Telescope (HST), and IUE satellites (Table 1). Our main goal was to search for H I (Lyα and Lyβ) and O vi absorption either at or near the systemic redshift of PKS 0558-504, or at a redshift consistent with that of the putative X-ray WHIM filament, tentatively detected in the RGS spectrum of PKS 0558-504. The available archival HST spectrum of PKS 0558-504 was taken with the STIS-G230 gratings, and so covers a wavelength interval (λ = 2760–2910 Å) not relevant to this analysis. The FUSE and IUE spectra, instead, cover two important regions: (1) the H I Lyβ and O vi regions (FUSE) and (2) the H I Lyα region (IUE). We retrieved these data sets from the MAST archive and analyzed them to search for a secure identification of the X-ray absorber.

FUSE observed PKS 0558-504 twice, in two different programs (P101, 1999, K. R. Sembach; C149, 2002, J. X. Prochaska). All FUSE observations after the end of operations were re-reduced using the final version of the CalFUSE pipeline (ver. 3.2.3; Dixon et al. 2007), and we used the resultant science calibrated files. We used specific IRAF scripts to co-add the data from the L12A channel, which covers the wavelength range 1087–1181 Å, with a total exposure time of 90.3 ks. The spectrum was then binned to two different resolutions: the natural resolution of FUSE (3 bins; 11 km s$^{-1}$) and a poorer resolution (20 bins; 70 km s$^{-1}$) with higher S/N per bin, specifically to search for broad, shallow absorption features.

We use the fitting package Sherpa in Ciao (ver. 4.1.2; Freeman et al. 2001), to search the FUSE spectrum for (1) AGN intrinsic absorption between −1000 and +1000 km s$^{-1}$ of the systemic redshift of PKS 0558-504; (2) intervening absorption at a redshift consistent with that of the putative X-ray WHIM filament. Specifically, for each of the two possible systems, we searched for absorption lines from (1) the N iii triplet at λ = 989.80 Å, λ = 991.51 Å, and λ = 991.57 Å; (2) the O vi doublet at λ = 1031.93 Å and λ = 1037.62 Å; and (3) the H i Lyβ at λ = 1025.72 Å. We confirm the non-detection of intrinsic (i.e., nuclear) ionized or neutral absorption, down to EW ≤ 30 mA (3σ) of Dunn et al. (2007). However, we do detect several absorption lines in the wavelength range 1137–1155 Å (Figure 8). The strongest of these lines is easily identified as Galactic Fe II, PII, and possibly H2 transitions. These lines are all relatively narrow, with typical FWHM ≃ 50–70 km s$^{-1}$, and exhibit two velocity components at v1 ≃ 0 and v2 ≃ +200 km s$^{-1}$ (for the low-ionization atomic transitions), and v1 ≃ 0 and v2 ≃ +70 km s$^{-1}$ (for the molecular transition; Wakker 2006; see Figure 8).

However, we also detect a broader absorption complex at the centroid wavelength of λ ≃ 1147.1 Å, and at single-line statistical significances of 4.1σ (Figure 8). We model this absorber with a negative Gaussian and list its best-fitting parameters and EW in Table 1.

This absorption line is broad (FWHM = 160$^{+50}_{-30}$) km s$^{-1}$ and cannot be identified with any strong Galactic transition. We identify this absorber as a BLB at z_{BLB} = (0.1183 ± 0.0001). The X-ray redshift of the O vii Kα absorber is consistent with z_{BLB}. At the best-fitting X-ray temperature of log T =

14 http://fuse.pha.jhu.edu/analysis/IRAF_scripts.html

Figure 7. 68%, 90%, and 95% log T−log N_H contours for the putative X-ray WHIM filament at z = 0.117 ± 0.001.

Figure 8. 1137–1155 Å portion of the FUSE spectrum of PKS 0558-504, in two different binning schemes: ~15 km s$^{-1}$, the FUSE resolution (top panel), and ~90 km s$^{-1}$ (bottom panel). Absorption lines’ identifications are labeled in both panels. Low- and high-velocity components of the low-ionization Fe and P and molecular H2 absorbers are marked in blue and green and blue and cyan, respectively, but only the much stronger low-velocity lines are fitted (with the exception of the high-velocity Fe (1144.94 Å line at λ = 1145.7 Å, which we fit because possibly partly contaminated by intervening H I absorption). The broad absorption complex that we tentatively identify as intervening H I Lyβ is clearly better seen in the heavily binned spectrum (bottom panel).

