DETECTING THE WARM–HOT INTERGALACTIC MEDIUM THROUGH X-RAY ABSORPTION LINES

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ABSTRACT

The warm–hot intergalactic medium (WHIM) at temperatures 105–107 K is believed to contain 30%–50% of the baryons in the local universe. However, all current X-ray detections of the WHIM at redshifts z > 0 are of low statistical significance (≲3σ) and/or controversial. In this work, we aim to establish the detection limits of current X-ray observatories and explore requirements for next-generation X-ray telescopes for studying the WHIM through X-ray absorption lines. We analyze all available grating observations of Mrk 421 and obtain spectra with signal-to-noise ratios (S/Ns) of ∼90 and 190 per 50 mÅ spectral bin from Chandra and XMM-Newton observations, respectively. Although these spectra are two of the best ever collected with Chandra and XMM-Newton, we cannot confirm the two WHIM systems reported by Nicastro et al. in 2005. Our bootstrap simulations indicate that spectra with such high S/N cannot constrain the WHIM with O vii column densities N(O vii) ≳ 1015 cm−2 (corresponding to an equivalent width of 2.5 mÅ for a Doppler velocity of 50 km s−1) at ≳3σ significance level. The simulation results also suggest that it would take >60 Ms for Chandra and 140 Ms for XMM-Newton to measure the N(O vii) at ≳4σ from a spectrum of a background QSO with flux of ∼0.2 mCrab (1 Crab = 2 × 10−8 erg s−1 cm−2 at 0.5–2 keV). Future X-ray spectrographs need to be equipped with spectral resolution R ∼ 4000 and effective area A ≥ 100 cm2 to accomplish the similar constraints with an exposure time of ∼2 Ms and would require ∼11 Ms to survey the 15 QSOs with flux ≥0.2 mCrab along which clear intergalactic O vi absorbers have been detected.

Key words: BL Lacertae objects: individual (Markarian 421) – intergalactic medium – quasars: absorption lines – X-rays: diffuse background

Online-only material: color figures

1. INTRODUCTION

Identifying the “missing baryons” is one of the major tasks of modern cosmology. Observations of the microwave background (e.g., Komatsu et al. 2011) and the big bang nucleosynthesis model combined with the measurement of deuterium abundance (e.g., Burles et al. 2001; O’Meara et al. 2006; Pettini et al. 2008) are converging on the cosmological baryon density of Ωb = 0.0455 ± 0.0028. At high redshift (z > 3), baryons exist primarily in the form of cool, photoionized intergalactic medium (IGM) that is traced by Lyα absorption forest lines (Rauch et al. 1997). In the present-day universe, matter detected in forms of photoionized IGM, stars, galaxies, intracluster medium, etc., adds up to only ∼50% of the baryons (Shull et al. 2011), leaving much of the inventory yet to be found (Fukugita et al. 1998; Fukugita & Peebles 2004). Cosmological numerical simulations for large-structure formation indicate that the missing baryons are still in the IGM, but at the current epoch they have been heated by gravitational shocks and galactic feedback to temperatures of 105–107 K when they fall into the gravitational potential wells of the dark matter cosmic web filaments (e.g., Cen & Ostriker 1999, 2006; Davé et al. 2001). The IGM at these temperatures, the so-called warm–hot intergalactic medium (WHIM), mainly absorbs and emits photons in the ultraviolet (UV) and X-ray wavelength bands.

Searching for the missing baryons has been conducted extensively in the UV band. Indeed, besides the cool phase Lyα absorbers (e.g., Weymann et al. 1998; Penton et al. 2000, 2004), the absorption lines of C iii, C iv, N v, O vi, Si iii, and Si iv have been routinely observed in spectra of background quasistellar objects (QSOs; e.g., Tripp et al. 2000, 2008; Prochaska et al. 2004; Lehner et al. 2006; Danforth & Shull 2005, 2008; Danforth et al. 2006; Thom & Chen 2008; Yao et al. 2011), suggesting that a significant amount of baryons exist in the highly ionized absorbers. These high ions, O vi in particular, are believed to trace the WHIM at the low-temperature end (≲105−106 K). However, all these ions can also be produced through photoionization in the intergalactic environment (Oppenheimer & Davé 2009; but see also Tepper-García et al. 2011 and B. Smith et al. 2012, in preparation, for a contrary view) and thus some of them may not contribute to the canonical WHIM (i.e., the shock-heated IGM expected from simulations). How many of these absorbers originate in the real WHIM is still under debate (Danforth & Shull 2008; Tripp et al. 2008). Ne vii and broad H i Lyα absorbers (BLAs) are complementary and valuable tracers of hot absorbing WHIM in UV bands. However, there are only a few detections with marginal significance of Ne vii (Savage et al. 2005; Narayanan et al. 2009, 2011), and detections of BLAs require very high signal-to-noise ratio (S/N) of spectra to resolve broad and weak signals from the continuua (Richter et al. 2006; Lehner et al. 2007; Savage et al. 2011; Danforth et al. 2010, 2011). Converting measurement of these UV absorbers to census of baryonic matter also depends on ionization fractions and metallicity of the IGM, which in many absorbers are still poorly known. Nevertheless, BLAs and O vi absorbers, although partially overlapped with photoionized Lyα absorbers, are estimated to contribute an additional ∼25% to the baryon inventory at the current epoch (e.g., Danforth & Shull 2008; Danforth et al. 2011; Shull et al. 2011).

X-ray observations of the intergalactic O vii and O viii emission/absorption features could provide essential information for establishing the existence of the WHIM and completing the baryon inventory in the local universe (Perna & Loeb 1998). At temperatures T > 106 K, hydrogen and helium are nearly...
completely ionized (Gnat & Sternberg 2007). Without metals, the thermal gas emits/absorbs photons through bremsstrahlung, which unfortunately is optically thin even at intergalactic scales (Bregman 2007). Because the K-shell transitions of all elements heavier than lithium and the L-shell transitions of elements heavier than iron lie in X-ray bands (Paerels & Kahn 2003), metals can greatly increase the emissivity of the gas. However, because of the density-squared dependence, the WHIM emission is expected to be weak and difficult to detect. In fact, the IGM emission has been directly observed only from the dense regions like intracluster and intragroup media (e.g., Wang et al. 1997; Mulchaey 2000; Allen et al. 2002; Sun et al. 2009). The WHIM emission signals were also claimed in the angular correlation of the diffuse X-ray background (Soltan et al. 1999; Ursino & Galeazzi 2006), but disentangling the real WHIM signal from the unresolved point sources and local Galactic hot diffuse gas has been a major uncertainty (e.g., Galeazzi et al. 2007).