15 With the exception of the high velocity component of the Fe (1144.94 Å absorber, at λ = 1145.7 Å, for which we measure FWHM = (100 ± 40). This absorber could be at least partly contaminated by intervening H I Lyβ absorption at z = (0.1170 ± 0.0001), i.e., still consistent with the X-ray redshift of the putative O vii intervening absorber, and so possibly representing a second H I component associated with this hot intervening WHIM filament.

16 There are also two known velocity components in high-ionization O vi Galactic (or Galactic halo) absorption, along the line of sight to PKS 0558-504, in the velocity ranges −115 to +135 km s$^{-1}$ (Savage et al. 2003) and +210 to +315 km s$^{-1}$ (Sembach et al. 2003).

17 The associated 1σ error here, and anywhere else in the paper, is only statistical. By taking into account the vagaries of continuum placement and fixed-pattern noise in the Li2A FUSE spectrum of PKS 0558-504, we estimate an additional 14% systematic 1σ uncertainty. This would reduce the significance of the broad line at λ = 1147.1 Å, from 4.1σ to 3.7σ.

18 We note that this line is also clearly visible in the co-added L12A spectrum, with a slightly larger, but consistent, EW. However, due to the unreliability of the L12A channel at λ ≥ 1140 Å (see footnote 8, Section 2), we conservatively decided not to consider this as a supporting evidence.
The width of the z_{BLB} H\textsc{i} absorber is marginally consistent, at a 2.5\sigma level, with the expected broadening (Figure 9). Here we therefore assume that the H\textsc{i} BLB is associated with the bulk of the X-ray O\textsc{vi} absorber.

There is no detectable O\textsc{vii} or N\textsc{iii} absorption associated with the z_{BLB} H\textsc{i} absorber. The non-detection of O\textsc{vii} puts a much more stringent lower limit on the temperature of the detected WHIM filament. At the best-fitting X-ray temperature $T \approx 300 \text{ K}$, the thermal speed of protons is $v_0 = 250 \text{ km s}^{-1}$ and so the expected broadening of H\textsc{i} is $\text{FWHM} \approx 400 \text{ km s}^{-1}$. The width of the $z_{BLB}$ H\textsc{i} absorber is 1.5\sigma above the expected Doppler parameter of $b \approx 165 \text{ km s}^{-1}$, for hydrogen in gas at $\log T \sim 6.5$.

### Table 3

| Redshift | $T (\text{in K})$ | $N_{HI}$ (10$^{21}$ cm$^{-2}$) | Metallicity | Thickness* (Mpc) |
|----------|------------------|-------------------------------|-------------|------------------|
| 0.118 ± 0.001 | 6.56$^{+0.19}_{-0.04}$ | $1.3^{+0.7}_{-0.4}$ (1–5)% $Z_\odot$ | 5$^{+2}_{-1}$ |

Note. *For a baryon volume density of $n_b = 10^{-4} \text{ cm}^{-3}$.

6.56 K, the thermal speed of protons is $\sqrt{2b} = 250 \text{ km s}^{-1}$ and so the expected broadening of H\textsc{i} absorption lines is $\text{FWHM} \approx 400 \text{ km s}^{-1}$. The width of the $z_{BLB}$ H\textsc{i} absorber is marginally consistent, at a 2.5\sigma level, with the expected broadening (Figure 9). Here we therefore assume that the H\textsc{i} BLB is associated with the bulk of the X-ray O\textsc{vi} absorber.

There is no detectable O\textsc{vii} or N\textsc{iii} absorption associated with the $z_{BLB}$ H\textsc{i} absorber. The non-detection of O\textsc{vii} puts a much more stringent lower limit on the temperature of the detected WHIM filament. At the best-fitting X-ray temperature the relative fraction of O\textsc{vii}, $\xi_{O\textsc{vii}} = 2.0^{+9.0}_{-0.8} \times 10^{-4}$, predicts (for unsaturated lines) $\text{EW(O\textsc{vii})} = 7.6^{+6.8}_{-0.6} \text{ mÅ}$. From the FUSE data we have $\text{EW(O\textsc{vii})} = 0.118 \lesssim 12 \text{ mÅ}$ at a 1\sigma confidence level (Table 2). By linearly interpolating between expected O\textsc{vii} fractions and EWs, we derive the 1\sigma upper limit on the fraction of O\textsc{vii} corresponding to the measured EW(O\textsc{vii}) upper limit, and from this the 1\sigma lower limit on the temperature of the absorber. This gives $T > 6.52$. Thus by combining the UV and X-ray constraints on the temperature of the WHIM filament, one gets $\log T = 6.56^{+0.17}_{-0.04}$ (Table 3).

The IUE satellite observed PKS 0558-504 twice with the “Short Wavelength Primary” (SWP), low-resolution ($\Delta \lambda = 6 \text{ Å}$) spectrometer, on 1987 September 22 and 1989 November 14–15. We retrieved the data products of these three observations from the MAST archive, and analyzed them with Sherpa (ver. 4.1.2; Freeman et al. 2001). The three SWP low-resolution spectra (LR) of PKS 0558-504, are dominated by the intrinsic nuclear AGN continuum and emission line spectrum. However, the two spectra with highest S/N (ObsIDs 37589 and 37604; Table 1) show also marginal evidence for a narrow absorption feature imprinted on the blue wing of the H\textsc{i} Ly\alpha broad emission line of PKS 0558-504, at $\lambda \approx 1360 \text{ Å}$ (Figure 10). We fitted the three spectra simultaneously with a model, consisting of a power law plus narrow and broad components of the H\textsc{i} Ly\alpha and N\textsc{v} AGN emission lines and a negative absorption line to model the absorption feature at $\lambda \approx 1360 \text{ Å}$. The best-fitting parameters for this absorption line are listed in Table 2. We tentatively identify this low-significance (1.7\sigma) absorber as an intervening broad H\textsc{i} Ly\alpha (BLA) at $z_{BLA} = 0.119 \pm 0.001$, a redshift consistent with that of the $z_{BLB}$ H\textsc{i} absorber detected by FUSE. Figure 10 shows a portion of the highest S/N 1989 IUE-SWP LR (ObsID 37604) spectrum of PKS 0558-504, with our best-fitting superimposed, and the residuals after subtracting the Gaussian at $\lambda = 1360 \pm 1 \text{ Å}$.

### 4.1. Summary of the Observational Evidence

The far-UV and X-ray spectra of PKS 0558-504 show evidence for complex absorption, which is unlikely to be intrinsic to the AGN itself (Section 5.1). Figure 11 summarizes these conclusions, by showing the residuals (in \sigma), in velocity space, to the best-fitting continuum models to the FUSE (top panel), IUE-SWP LR (1989, second panel from the top) and XMM-Newton (GO: third and fifth panels from the top; CAL: fourth panel from the top) spectra of PKS 0558-504. The residuals are centered around the absorption lines that we identify as H\textsc{i} Ly\beta, H\textsc{i} Ly\alpha, O\textsc{vi} Ly\alpha, and Fe\textsc{xvii} L (\lambda = 15.015 \text{ Å}, rest frame), at a mean common redshift of $z = 0.118 \pm 0.001$ (all lines are consistent with this redshift). The red arrows in the figures indicate the best-fitting centroid of each line in their respective spectra.

The Fe\textsc{xvii} L (\lambda = 15.015 \text{ Å}) line (bottom panel) is only seen at 1.5\sigma and 2\sigma in the RGS1 GO and RGS2 CAL spectra (Figures 5 and 6), and is not visible in either the RGS2 GO or in

19 http://archive.stsci.edu/index.html
20 http://cxc.harvard.edu/ciao/index.html
the RGS1 CAL spectra, although all data are consistent with the presence of this line at the strength predicted by the best-fitting WHIM model. The O viii Kα line is present both in the GO (third panel from the top) and CAL (fourth panel from the top). RGS1 spectra (the RGS2 is blind in this spectral region). Finally, possible H1 lines are seen both in the FUSE (top panel) and IUE-SWP LR spectra: a BLB is detected in the high-resolution FUSE spectra, at redshifts z = 0.118 ± 0.001. Both redshifts are consistent with that of the H1 BLB expected, and not seen. The feature labeled “FPN” (fixed pattern noise) in the first and second panels from the top, is a known FUSE Lyα/F2A segment instrumental feature (e.g., Sembach et al. 2004).