Unlike emission lines, absorption lines measure the column densities and thus directly sample the total mass of the intervening gas along a line of sight. Oxygen is the most abundant metal element. In contrast with O vi as a minority ionization state, O vii is the most abundant ion for a gas at temperatures of $T \sim 10^{5.5} - 10^{6.3}$ K, and O viii takes over when $T \gtrsim 10^{6.3}$ K (Gnat & Sternberg 2007). Thus, they have advantages over O vi in estimating the total baryon contained in highly ionized absorbers. O vii and O viii, whose production ionization potentials are 138.1 eV and 739.3 eV, respectively, compared with 113.9 eV of O vi, are also hard to produce through photoionization in the IGM environment (e.g., Cen & Fang 2006; Chen et al. 2003). Theoretical calculations indicate that the O vii column density is about 10 times higher than O vi in a shock-heated gas (i.e., $N_{O\,\text{vii}} \gtrsim 10 N_{O\,\text{vi}}$) whereas $N_{O\,\text{vii}} \lesssim 3 N_{O\,\text{vi}}$ in a photoionized gas (Furlanetto et al. 2005). Therefore, observations of the IGM O vii and O viii absorption lines are crucial, not only for constraining the properties of the WHIM at the high-temperature end but also for probing the nature of the commonly observed O vi absorbers.

Unfortunately, most attempts at searching the X-ray WHIM absorption lines have been frustrated. O vii and O viii absorption lines at $z = 0$ have been unambiguously detected in many background QSOs. However, all these X-ray absorptions are inconsistent with an intergalactic origin (Fang et al. 2006; Bregman & Lloyd-Davies 2007; Yao et al. 2010), but rather can be attributed to the Galactic diffuse hot gas (e.g., Yao & Wang 2005, 2007; Yao et al. 2008, 2009; Wang et al. 2005). Perhaps the most compelling intergalactic result is the detection of O vii absorption at the redshift of the large galaxy structure Sculptor Wall ($z_{abs} = 0.03$) along the QSO sight line H2356-309 ($z_{QSO} = 0.165$), albeit of low significance ($\sim 3\sigma$; Buote et al. 2009; Fang et al. 2010). However, because of the high number density of galaxies along the sight line, the absorption may sample the halo gas of one or more intervening galaxies with small impact distances ($\lesssim 50$ kpc; Williams et al. 2010), i.e., mimicking the O vii and O viii absorption lines at $z = 0$. Therefore, it may not be representative of the typical WHIM. Furthermore, attempts at searching for the similar absorption features at the redshift of another large structure, Pisces-Cetus along the same sight line, failed (Zappacosta et al. 2010). All other claimed WHIM O vii and O viii absorptions have been highly debated. For instance, the detected O viii absorption line at $z = 0.0554$ in the Chandra spectrum of PKS 2155-304 (Fang et al. 2002b, 2007) cannot be confirmed by the XMM-Newton observations (Cagnoni et al. 2004), although at nearby redshift a small galaxy group and the corresponding UV O vii and Lyα absorption lines have been identified (Shull et al. 1998, 2003). Nicastro et al. (2005) obtained a spectrum with unprecedented S/N during the burst states of Mrk 421 and reported two WHIM detections at $z = 0.011$ and $z = 0.027$. Again, observations with XMM-Newton cannot confirm the detections and reported significances have also been questioned (Kaastra et al. 2006; Rasmussen et al. 2007). Williams et al. (2010) recently found a galaxy filament at $z = 0.027$, which makes the reported O vii WHIM detections along the Mrk 421 sight line a subject of discussions again.

In this work, we aim to provide detection limits of current X-ray observatories, Chandra and XMM-Newton, in measuring the WHIM through X-ray absorption lines and to establish requirements (e.g., effective area and spectral resolution) for next-generation X-ray telescopes. We begin our investigation by scrutinizing the controversial WHIM detections along the Mrk 421 sight line. We extensively explore all the available Chandra and XMM-Newton observations and then run bootstrap simulations to test the reliability of any absorption feature.

The paper is organized as follows. In Section 2 we describe the observations and our data reduction processes, and in Section 3 we report the data analysis results and compare them with previous work. In Section 4, we run bootstrap simulations to explore the detection limits of Chandra and XMM-Newton and to establish requirements of next-generation X-ray telescopes. We summarize our results in Section 5.

Throughout the paper, we adopt the atomic data from Verner et al. (1996) and solar abundances from Asplund et al. (2009). We conduct our data analysis within XSPEC (version 12.6; Arnaud 1996) and report the 1σ confidence range or $3\sigma$ limit for a fitting parameter. We take the flux normalization of 1 Crab $= 2 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ at 0.5–2.0 keV. Thus, 0.2 mCrab is $2.15 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ for a flat spectrum in wavelength space, which corresponds to $2.34 \times 10^{-4}$ photons s$^{-1}$ cm$^{-2}$ Å$^{-1}$ around the O viii Kα (21.602 Å) at the rest frame. We define the measurement significance level (SL) of an absorption line as

$$SL = \frac{EW}{\Delta EW},$$

where EW and $\Delta EW$ are the equivalent width and its 1σ uncertainty, respectively, for an absorption line.

## 2. OBSERVATIONS AND DATA REDUCTION

We used all grating observations of Mrk 421 observed with both Chandra and XMM-Newton that are available as of 2011 April. Since Mrk 421 is a calibration source for both observatories, observations were taken on a nearly regular basis. The Chandra data were downloaded from the CXO archive Web site, which included 26 observations taken with the Low Energy Transmission Grating (LETG; ObsIDs of 1715, 4149, 4149, 5171, 5318, 5331, 5332, 6925, 8378, 8396, 10664, 10665, 10667, 10668, 10669, 10671, 11605, 11606, 11607, 11966, 11970, 11972, 11974, 12121, 12122, and 13097) with total exposure of 752.8 ks. This data set does not include observations taken with imaging mode and those with the High Energy Transmission Grating (HETG). A quick estimate indicates that these excluded observations would contribute an additional <10% to the total spectral counts, and thus our results will not be noticeably affected with or without them. For each employed

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3 http://cda.harvard.edu/chaser/mainEntry.do
observation, we used software package CIAO (version 4.3)\(^4\) and followed the standard procedure to re-calibrate, extract the spectrum, and calculate the instrumental redistribution matrix file (RMF) and ancillary response file (ARF). For observations that used the Advanced CCD Imaging Spectrometer (ACIS) as the detector, we only utilized the first grating orders. The High Resolution Camera (HRC) does not have spectral resolution itself, and the spectral orders in observations with HRC cannot be sorted out. Therefore, for these observations, we calculated the RMFs and ARFs up to six grating orders and combined them as one in spectral analysis to account for contributions from different orders (see descriptions in Section 3). To improve spectral S/N, we utilized the user-developed IDL tools (Yao & Wang 2007) to combine the negative and positive spectral orders, co-add spectra of different observations, and calculate the averaged RMF and ARF by using the spectral counts around 20 Å as weights. The claimed two WHIM detections were based on a subset of the observations listed above (Nicastro et al. 2005; e.g., ObsIDs of 1715, 4148, and 4149\(^5\)). To scrutinize the reported WHIM detections, we produced three co-added spectra and the corresponding RMFs and ARFs, based on observations used by Nicastro et al. (Spectrum I), observations not included in their work (Spectrum II), and all observations together (Spectrum III), respectively. Figures 1–3 show six portions of these spectra.

A total of 76 XMM-Newton observations were downloaded from the XMM-Newton science archive.\(^6\) We used script package SAS (version 10.0)\(^7\) to reprocess these observations. To avoid the severe contamination from the background flares, for each observation we calculated the count rate on the chip CCD\(^9\) and created good time intervals (GTIs) by excluding time periods with rates higher than 0.2 counts s\(^{-1}\). After this filter, there are 54 remaining observations, and each of them has integrated GTIs longer than 5 ks. We then extracted spectra, calculated RMFs for each of the exposures taken with the Reflection Grating Spectrometer (RGS), and combined the spectra of these 54 observations and the corresponding RMFs by running the script rgscombine to get the final co-added spectrum (Spectrum IV; Figure 4), which has a total exposure of 1.2 Ms.

We used a bin size of 25 mÅ to re-bin all the co-added spectra, which is equivalent to an oversample factor of 2 for a ~50 mÅ

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\(^4\) http://cxc.harvard.edu/ciao/index.html

\(^5\) Nicastro et al. (2005) in fact also included two additional HETG observations, which contributed negligible spectral counts to their final spectrum.

\(^6\) http://xmm.esac.esa.int/xsa/index.shtml.

\(^7\) http://xmm.esac.esa.int/sas/.
resolution element of the LETG and RGS. Table 1 summarizes the S/Ns of these spectra.

3. SPECTRAL ANALYSES, RESULTS, AND DISCUSSION

Our goal in this section is to examine the WHIM detections at redshifts $z = 0.011$ and $z = 0.027$. Nicastro et al. (2005) reported the WHIM absorption from transitions of Ne IX Kα, O vii Kβ, O viii Kα, O vii Kβ, N vii Kα, and C iv Kα (Table 2 and Figure 8 in Nicastro et al. 2005), whose rest-frame wavelengths are 13.447, 18.629, 18.969, 21.602, 28.787, and 33.736 Å, respectively (Verner et al. 1996). Therefore, we focus our attention on spectral ranges covering these transitions.

Obtaining a good continuum model is crucial to absorption-line measurement. Since all co-added Chandra spectra contain the contribution from HRC observations, to account for grating-order-overlapping issues (Section 2), we decide to fit a broad range of the spectra from 7 to 40 Å, which covers the transitions to be examined. For ease of comparison of three Chandra spectra, we jointly fit Spectra I, II, and III. We first use a Galactic absorption modified power law ($\text{wabs*powerlaw}$ in xspec) to fit the continuum emission, with neutral hydrogen column density $N_H$ linked together while the power-law index $\Gamma$ and normalization are allowed to vary. We obtain an unacceptable fit with $\chi^2 = 11,646$ over 3590 degrees of freedom (dof), and we find that some “broad” features cannot be accounted for by this simple model. These features are mainly due to imperfect instrumental calibration around node boundaries, CCD chip gaps plus dithering effects, the oxygen absorption edge, and imperfect cross calibration between ACIS and HRC observations (Marshall et al. 2004; Nicastro et al. 2005). We then use Gaussian profiles to compensate the uncounted calibration residuals. To minimize the effect of the known strong interstellar medium (ISM) absorption lines on continuum modeling, we include narrow absorption lines (with widths $\sigma \lesssim 50$ km s$^{-1}$) of O i, O ii, C vi, O vi, O vii, and Ne ix Kα and O vii Kβ transitions at their rest-frame wavelengths (Verner et al. 1996; Juett et al. 2006; Yao et al. 2009) in our spectral fitting. The centroid energies and widths of these Gaussians are linked together while the normalizations are allowed to vary in the jointly spectral fitting. We find that, besides these narrow absorption lines produced in the ISM, we need 1 narrow and 10 broad Gaussian profiles to obtain an acceptable fit, and locations of these Gaussians are 10.53, 13.80, 14.60, 17.90, 18.19, 19.02, 19.10, 23.24, 23.31, 23.66, and 29.89 Å with widths ($\sigma$) of 0.61, 2.56, 0.04, 0.00054, 0.17, 1.36, 0.10, 1.45, 1.69, 0.41, and 0.39 Å. The final $\chi^2 = 4448.2$ with 3512 dof and the constrained $N_H = 1.092 \pm 0.06 \times 10^{20}$ cm$^{-2}$, and $\Gamma = 2.131 \pm 0.001$, 2.011 \pm 0.001, and 2.067 \pm 0.001 for Spectra I, II, and III, respectively. Because the absorption line measurement depends only on the local continuum, and because the centroids of these Gaussian profiles do not directly superpose on the wavelengths of the putative WHIM absorption lines, these Gaussian profiles will not

![Figure 2](image-url)
Figure 3. Same as Figure 1, except that the spectrum (Spectrum III) was extracted from all available Chandra-LETG observations.
(A color version of this figure is available in the online journal.)

Table 1
Spectral Analysis Results

| Line    | Redshift | \( \text{S/N} \) | EW (mÅ) | \( \text{S/N} \) | EW (mÅ) | \( \text{S/N} \) | EW (mÅ) | \( \text{S/N} \) | EW (mÅ) |
|---------|----------|----------------|---------|----------------|---------|----------------|---------|----------------|---------|
| O vii   | \( z = 0 \) | 68.9 | 10.9 ± 0.9 | 64.9 | 12.5 ± 0.9 | 94.5 | 11.7 ± 0.6 | 193.0 | 14.9 ± 0.6 |
|         | \( z = 0.011 \) | 67.6 | <3.0 | 62.8 | <1.5 | 92.2 | <1.6 | ... | ... |
|         | \( z = 0.027 \) | 66.2 | <3.1 | 60.6 | <1.5 | 89.6 | <2.0 | ... | ... |
| O viii  | \( z = 0 \) | 68.9 | 11.3 ± 1.0 | 64.9 | 11.8 ± 1.1 | 94.5 | 11.6 ± 0.9 | ... | ... |
|         | \( z = 0.011 \) | 67.6 | 3.3 ± 1.2 | 62.8 | <2.0 | 92.2 | 2.0 ± 1.1 | ... | ... |
|         | \( z = 0.027 \) | 66.2 | <3.3 | 60.6 | <1.5 | 89.6 | <2.0 | ... | ... |

Notes. The S/N is given per 50 mÅ resolution element around the lines, and EW is the measured equivalent width. Error ranges are quoted at 1σ significance level, while the upper limits are at 3σ.

a Measurements are obtained from the spectrum corresponding to observations used by Nicastro et al. (2005; Spectrum I; Figure 1).
b Measurements are obtained from the spectrum corresponding to those observations not used by Nicastro et al. (Spectrum II; Figure 2).
c Measurements are obtained from the spectrum corresponding to all observations (Spectrum III; Figure 3).
d EW measurements in these three rows are obtained from the best-fit continua without compensation of the 11th broad Gaussian (blue curves in Figures 1–4).
e The measured upper limits to EW of the O vii Kα are obtained by fixing the line centroid at \( z = 0.028 \) instead of \( z = 0.027 \), since Nicastro et al. (2005) reported an O vi line at the former redshift. See the text for details.
f EW measurements in these three rows are obtained from the best-fit continua with compensation of the 11th broad Gaussian (red curves in Figures 1–3). However, since the 11th broad Gaussian profile is statistically unnecessary, these measurements are for comparison purposes only.

have any effect on the line EW measurement conducted below. The XMM-Newton spectrum (Spectrum IV) does not have the grating-order-overlapping issue, so we use the wabs*powerlaw model to fit the six narrow spectral ranges as plotted in Figure 4. We exclude the bad pixels in our spectral analysis and obtain \( \chi^2/\text{dof} = 1.36, 1.49, 1.49, 1.28, 1.75, \) and 1.56 with dof of 137, 75, 103, 105, 116, and 104, respectively. Figures 1–4 show these best-fit continua with the ISM absorption lines removed from spectral models.