(A color version of this figure is available in the online journal.)

Figure 11. Residuals (in σ), in velocity space, to the best-fitting continuum (plus ISM + v-velocity lines, in the case of FUSE) models to the FUSE (first and second panels from the top), IUE-SWP LR (1989, third panel from the top) and XMM-Newton (GO: fourth and sixth panels from the top; CAL: fifth panel from the top) spectra of PKS 0558-504. The residuals are centered around the absorption lines that we identify as H1 Lyβ, H1 Lyα, O viiii Lyα, and Fe xvii L (λ = 15.015 Å, rest frame), at a mean common redshift of z = 0.118 ± 0.001. The red arrows in the figures indicate the best-fitting centroid of each line in their respective spectra. The red segment labeled “O viii” in the second panel from the top, mark the spectral region where O vii associated with the H1 BLB is expected, and not seen. The feature labeled “FPN” (fixed pattern noise) in the first and second panels from the top, is a known FUSE Lyα/F2A segment instrumental feature (e.g., Sembach et al. 2004).

21 For unsaturated lines, the EW ratio of two electronic transitions 1 and 2 from the same series of the same ion X, is linearly related to the product between their oscillator strength (f) ratio times the square of their rest-frame wavelength (λ) ratio; i.e., \( \frac{EW_{X1}}{EW_{X2}} = \frac{(f_{X1}/f_{X2})}{(\lambda_{X1}/\lambda_{X2})^2} \). Thus, for the Lyα and Lyβ transitions of H1, one expects \( \frac{EW_{H1Lyα}}{EW_{H1Lyβ}} = 7.4 \).

The combined statistical significance of this detection is 5.2σ (4.6σ if systematics are considered, and the small contribution from the putative H1 BLA is not included).

5. DISCUSSION

5.1. Ruling Out Intrinsic Absorption

The far-UV and X-ray absorber along the line of sight to PKS 0558-504 is only ~ −6000 km s⁻¹ from the systemic redshift of PKS 0558-504. In principle, then, it could be identified with a high-speed outflow ejected from the Seyfert’s nuclear region in the direction of our line of sight. Such phenomena are common in AGNs and are known with the name of “Warm Absorbers” (WAs, in X-rays; e.g., George et al. 1998; Piconcelli et al. 2005) or “Narrow Absorption Line” absorbers (NALs, in the UV; e.g., Crenshaw et al. 2003). However, we note that, the physical, chemical and dynamical properties of the detected absorber are all quite different from those typically found in WAs and NALs, commonly detected in Seyferts and higher luminosity quasars.

WA/NAL outflow velocities typically span a range of few hundreds to few thousand km s⁻¹, with >80% of the objects having vout < 1500 km s⁻¹ (e.g., Blustin et al. 2005 for WAs in X-rays, and Kriss 2002 Crenshaw et al. 2003 for NALs in the UV) and are normally found to be present in several physical (temperature and densities) and velocity components in a single object both in X-rays (e.g., Krongold et al. 2003, 2005, 2009) and in the UV (e.g., Kriss 2002; Crenshaw et al. 2003). Here we measure an extreme velocity outflow of ~6000 km s⁻¹ and do not detect any other X-ray or FUV systems at lower velocity. The existence of very high ionization (Fe xxv and Fe xxvi) X-ray outflows, with sub-relativistic (i.e., ~0.1c) outflow velocities has been recently proposed for few objects (Reeves et al. 2009, and reference therein), but the existence and identification of these features are still highly debated (e.g., Uttley 2009). In all such proposed cases, however, the high-ionization absorber has very high equivalent hydrogen column density (few × 10²³ cm⁻²), is seen often together with other lower velocity, lower ionization components, and in some cases requires super-solar Fe abundance (Reeves et al. 2009, and references therein). We checked the high S/N XMM-Newton GO EPIC spectrum of PKS 0558-504 for the presence of blueshifted He- or H-like Fe absorption and did not find any down to equivalent hydrogen column densities of ≥10²⁵ cm⁻².