Now, let us examine the existence of the reported WHIM absorption lines. Figures 1–4 show the same portions of Chandra and XMM-Newton spectra as shown in Figure 8 of...
In Nicastro et al. (2005), they demonstrated their detections of the WHIM absorption lines at $z = 0.011$ and $z = 0.027$ from transitions of Ne IX Kα, O vii Kβ, O viii Kα, O vii Kβ, N vii Kα, and C iv Kα. In particular, Figure 1 reproduces their Figure 8, as they were extracted from the same Chandra observations. Several bad pixels of the RGS accidentally fall around the 21.8 Å region and cause an instrument feature (Figure 4). Although a careful calibration could yield a correct instrumental response of the RGS, in this work we do not use the XMM-Newton spectrum to assess the WHIM detection at $z = 0.011$. Visual inspection reveals that none of the above WHIM lines reported by Nicastro et al. (2005) are detected in the Chandra observations they analyzed previously (Figure 1), in the newly available Chandra observations (Figure 2), and in the XMM-Newton observations (Figure 4).

The reported WHIM detections could be due to the improper continuum placement on the spectrum. Visual inspection also reveals that there might be an absorption feature at $\sim$21.8 Å in Spectrum I, which corresponds to the reported O vii Kα WHIM absorption line at $z = 0.011$ (panel (c) in Figure 1). However, such an absorption feature is not visible in Spectra II and III (panel (c) in Figures 2 and 3), and its significance in Spectrum I depends largely on how the local continuum is placed. Please note that our spectral profiles of the local continua were obtained by jointly fitting Spectra I, II, and III (see above), and the best-fit model seems to account for the general spectral variation reasonably well. To quantitatively assess the existence of the O vii Kα WHIM line at $z = 0.011$, in the joint analysis of Spectra I, II, and III, in addition to the 10 Gaussian profiles, we add the 11th “broad” Gaussian to the local continuum and another narrower Gaussian with width$^8$ $\sigma = 50$ km s$^{-1}$ to represent the WHIM absorption line. Again, we link the line centroids and widths together in our joint fitting but allow the normalizations to vary among Spectra I, II, and III. The best fit yields a line centroid of 21.90 Å and $\sigma = 0.050$ Å for the “broad” component and a centroid of 21.87 Å for the narrow component. The red curves in panel (c) of Figures 1–3 show the modified local continua. These additional components reduce the $\chi^2$ of 26.4 by adding nine dof in total. However, applying the best-fit models to individual spectra yields a $\chi^2$ change of 13.7, 4.3, and 10.4 by introducing five additional dof to spectral fitting of Spectra I, II, and III, respectively. All these Chandra spectra can be well described by the same continuum profile with various normalizations, which has been proved to be reasonable to other wavelength ranges (panels (a)–(b) and (d)–(f) in Figures 1–3). Because we find essentially no improvement in

$^8$ Different widths yield nearly identical results as long as the line is still unresolved by the instrument. Please see Section 4.1 for justifications for the line width.
The findings in this work are consistent with the previous calibration observations of lines originating from the ISM (Savage et al. 2005). We next attempt to measure the EWs of the putative WHIM absorption lines. Since we have not consistently detected any WHIM absorption of any transitions reported by Nicastro et al. (2005), we focus here on measuring the upper limit to the EW of the O\textsc{vii} \(K\alpha\) line, which is expected to be the most abundant transition in a broad temperature range of the WHIM (Section 1). At redshifts \(z = 0.011\) and \(z = 0.027\), the rest-frame O\textsc{vii} \(K\alpha\) at 21.60 Å is shifted to 21.84 and 22.19 Å, respectively, and therefore our measurements are obtained from the spectral range described by the continuum colored as blue in panel (c) of Figures 1–4. To make a fair comparison with the results obtained by Nicastro et al. (2005), we also make similar measurements by using the continuum colored as red. We should emphasize that the latter measurements are only for comparison purposes, since the additional component to the local continuum that “amplifies” the significance of the absorption line at 21.8 Å is statistically unnecessary. Our results are reported in Table 1.

In summary, our analysis and results do not support the existence of the two WHIM systems at \(z = 0.011\) and \(z = 0.027\). We analyze all the available Chandra and XMM-Newton observations of Mrk 421 and have not seen any consistent WHIM absorption of any transition at either \(z = 0.011\) or \(z = 0.027\) reported by Nicastro et al. (2005). We measure the EW of the O\textsc{vii} \(K\alpha\) absorption line. For the system at \(z = 0.027\), we obtain a firm 3\(\sigma\) upper limit of EW < 1.5 mÅ from the spectrum (Spectrum II) extracted from the newly available Chandra observations, in contrast to EW = 2.2 \(\pm\) 0.8 mÅ obtained by Nicastro et al. For the system at \(z = 0.011\), we confirm the existence of a small dip in the spectrum (Spectrum I) identical to that used by Nicastro et al. (2005), but a similar spectral feature is absent in Spectrum II. The measurement of the line heavily depends on how the local continuum is placed, and the additional spectral component that amplifies its significance is statistically unnecessary. We obtain an upper limit of EW < 1.5 mÅ from the new spectrum, in contrast to EW = 3.0\(^{+0.8}_{-0.8}\) mÅ reported by Nicastro et al. (2005). The findings in this work are consistent with the previous investigation made by Kaastra et al. (2006), in which the authors scrutinized the same data set used by Nicastro et al. and a subset of calibration observations of Chandra and XMM-Newton. Therefore, we conclude that there is no WHIM line detected at either \(z = 0.011\) or \(z = 0.027\) along the Mrk 421 sight line.

There are also other important absorption lines in the spectral range of interest (Figures 1–4). The prominent lines are O\textsc{vii}, Ne\textsc{iix}, C\textsc{iv} \(K\alpha\), and O\textsc{vii} \(K\beta\) at \(z \approx 0\), and the O\textsc{vi} \(K\alpha\) with rest-frame wavelength 22.0 Å at \(z \approx 0\) is also visible in all four spectra albeit less significant. Again, we only measure the EWs of O\textsc{vii} \(K\alpha\) and report them in Table 1. The O\textsc{vii} line at \(z \approx 0\) can be well explained as absorption from the Galactic diffuse ISM (Yao & Wang 2007), and the O\textsc{vi} line is also believed to originate from the ISM (Savage et al. 2005).

It is worth noting that the EW of O\textsc{vii} \(K\alpha\) at \(z \approx 0\) measured from XMM-Newton observations is \(\gtrsim\)3\(\sigma\) larger than that obtained from Chandra observations (Table 1). Such a discrepancy in O\textsc{vii} has also been measured by Kaastra et al. (2006). The causes of this discrepancy are still under investigation, and the results will be published elsewhere. In this paper, we mainly focus on X-ray absorption measurements of the WHIM and will not discuss these non-WHIM measurements any further.

4. Bootstrap Simulations

In Sections 2 and 3, we reprocessed all the available observations and obtained two spectra with the highest \(S/Ns\) ever collected with Chandra and XMM-Newton. Despite the increased \(S/N\), we still cannot confirm the X-ray WHIM detections reported by Nicastro et al. (2005). Given such a frustrating situation (see also discussions in Section 1), several crucial questions need to be answered before further major time allocations search for the WHIM through X-ray absorption line measurement: How high \(S/Ns\) are needed to firmly establish a WHIM detection? What is the O\textsc{vii} column density range suitable for Chandra and XMM-Newton to explore with reasonably long exposure time? Is it possible to conduct a systematic study of the WHIM using the current X-ray telescopes? If not, what are the requirements for next-generation X-ray telescopes?

4.1. Expected WHIM Properties and Required Instrumental Sensitivities

Before running bootstrap simulations to address these questions, we first review the WHIM properties based on the results of numerical simulations. We then estimate the required instrumental sensitivity to detect the WHIM by answering the following two specific questions: First, what O\textsc{vii} column density is needed to probe the majority of the baryons contained in the O\textsc{vii}-bearing WHIM? Cosmological simulations predict different O\textsc{vii} column density distributions per unit redshift with different recipes for galactic feedback and intergalactic photoionization (Fang et al. 2002a; Cen & Fang 2006; B. Smith et al. 2012, in preparation). In Figure 5 we convert two recent distributions (Figure 5 in Cen & Fang 2006 and figures in B. Smith et al. 2012, in preparation) to the fraction of baryons contained in the O\textsc{vii}-bearing WHIM as a function of O\textsc{vii} column density. In this conversion, we assume a single temperature and uniformly distributed metallicity for all absorbers. However, B. Smith et al. (2012, in preparation) find covariance between \(N_{\text{O\textsc{vii}}}\) and

\[ \frac{\text{EW}_1 - \text{EW}_2}{\sqrt{\text{DEW}_1^2 + \text{DEW}_2^2}}, \]

where DEW is the 1\(\sigma\) error of EW measurement.

\[ \text{log}(N_{\text{O\textsc{vii}}}(\text{cm}^{-2})) \]

\[ \text{Cen & Fang (2006)} \]

\[ \text{CIE} \]

\[ \text{CIE+photoionization} \]

Figure 5. Fraction of baryons contained in the O\textsc{vii}-bearing gas as a function of O\textsc{vii} column density. The solid line is derived from Figure 5 in Cen & Fang (2006). The dashed and dotted lines are derived from figures in B. Smith et al. (2012, in preparation), which consider collisional ionization equilibrium (CIE) only and CIE plus photoionization, respectively. See the text for details.
metallicity, and the WHIM is expected to be multiphase. To obtain a more realistic distribution, one should consider the ionization and metallicity correction together. However, without a detailed description of the WHIM properties (which in fact are our final goals), such a correction is difficult to apply. Considering the general trend that higher column density absorbers have higher metallicity, the plotted baryon fractions contained in the higher column absorbers (e.g., \( N_{\text{O vii}} > 10^{15} \text{ cm}^{-2} \)) should be regarded as upper limits. Furthermore, since there is no clear sign of convergence at low column densities (Cen & Fang 2006; B. Smith et al. 2012, in preparation), in our conversion we use a 4- or 6-degree polynomial to fit the number density distributions, which artificially generate turnover at column densities \( 10^{10} - 10^{12} \text{ cm}^{-2} \). The low column density absorbers could contain even more baryons if the distributions converge at lower columns. Nevertheless, Figure 5 gives an estimate of the baryon fraction distribution, which indicates that ~55% (or 65%) of baryons are contained in absorbers with \( N_{\text{O vii}} > 10^{14.5} \text{ cm}^{-2} \) and that ~30% (or 45% or 55%) of baryons are contained in absorbers with \( N_{\text{O vii}} > 10^{15} \text{ cm}^{-2} \).

Another important, yet to be determined property is the dispersion/Doppler velocity \( b_v \) of the O vii-bearing gas. This property, although not essential for the detectability of Chandra and XMM-Newton (Section 4.2), is important for estimating the required spectral resolution of future X-ray instruments (Section 4.3). Here we use O vi to as a reference. Assuming most detected IGM O vi tracing the WHIM at temperatures \( \sim 10^5 \text{ K} \) and the total \( b_v \) being a combination of thermal and turbulent motions through quadrature \( b^2_v = b^2_{\text{th}} + b^2_{\text{turb}} \), the median \( b_v \) = 30 km s\(^{-1}\) of the O vi absorption lines (Danforth & Shull 2008; Tripp et al. 2008) suggests a turbulent velocity of \( b_{\text{turb}} \sim 24 \text{ km s}^{-1} \) for the O vi-bearing gas. Higher temperature gas may have higher turbulent velocity. Thus, \( b_v \) of the O vii-bearing gas at temperatures \( \sim 10^6 \text{ K} \) is expected to be \( >40 \text{ km s}^{-1} \). Another useful reference is the hot phase Galactic ISM traced by the O vi absorption line at \( z \approx 0 \), although the IGM environment could be substantially different from the ISM. Nevertheless, along the Mrk 421 and LMC X-3 sight lines, the \( b_v \) of the O vii gas can be as large as 100 km s\(^{-1}\) (Wang et al. 2005; Yao & Wang 2007; Yao et al. 2009). We therefore will explore three \( b_v \) values, 50, 75, and 100 km s\(^{-1}\), in our simulations.

Second, what is the flux limit that X-ray telescopes should reach in order to statistically investigate the WHIM? The answer to this question depends largely on how many WHIM systems are planned to detect. Clearly when more systems are detected, one can investigate WHIM properties, like thermal and dynamic properties, metallicities, and their evolution with redshift. To obtain a spectrum with a requested S/N, the required exposure time is inversely proportional to the flux of a QSO. And the higher the redshift of a QSO, the higher possibility there is of intervening WHIM absorbers along the line of sight. Therefore, to estimate the number of WHIM systems that could be detected, one should create a target list by considering the QSO redshift and flux as a whole.

In this work, instead of providing a target list for the WHIM investigation, we require that future X-ray telescopes be able to observe and search for the corresponding O vii absorbers along the majority of the sight lines where IGM O vi absorbers have already been reported (Section 1). In this regard, we examine the target lists in Danforth & Shull (2008) and Tripp et al. (2008) and find that there are ~80 IGM O vi systems along 28 QSO sight lines reported so far. Among them, we have assembled the available soft X-ray fluxes\(^{10} \) for 24 sight lines from the bright source catalogs of Einstein, ASCA, BeppoSAX, and ROSAT and from several pointing observations with XMM-Newton and Chandra (Wilkes & Elvis 1987; Ueda et al. 2005; Reeves & Turner 2000; Verrecchia et al. 2007; Bianchi et al. 2009; Papadakis et al. 2007; Foschini et al. 2006; Porquet et al. 2004; White et al. 2000; Leighly et al. 2007). These fluxes range from 0.006 to 46.5 mCrab with a median of ~0.3 mCrab. Fifteen of them have fluxes >0.2 mCrab and sample a total redshift path length of \( \Delta z \approx 2.1 \). For the WHIM O vii absorbers with \( N_{\text{O vii}} > 10^{15} \text{ cm}^{-2} \), Cen & Ostriker (2006) predicted the absorber frequency to be \( d N / d z \sim 7 \), and B. Smith et al. (2012, in preparation) predicted the frequency to be ~20 considering collisional ionization only and \( d N / d z \sim 5 \) if photoionization is included. For absorbers with \( N_{\text{O vii}} > 10^{14.5} \text{ cm}^{-2} \), \( d N / d z \) is predicted to be ~18, 12, and 110, respectively. Therefore, X-ray telescopes should be able to facilitate absorption line study from background sources with flux of ~0.2 mCrab, and >10 WHIM systems with \( N_{\text{O vii}} > 10^{15} \text{ cm}^{-2} \) and >24 systems with \( N_{\text{O vii}} > 10^{14.5} \text{ cm}^{-2} \) are expected in these sources along which the corresponding O vi absorptions are already known.