WA metallicities, when measured, are typically found to be at least Solar (e.g., Fields et al. 2005, 2007), in sharp contrast with the 1%–5% Solar value we measure for this absorber. We stress that our metallicity estimate for the z = 0.118 ± 0.001 absorber is virtually model independent. The H1 fractions in purely photoionized or collisionally ionized clouds of gas that best-fit the RGS spectra of PKS 0558-504, are almost indistinguishable from the H1 fraction that we derive from our best-fitting hybrid-ionization WHIM models. So, the metallicity correction needed to reconcile the H1 BLB (FUSE) and BLA (IUE) column density measurements with the X-ray equivalent hydrogen column density estimate is independent of the model used to fit the X-ray data.

Finally, we stress that high-ionization WAs are virtually always found to coexist with lower-ionization phases (e.g., HIP and LIP; Krongold et al. 2003, Andrade-Velasquez et al. 2010), which in turn are often one to one associated with NAL components in the UV. In the case of PKS 0558-504 we do not detect any intrinsic O vi or C iv absorption (see also Dunn et al.
2007). All this makes the identification of the detected absorber with a high velocity nuclear ionized outflow, unlikely.

A WA with unprecedented velocity, metallicity, and ionization phases appears to us to be less likely than the well-predicted WHIM possibility. We therefore tentatively identify this complex absorber with an intervening WHIM filament at the mean common redshift of $z = 0.118 \pm 0.001$, and in the following discussion associate the X-ray absorber with the far-UV BLB and BLA detected in the FUSE and IUE spectra.

5.2. Metallicity and Thickness of the WHIM Filament

In principle, the detection of clearly associated metal and H\textsc{i} transitions from the same WHIM filament, allows one to measure the metallicity of the absorber. In our case, the spectral resolution of the X-ray data is much poorer than that of the superior quality FUSE data, and the best-fitting width of the H\textsc{i} BLB absorber tentatively identified at a redshift consistent with that of the X-ray absorber (FWHM = $160^{+50}_{-30}$ km s$^{-1}$), is narrower than the expected H\textsc{i} BLB thermal width in gas with the temperature inferred from the X-ray data. Thus, a direct association between the H\textsc{i} BLB and the O vii absorbers cannot be clearly established, based on these data. However, both the redshifts of the H\textsc{i} BLB and the O vii absorbers is, within the large uncertainties (e.g., Figure 9), with the hypothesis that the bulk of the H\textsc{i} and the O vii absorbers are imprinted by the same gas. Under this assumption, we then estimate the metallicity of the putative WHIM filament, and note that this estimate would translate in a lower limit if the BLB and the metal absorbers were structured or not one-to-one associated.

From the measured temperature, $\log T = 6.56^{+0.19}_{-0.04}$ we derive the relative fraction of H\textsc{i} compared to total H: $\xi_{\text{H}} = (5.4^{+0.5}_{-0.6}) \times 10^{-8}$. As already mentioned in Section 3.3, the best-fitting temperature of the absorber is virtually independent of metallicity. We checked this by building two additional grids of models (other than the one with $Z = Z_\odot$ used to fit the X-ray data) with metallicity of $Z = 0.1 Z_\odot$ and $Z = 0.01 Z_\odot$. Figure 12 shows the O vii to H\textsc{i} fractional abundance ratio as a function of the temperature of the gas, for $Z = Z_\odot$ (black, solid curve), $Z = 0.1 Z_\odot$ (red, solid curve), and $Z = 0.01 Z_\odot$ (green, dashed curve). The ionization balance of the gas, at equilibrium, is virtually independent of the value of $Z$. From the metal-independent ionization correction value (i.e., $\xi_{\text{H}} = (5.4^{+0.5}_{-0.6}) \times 10^{-8}$), and the intrinsic (i.e., at $z = 0.1183$) H\textsc{i} column of $N_{\text{H}} = (9 \pm 2) \times 10^{13}$ cm$^{-2}$ (inferred from the measured EW(BLBB) = 66 $\pm$ 16 m\AA; FWHM(BLBB) = $160^{+50}_{-30}$ km s$^{-1}$), we can thus derive the expected equivalent H\textsc{i} column density of the absorber, which turns out to be $N_H = (1.7^{+0.3}_{-0.2}) \times 10^{21}$ cm$^{-2}$ (Table 3). Our best-fitting WHIM model measures $N_{\text{H}} = (3.2^{+1.1}_{-1.6}) \times 10^{21} (Z/Z_\odot)^{-1} \times 10^{-8}$. This gives $Z/Z_\odot = 0.02^{+0.02}_{-0.01}$ or $Z = (1-4)\% Z_\odot$ (Table 3).