4.2. Detection Limits of Current X-Ray Telescopes

We now use bootstrap simulations to examine the detectability of Chandra-LETG and XMM-Newton-NGS. In our simulations, we utilize the user-developed absorption line model abslinel (Yao & Wang 2005) to model O vi absorbers with column density \( N_{\text{O vii}} \) and dispersion velocity \( b_v \) and use a power-law (PL) continuum to model an emission spectrum. With the input parameters of \( N_{\text{O vii}}, b_v \), PL normalization, and an exposure time, we simulate two spectra within Xspec, using the RMFs and ARFs produced in Section 2, to mimic Chandra observations and XMM-Newton observations, respectively. From the simulated spectra, we use a Gaussian profile to represent the absorption line and measure its EW and uncertainty \( \Delta \text{EW} \) at the expected wavelength position and then calculate the line SL (Equation (2)). For a set of parameters, we repeat this procedure 1000 times and record the measurement SL of the line. We then sort the SL and select the 100th value (i.e., 90% simulation trials yield the SL equal to or higher than the selected value). We make the same measurement for various combinations of different exposure times, \( b_v \), and \( N_{\text{O vii}} \). Since the FWHM of the line-spread function (LSF) of both Chandra-LETG and XMM-Newton-NGS is ~50 mA, which is much broader than the expected \( b_v \) values of the WHIM O vi absorbers (Section 4.1), all simulated absorption lines appear unresolved. What really matters for measurement is the effective EW of an absorption line. To provide a direct comparison to observations, we convert the combination of \( N_{\text{O vii}} \) and \( b_v \) to EW through the curve of growth (COG), and the combination of exposure time, RMF, and ARF to S/N per 50 mA resolution element. For reference, we plot the COG of the O vii \( \text{K}\alpha \) line in Figure 6.

Figure 7 shows our simulation results. Taking the simulations for Chandra-LETG for an example, our results can be interpreted as follows: from a spectrum with S/N = 50 per resolution element, an O vii \( \text{K}\alpha \) absorption line with EW = 3.4, 5.7, 8.1, and 10.3 mA can be measured at \( >2\sigma \), \( 4\sigma \), \( 6\sigma \), and \( 8\sigma \) SLs, respectively, in 900 out of 1000 observations. In other words, to measure the absorption line with these EWs at \( 2\sigma, 4\sigma \),

\(^{10}\) We use a power-law form \( f(E) \sim E^{-1.1}dE \) to convert the reported flux to the energy range of 0.5–2.0 keV (Section 1).
6σ, and 8σ or higher SLs, a spectrum with S/N ≥ 50 is required. Interestingly, the measured line significances behave nicely like PL functions in the EW-S/N space. For reference, we formulize them as

\[
\log(\text{EW}) = \alpha \times \log(\text{S/N}) + \sum_{i=0}^{3} \beta_{i} \times \text{SL}^i, \tag{2}
\]

where SL is 2, 3, 4, 5, 6, 7, or 8. For Chandra simulations, \(\alpha = -0.932, \beta_{0-3} = 1.79108, 0.188439, -0.0148031,\) and \(0.000476159,\) and for XMM-Newton, \(\alpha = -0.970, \beta_{0-3} = 2.14183, 0.217703, -0.0197475,\) and \(0.000748764.\)

Let us use our simulation results to further examine the two putative WHIM systems. In Figure 7, we also plot the EWs reported by Nicastro et al. (2005) and their 1σ errors at the corresponding S/N positions of Spectrum I. We find that their reported SLs appear to be consistent with expectations of our simulations. However, we stress again that their SL measurement could have been largely impacted by the improper continuum placement (Section 3). Our simulations indicate that an O\textsc{vii} absorption line with EW = 3.0 mÅ at \(z = 0.011\) (Nicastro et al. 2005) should be measured at \(\gtrsim 3.7\sigma\) SL from Chandra Spectrum III with S/N = ~ 92 (Equation (2); Figure 7). This is in contrast to the fact that we only obtain an upper limit (Figure 3; Table 1). At \(z = 0.027,\) an O\textsc{vii} line with EW = 2.2 mÅ should be detected at \(\gtrsim 2.3\sigma\) from the co-added Chandra and XMM-Newton spectra, which, again, is in contrast to the fact that we only obtain upper limits. We therefore conclude that the putative O\textsc{vii} WHIM absorptions, if they exist at all, must have lower EWs than reported.

Is the reported WHIM absorption at \(z = 0.027\) associated with a galaxy filament? Williams et al. (2010) discovered a filament of late-type galaxies at \(z = 0.027,\) suggesting a possible association between the reported WHIM absorber and the filament. In the spectrum of PKS 0405–123 observed with the Cosmic Origins Spectrograph (COS) aboard the Hubble Space Telescope, a similar association has also been suggested by a broad O\textsc{v}i absorption line (Savage et al. 2010). The authors estimated that the WHIM contained within the abundant late-type galaxy groups could make up to 15% of the total baryons in the local universe. However, the non-detection of O\textsc{vii} at \(z = 0.027\) in this work leads us to conclude that there is, if at all, much less O\textsc{vii} than reported. A recent search in a high-S/N COS spectrum of Mrk 421 also failed to find any absorption feature of BLA at the redshift (Danforth et al. 2011). Similarly, there is no detected hot intragroup O\textsc{vii}-bearing gas in our Local Group (Fang et al. 2006; Yao & Wang 2007; Bregman 2007). Therefore, if there is any gas associated with the galaxy filament at \(z = 0.027\) along the Mrk 421 sight line, it must be at higher temperatures \((T > 10^6\text{ K})\) and/or be metal-poor and thus contain too little O\textsc{vii} and H\textsc{i} to be detected.