With an estimate of the equivalent hydrogen column density of the absorber in hand, we can estimate the thickness of the absorber along the line of sight. This is given, assuming homogeneity by the ratio between the column and the volume baryon densities of the absorber: $D = N_{\text{H}}/n_{\text{b}}$. The value of $n_{\text{b}}$ is not constrained by the XMM-Newton data of PKS 0558-504. However, hydrodynamical simulations that include feedback from GSW predict that $n_{\text{b}}$ in the WHIM correlates with temperature (e.g., Figure 3 in Cen & Ostriker 2006), and that for a given temperature, lower metallicities are normally found in higher density environments (e.g., Figure 14 in Cen & Ostriker 2006). From Figure 14 of Cen & Ostriker (2006), at $T \sim 5 \times 10^6$ K, metallicities of the order of $\log(Z/Z_\odot) \approx -1.5$ are reached at overdensities, compared to the average density of the universe $\left(\delta = n_b/(n_{\text{b}}) \right) \approx 300$. At $z = 0.118$ and assuming $h = 0.7$, and $\Omega_m = 0.046$, this gives $n_b \approx 10^{-4}$ cm$^{-3}$. This implies $D \approx 5^{+2}_{-1} \times (n_b/(n_{\text{b}}))^{-1}$ Mpc.

Table 3 summarizes the physical and geometrical parameters of the WHIM filament at $z = 0.118 \pm 0.001$, along the line of sight to PKS 0558-504.

5.3. Number Density and Cosmological Mass Density of WHIM

A tentative O vii detection along a single line of sight cannot be used to measure the number density of O vii filaments and the cosmological mass density in the WHIM. However, we think that, in this particular case, this exercise is instructive because it clearly shows the serendipitous nature of the detection, and its bias toward dense (i.e., high EW) and rare absorbers.

We estimate the number density of O vii WHIM filaments, $n_{\text{O vii}}$, by taking into account the large Poissonian errors associated with small number statistics (Gehrels 1986). We get $n_{\text{O vii}}/d_z = 7.3_{-6.6}^{+21.1}$ and $\Omega_{\text{WHIM}} = 10^{-7.5}$ (90% significance). These numbers should be compared to the expected number density of WHIM filaments along a random line of sight, and to the total number of baryons as inferred by

22 This is because super-winds are very efficient in metal-polluting the IGM in the proximity of the host galaxy, but can only spread a finite amount of metals in a finite volume. Therefore, IGM regions with lower primordial baryon densities will increase their gas metal content more than regions with initially higher baryon densities.

23 This is consistent with our a priori assumption of freezing the value of the baryon density to $n_b = 10^{-5}$ cm$^{-3}$ in our fit to the X-ray data, since at $n_b \geq 10^{-5}$ cm$^{-3}$ the contribution of photoionization is negligible, and the best-fitting temperature and column densities are not affected by the exact value of this parameter.

24 We do not try to include systematics here, because of the already big (and probably dominating) statistical uncertainties associated with a single detection, which allow for the estimate to be consistent with all possible theoretical predictions.
both microwave background anisotropies ($\Omega_0 = 0.046 \pm 0.002$; Bennett et al. 2003; Spergel et al. 2003) and by the standard “big-bang nucleosynthesis” when combined with light-element ratios ($\Omega_0 = 0.044 \pm 0.004$, Kirkman et al. 2003). From Cen & Fang (2006, their Figure 4), we derive $d_{N_{\text{UV}}}/dz$ (EW $\gtrsim 9$ mÅ) $\approx 0.8$. This is consistent with the $90\%$ significance lower limit of our estimate. Similarly, our estimate of $\Omega_{\text{WHIM}}/\Omega_0 = 3.9^{+1.7}_{-1.5}$ greatly exceeds the expected value of about $40\%$–$50\%$ at $z \approx 0$ (e.g., CO06), but is consistent within the large $90\%$ uncertainties. This is not surprising, since the WHIM detection we report is a serendipitous discovery in the spectrum of a target whose observations were not planned with this aim, and as such is biased toward dense (i.e., high EW) and rare absorbers.

5.4. Caveats and their Solutions

Although the association between UV and X-ray absorbers reported here makes this detection of a probable WHIM filament the first for which a metallicity measure is possible, we caution that, due to instrumental limitations and uncertainties, a definitive identification of this absorber with an intervening WHIM filament is not possible with the current data.

First, the absorption that we identify here in X-ray as an O viii Ly$\alpha$ at $z = 0.117 \pm 0.001$, could also, in principle, be identified as O vi K$\beta$ near the systemic redshift of PKS 0558-504. We reject this interpretation based on the non-detection of associated O viii K$\alpha$ absorption with the predicted strength ($\gtrsim 6$ times stronger than the detected line)—together with several other strong lines that should be detectable in the X-ray spectrum (C vi, N vi, N vii, Ne ix, etc.)—and the lack of intrinsic O vi absorption in the RGS and FUSE spectra of PKS 0558-504, respectively. Moreover, the absorption seen both in FUSE and IUE and here identified as H i absorption cannot plausibly be identified with any transition at or near the systemic redshift of the target. Unfortunately, however, the O vii K$\alpha$ transition which would be associated with O vi K$\beta$ at $z \approx z_{\text{ion}}$, falls close to a strong RGS instrumental feature, which makes the source-frame absorption hypothesis difficult to reject with high confidence. The identification of the reported X-ray absorber with intrinsic nuclear O vii K$\beta$ is thus unlikely, but not impossible based on the current X-ray data only. The only way of confirming the intervening origin of the X-ray absorber would be to clearly detect the other two lines predicted by the best-fitting WHIM model (one of which already hinted in the GO RGS1 and CAL RGS2 spectra of PKS 0558-504): i.e., Fe xvii L ($\lambda = 15.015 \AA$) and Ne ix K$\alpha$, which fall at $\lambda = 15.02$ and $\lambda = 16.77 \AA$. This is a task that only the Chandra LETG grating could accomplish, thanks to its 40 cm$^2$ effective area at these energies (versus $\sim 50$ cm$^2$ for the RGS2 and $\sim 15$ cm$^2$ for the Chandra MEG), and factor of $\sim 2.5$ better spectral resolution, compared to the RGS.

Second, while our identification of the absorber as a system at $z = 0.118 \pm 0.001$ is the most probable with the currently available data, its origin might not be intervening. The absorber could also be intrinsic to the nuclear Seyfert environment, outflowing from the nucleus of PKS 0558-504. We discuss this possibility in Section 5.1, and conclude that the physical parameters inferred for this absorber, make this interpretation unlikely. A way to definitely exclude this possibility is to look for variability of the X-ray and far-UV features reported here. Observations with the HST-COS of the far-UV spectrum of PKS 0558-504 would not only definitely confirm or rule out the existence of Ly$\alpha$–$\beta$ absorption at $z = 0.1183 \pm 0.0001$ (the redshift in FUSE), but would also test for opacity (i.e., ionization state and/or column density) variability of this absorber, which, if detected, would make the WHIM identification impossible. Analogously, new high S/N X-ray (Chandra) high-resolution spectra of PKS 0558-504 would allow one to check for variability of the X-ray absorber.

A third observation that can help shedding light on the true identification of this absorber, by either strongly supporting or weakening the support for its intervening nature, is a measure of the galaxy density in the region surrounding the putative WHIM filament at $z = 0.118$. WHIM filaments are supposed to correlate strongly with concentrations of galaxies and with large-scale structure (e.g., Stocke et al. 2006). Unfortunately, the line of sight to PKS 0558-504 lies in the Southern sky, at a location which is currently poorly investigated: none of the major galaxy surveys or deep surveys (e.g., 2dF$^{25}$, 6dF$^{26}$, SDSS$^{27}$), covers this region of the sky. Wide-field, multi-band observations, centered on the line of sight to PKS 0558-504, and sensitive down to a fraction of $L^*$ at $z = 0.118$, would allow photometric redshifts of the galaxies in the field to be determined with sufficient accuracy to exclude foreground and background objects. Spectroscopic follow-ups would then allow one to precisely estimate the galaxy density at $z = 0.118$ in a surrounding area around the line of sight to PKS 0558-504, to investigate the association of WHIM filaments and LLSs.

6. CONCLUSIONS

We reported on the first combined and possibly associated far-UV and X-ray tentative detection of a WHIM filament at a mean common redshift of $z = 0.118 \pm 0.001$, along the line of sight to the Seyfert PKS 0558-504. Our main findings are the following.