Our simulation results also have important implications for using current X-ray observatories to search for the WHIM absorption. First, Chandra and XMM-Newton can probe the WHIM absorbers with \(N_{\text{O vii}} \gtrsim 10^{15}\text{ cm}^{-2}\) with exposure times of \(\sim 1\text{ Ms}\) from a QSO spectrum with a flux of \(\sim 0.2\text{ mCrab}.)\) The O\textsc{vii} column densities correspond to EWs of \(\gtrsim 10–15\text{ mÅ}\) (Figure 6), which require a Chandra (XMM-Newton) spectrum with S/N = 18–27 (41–63) to measure it at \(\gtrsim 4\sigma\) significance levels (Figure 7; Equation (2)). To collect a spectrum with such an S/N, it takes 1.4–3.1 Ms for Chandra (adopting \(A = 20\text{ cm}^2\text{ effective area}\)) and 3.6–8.5 Ms for XMM-Newton (adopting \(A = 40\text{ cm}^2\text{ effective area}\)) from a QSO with 0.2 mCrab flux. This is consistent with the commonly detected O\textsc{vii} absorption lines, which trace the Galactic hot ISM, in the spectra of local QSOs \((z \lesssim 0.1)\) with fluxes \(> 2\text{ mCrab}\) (Fang et al. 2006; Bregman 2007; Yao & Wang 2007). However, the simulated \(dN/dz\) of O\textsc{vii} drops by about two orders of magnitude between \(N_{\text{O vii}} > 10^{15}\text{ cm}^{-2}\) and \(N_{\text{O vii}} > 10^{16}\text{ cm}^{-2}\) (B. Smith

**Figure 6.** COG of the EW of the O\textsc{vii} Kα absorption line vs. O\textsc{vii} column density with three different Doppler dispersion velocities \((b_i).\)

**Figure 7.** 2σ, 4σ, 6σ, and 8σ detection significance of O\textsc{vii} Kα vs. S/N per 50 mÅ resolution element with (a) Chandra-LETG and (b) XMM-Newton-RGS. The vertical red and blue lines mark the S/N levels of the final co-added spectra around the claimed O\textsc{vii} lines at \(z = 0.027\) and \(z = 0.011\), respectively. The red triangle and blue diamond indicate the detections and their 1σ ranges reported by Nicastro et al. (2005). In simulations, the instrumental response files were taken from Chandra observation with ID 4148 and XMM-Newton observation with ID 0099280201.

(A color version of this figure is available in the online journal.)
et al. 2012, in preparation), meaning that such high column \( O\text{vii} \) absorbers are extremely rare and may only exist in the circumgalactic environment around galaxy structures (e.g., Fang et al. 2010).

Second, it is likely infeasible to conduct a systematic study of the WHIM with \textit{Chandra} or XMM-\textit{Newton}. The EW for \( N_{\text{Ovii}} = 10^{15} \text{cm}^{-2} \) is \( \sim 2.5 \text{mA} \) (Figure 6), which requires a spectrum with \( S/N \sim 120 \) \((\text{Chandra})\) and 260 \((\text{XMM-\textit{Newton}})\) to measure it at 4\( \sigma \) significance level (Figure 7). It would require 61 Ms for \textit{Chandra} and 144 Ms for XMM-\textit{Newton} to collect a spectrum with such a high \( S/N \) from a QSO with 0.2 mCrab flux. Even for a blazar at its burst state like Mrk 421, it still takes 0.6 (1.4) Ms \textit{Chandra} (XMM-\textit{Newton}) time from the source continuously being bright at 50 mCrab level. It would take 341 Ms for \textit{Chandra} and 804 Ms for XMM-\textit{Newton} to complete the survey of the 15 background QSOs with fluxes \( \gtrsim 0.2 \) mCrab along which IGM \( O\text{vii} \) has been reported (Section 4.1). Furthermore, since the expected WHIM \( O\text{vii} \) absorption lines cannot be resolved, it is impossible to study the dynamics of the WHIM with either \textit{Chandra}-LETG or XMM-\textit{Newton}-RGS. Clearly, we need new X-ray spectrographs with much improved spectral resolution and much larger collecting area to systematically study the WHIM.

### 4.3. Requirement for Next-generation X-Ray Telescopes

The goal in this section is to establish the required spectral resolution and effective area for next-generation X-ray tele-
scopes. Since there is no existing X-ray telescope with spec-
tral resolution better than those of \textit{Chandra} and XMM-\textit{Newton}, we use Gaussian profiles to simulate the LSFs of the putative X-ray spectrographs. We assume a spectral resolution, which is defined\(^{11} \) as \( R = \lambda/\Delta\lambda \), of 1500, 3000, 4000, and 6000, respectively, with effective area of \( A = 1000 \text{cm}^2 \) throughout the whole wavelength coverage. We use four spectral bins within an FWHM spectral range (i.e., an oversample factor of 4) in our simulations. With a set of selected \( R \), \( N_{\text{Ovii}} \), and \( b_\text{v} \) of the \( O\text{vii} \)-bearing gas, we follow the same procedure as described in Section 4.2 to simulate an absorption spectrum of a background source with 0.2 mCrab flux for an assumed exposure time and then measure the EW and \( \Delta \sigma \) from the simulated spectrum. We repeat the procedure 1000 times and select the SL value so that 90\% trials have the same or higher SL. In a real observation, background source flux, instrumental effective area, and exposure time can compensate each other, so we define their product (FAE) as a figure of merit. Figure 8 shows our simulation results. For reference, we also label the corresponding EW to the labeled \( N_{\text{Ovii}} \) at the top \( X \)-axis of the plots. Table 2 summarizes the required exposure time for the future spectrograph with 1000 \text{cm}^2 effective area and different spectral resolutions to constrain the \( O\text{vii} \) absorption with \( N_{\text{Ovii}} = 10^{15} \text{cm}^{-2} \) and three different \( b_\text{v} \) values at \( >4\sigma \) and \( 6\sigma \) significance levels from a background source with 0.2 mCrab flux.

Our simulation results deserve some explanation. First, each significance contour has a steep PL plus a relatively flat floor in the logarithm FAE-\( N_{\text{Ovii}} \) space, which roughly corresponds to the shape of the COG (Figure 6). The transition locations indicate the column densities from which the saturation of a line begins to affect the measurement. Second, to constrain \( N_{\text{Ovii}} = 10^{15} \text{cm}^{-2} \) at the same significance levels, it takes an increasingly long time with increasing \( b_\text{v} \) for all resolutions except for \( R = 1500 \) (Table 2). This is mainly due to line broadening. With \( R = 1500 \), no lines with \( b_\text{v} \) \( \lesssim 120 \text{km s}^{-1} \) can be resolved, since the intrinsic line width is narrower than the instrumental LSF. Therefore, the simulations are analogous to those for \textit{Chandra} and XMM-\textit{Newton}, which explains the required exposure times being essentially the same for all \( b_\text{v} \) values. At \( R \gtrsim 3600 \), a line with \( b_\text{v} \gtrsim 50 \text{km s}^{-1} \) becomes resolved. Because the column density \( N_{\text{Ovii}} = 10^{15} \text{cm}^{-2} \), lines lie on the linear part of the COG (Figure 6), an increased \( b_\text{v} \) does not increase the EW but broadens the line profile and therefore requires longer exposure to pick up the absorption signals from the continuum.