1. O viii Ly$\alpha$ absorption is tentatively identified at $z = 0.117 \pm 0.001$ in two independent XMM-Newton RGS1 spectra of the Seyfert galaxy PKS 0558-504: a high S/N 480 ks net GO spectrum taken in 2008, and the sum of a number of much lower S/N spectra taken between 2000 and 2001 as part of an XMM-Newton calibration campaign, with a total net exposure of 309 ks. The combined, single-line significance of these two detections is $2.8\sigma$.

2. When fitted with a model including proper parameterizations of the continua together with our hybrid (collisional ionization plus photoionization) WHIM absorption model, the two full-band RGS1 and RGS2 spectra are consistent with the presence of a WHIM filament at $z = 0.117 \pm 0.001$ with log $T = 6.56^{+0.19}_{-0.17}$ and $N_H = (3.2^{+3.7}_{-1.6}) \times 10^{19}(Z/Z_{\odot})^{-1}$ cm$^{-2}$. Based on X-ray data only, the parameters of this model are poorly constrained and both represent only lower limits at a $3\sigma$ statistical confidence level.

3. Archival FUSE data of PKS 0558-504 show the presence of a broad absorption complex at $\lambda = 1147.1 \pm 0.1$, with single-line statistical significance of $4.1\sigma$ ($3.7\sigma$ when systematics are included). This line can be identified as broad H i Ly$\beta$ at $z_{\text{BLB}} = (0.1183 \pm 0.0001)$, consistent with the redshift of the putative X-ray O vii Ly$\alpha$, within the large X-ray uncertainties. The width of this BLB absorber is marginally consistent, at a $2.5\sigma$ level, with the thermal width of H i ions in gas with log $T = 6.56^{+0.19}_{-0.17}$ (the best-fit temperature derived from the X-ray data).

$^{25}$ http://www.mso.anu.edu.au/2dFGRS/
$^{26}$ http://www.aao.gov.au/local/www/6df/
$^{27}$ http://www.sdss.org/
4. Archival IUE-SWP, low-resolution, spectra of PKS 0558-504 taken in 1987 and 1989, also hint to the presence of an unresolved intervening H I Lyα at z_{BLA} = 0.119 ± 0.001, with a single-line statistical significance of only 1.7σ. The redshift of this absorber is consistent, within their relative 1σ uncertainties, with the redshift z_{BLA} of the H i absorber detected with FUSE. The BLA (IUE) to BLB (FUSE) EW ratio of these two lines is consistent with the expected unsaturated value.

5. We tentatively associate the O viii Lyα X-ray absorber at z = 0.117 ± 0.001, with the far-UV BLB and BLA absorbers at z_{BLB} = (0.1183 ± 0.0001) and z_{BLA} = 0.119 ± 0.001, respectively, and identify them with an intervening WHIM filament at the mean common redshift of z = 0.118 ± 0.001. The combined significance of this detection is 5.2σ (4.6σ if systematics in the FUSE continuum modeling are taken into account and the IUE H i BLA line is not considered).

6. The above identification allows us to estimate for the first time the equivalent hydrogen column density of the absorber and so its metallicity under the assumption that the bulk of the H i BLB and the O vii absorbers are physically associated. These turn out to be N_H = (1.5+0.4)×10^{21} cm^{-2} and Z = (1−4)% Z_⊙. If the H i BLB and the O vii absorbers are not directly associated or are structured, the above estimate represent upper and lower limits, respectively.

7. The non-detection of associated O vi absorption in the FUSE spectrum of PKS 0558-504, allows us to put a stringent lower limit on the temperature of the absorber: by combining X-ray and FUSE data we obtain log T = (6.56^{+0.19}_{−0.04}) K.

8. From the theoretical correlation between the temperature of WHIM filaments and their overdensity (relative to the average density in the universe) and the expected three-dimensional metallicity–temperature–overdensity relationship, we derive an overdensity of δ ~ 300 for our system, and therefore a thickness along the line of sight of 5+2−1 Mpc.

9. Finally from this single detection we extrapolate the number density of O vii Lyα WHIM absorbers and the cosmological mass density of WHIM. Both are consistent, within their large 1σ uncertainties due to the low-number statistics, with the expected values, but their central values are significantly higher due to the natural bias toward dense (i.e., high EW) and rare absorbers associated with serendipitous WHIM detections.

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