A spectrograph with spectral resolution of \( R \gtrsim 3600 \) is required to resolve the expected WHIM \( O\text{vii} \) absorption lines. As we discussed in Section 4.1, the lower limit to the dispersion velocity of the WHIM \( O\text{vii} \) absorbers is expected to be \( b_\text{v} \gtrsim 50 \text{km s}^{-1} \), which is equivalent to an FWHM of 83.3 \text{km s}^{-1} for a Gaussian profile fit. Although we can measure \( b_\text{v} \) by comparing the different saturation levels of the \( K\alpha \) and \( K\beta \) transients of \( O\text{vii} \) from the “low”-resolution observations made with \textit{Chandra} and XMM-\textit{Newton} (e.g., Yao & Wang 2005, 2007), such a technique cannot be applied to a column density as low as \( N_{\text{Ovii}} \sim 10^{15} \text{cm}^{-2} \) because saturation is negligible and the \( K\beta \) line becomes too weak to be detectable. Therefore, we have to rely on the instrumental resolution (\( R \sim 3600 \)) to resolve the line and obtain the dynamical and kinematic information of \( O\text{vii} \) absorbers. Please note that, to date, the X-ray spectrograph with the highest spectral resolution is the High Energy Transmission Grating Spectrograph (HETGS; Canizares et al. 1986) aboard \textit{Chandra}, which has two sets of gratings: the high energy grating (HEG) and medium energy grating (MEG) with resolutions of \( \sim 1700 \) and 900 at 20 \text{Å}. Clearly, they are still not high enough for resolving the expected WHIM absorption line. Furthermore, the small effective area (<1 \text{cm}^2 and \( \sim 2 \text{cm}^2 \)) around 20 \text{Å} makes the HETGS infeasible for the task discussed here (please also see below). Figure 9 shows the necessity for high spectral resolution by comparing the LSFs of XMM-\textit{Newton}, \textit{Chandra}, and a next-generation X-ray spectrograph with \( R = 4000 \) and the corresponding simulated spectra. It demonstrates that an absorber with two velocity components separated by 150 km s\(^{-1}\) cannot be resolved by XMM-\textit{Newton} (\textit{Chandra}) even from a spectrum with \( S/N \) as high as 350 (200), but it can be clearly resolved by the next-generation spectrograph from a spectrum with \( S/N \sim 30 \).

With \( R = 4000 \), an effective area of \( A \gtrsim 100 \text{cm}^2 \) is needed for the spectrograph to systematically survey the WHIM \( O\text{vii} \) along 15 sight lines within 6 months. Assuming that all \( O\text{vii} \) absorbers have \( b_\text{v} = 75 \text{km s}^{-1} \), it would take 11.2 Ms for a spectrograph with \( R = 4000 \) and \( A = 100 \text{cm}^2 \) to finish

\(^{11}\) We use the FWHM of the LSF as \( \Delta\lambda \).

\[ \text{Table 2} \]

Simulation Results for Future X-ray Spectrographs

| \( R \) (50 km s\(^{-1}\)) | \( \sigma \) (75 km s\(^{-1}\)) | \( \Delta \sigma \) (100 km s\(^{-1}\)) |
|-----------------|-----------------|-----------------|
| 1500            | 416.9 (808.8)   | 398.8 (794.6)   | 414.6 (799.5) |
| 3000            | 217.4 (433.9)   | 237.6 (492.6)   | 277.8 (549.9) |
| 4000            | 171.1 (350.3)   | 212.1 (425.7)   | 241.2 (523.0) |
| 6000            | 126.3 (275.6)   | 162.9 (368.2)   | 208.3 (461.7) |

\[ \text{Notes.} \] Required exposure times in units of ks for future X-ray spectrographs with various spectral resolutions to obtain \( >4\sigma \) significance measurement of \( O\text{vii} \) \( K\alpha \) with \( N_{\text{Ovii}} = 10^{15} \text{cm}^{-2} \) and different dispersion velocities. The values in parentheses are required exposures for \( >6\sigma \) constraint (Figure 8).
surveying those 15 QSOs with $\gtrsim 0.2$ mCrab (Section 4.1) and measure the intervening WHIM absorbers with $N_{\text{OVII}} \sim 10^{15}$ cm$^{-2}$ at $\gtrsim 4\sigma$ significance. Assuming a 70% on-target timing efficiency, this is equivalent to a half year. To constrain the absorbers with $N_{\text{OVII}} \sim 10^{14.5}$ cm$^{-2}$ with the same amount of exposure time, $A = 1000$ cm$^2$ is required (Figure 8).

In this section, we focused on the instrumental requirement particular for the study of the WHIM. In fact, X-ray absorption/emission line diagnostics can also provide essential information for the physics of the ISM, stellar coronae, black hole accretion and outflow, quasar accretion and feedback, etc., and remarkable progress has already been made with Chandra and XMM-Newton observations (e.g., Yao & Wang 2006; Testa et al. 2008; Miller et al. 2006; Arav et al. 2007). With an X-ray spectrograph equipped with $R \sim 4000$ and $A \sim 100$ cm$^2$, we should be able to explore all these fields in great detail.

5. SUMMARY

1. We analyzed all available (as of 2011 April) grating data and obtained two co-added spectra with $S/N \sim 90$ per 50 mÅ resolution element from Chandra observations and $S/N \sim 190$ from XMM-Newton observations. Neither Chandra nor XMM-Newton observations support the existence of the two WHIM systems previously reported by Nicastro et al. (2005).

2. We ran bootstrap simulations for the detecting limits of the current X-ray telescopes. We find that the reported EWs of the O vii Kα at $z = 0.011$ and $z = 0.027$ should have been measured at $\gtrsim 3.7\sigma$ and $\gtrsim 2.3\sigma$, in contrast to the fact that we only obtained upper limits to the EWs.

3. According to the numerical simulations, the WHIM absorbers with $N_{\text{OVII}} \gtrsim 10^{15}$ cm$^{-2}$ could sample $\gtrsim 30\%$–$50\%$ of the O vii-bearing baryons. To systematically survey the 15 QSO sight lines along which the IGM O vi absorbers have been detected, future X-ray telescopes should be able to facilitate the WHIM study via the X-ray absorption line spectroscopy from background QSOs with fluxes of $\sim 0.2$ mCrab to find $\gtrsim 10$ WHIM systems. It takes an impractically long (341 Ms for Chandra and 804 Ms for XMM-Newton)
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Figure 9. Panel (a) shows LSFs of XMM-Newton-RGS (taken from observation 0099280201), Chandra-LETG (taken from observation 4148), and a future spectrograph (denoted as “Next-X”) approximated with a Gaussian with FWHM = 75 km s\(^{-1}\). The Next-X uses the right-hand scale. Panels (b)–(d) show the same absorption model (red curves) with two velocity components separated by 150 km s\(^{-1}\) and both characterized as \(N_{\text{Ovii}} = 10^{15} \text{cm}^{-2}\) and \(b_v = 50 \text{ km s}^{-1}\) with corresponding simulated absorption spectra (histograms) of (b) XMM-Newton-RGS, (c) Chandra-LETG, and (d) Next-X with S/N (per 50 mÅ for XMM-Newton and Chandra and per 5.4 mÅ for Next-X) = 350, 200, and 30, respectively.

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

4. It would require \(\sim 11 \text{ Ms on-target exposures for future X-ray spectrographs equipped with spectral resolution } R \gtrsim 4000 \text{ and effective area } A \gtrsim 100 \text{ cm}^2 \text{ to finish the survey.}

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