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# Probing the Local Group Medium toward Mkn 421 with *Chandra* and *FUSE*

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## ABSTRACT

We report the detection of highly-ionized gas at  $z \sim 0$  seen in resonant UV and X-ray absorption lines toward the  $z = 0.03$  blazar Mkn 421. A total of 13 X-ray and 3 UV lines were measured (or upper limits derived), including three lines in the O VII K-series and  $K\alpha$  transitions from neon, carbon, and nitrogen. From the three O VII lines we derive a  $2\sigma$  Doppler parameter constraint of  $24 < b < 55 \text{ km s}^{-1}$ . The *FUSE* spectrum shows strong Galactic low-velocity O VI 1032 Å absorption as well as a possible weak O VI high-velocity component (HVC). The Doppler parameter of the low-velocity O VI measured with *FUSE* is  $\sim 3\sigma$  higher than that derived from the O VII line ratios, indicating that the O VII and Galactic O VI arise in different phases. This velocity dispersion, along with limits on the gas temperature and density from the X-ray line ratios (assuming a single phase with collisional ionization equilibrium plus photoionization) are all consistent with an extragalactic absorber. However, the O VII Doppler parameter is inconsistent with the high temperature required to produce the observed O VI<sub>HVC</sub>/O VII ratio, implying that the HVC is probably not related to the O VII. In addition, the O VI $_{K\alpha}$  line detected by *Chandra* implies a

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column density  $\sim 4$  times higher than the 1032 Å absorption. Although an extragalactic absorber is fully consistent with the measured column density ratios, a Galactic origin cannot be ruled out given the uncertainties in the available data.

*Subject headings:* Galaxy: halo — intergalactic medium — quasars: absorption lines

## 1. Introduction

At both low and high redshifts, the intergalactic medium (IGM) is thought to be the dominant reservoir of baryonic matter in the universe. Essentially all of the baryons at  $z \sim 2$  are accounted for in the “forest” of H I Lyman- $\alpha$  absorption lines seen against background quasars (Weinberg et al. 1997). In the local universe, numerical simulations predict that most of the IGM is in the form of a shock-heated “warm-hot IGM” (WHIM) with  $T \sim 10^5 - 10^7$  K and densities  $n_H \sim 10^{-6} - 10^{-5} \text{ cm}^{-3}$  (Cen & Ostriker 1999; Davé et al. 2001). Hydrogen is mostly ionized at these temperatures, rendering it difficult or impossible to detect. However, H-, He-, and Li-like ions of heavier elements can exist under these conditions, producing a “forest” of low- $z$  intervening UV/X-ray absorption lines in quasar spectra (Hellsten et al. 1998; Perna & Loeb 1998). In particular, O VI, O VII, and O VIII are expected to produce the strongest lines (depending on the temperature and ionizing background).

The required sensitivity to detect such absorption systems is now available with the advent of such facilities as the *Chandra* X-ray observatory, *XMM-Newton*, *Hubble Space Telescope*, and the *Far Ultraviolet Spectroscopic Explorer (FUSE)*. High signal-to-noise observations along four lines of sight reveal such intervening absorption systems with temperatures and densities consistent with the WHIM (Nicastro et al. 2005a,b,c; Mathur et al. 2003; Fang et al. 2002, Fang et al., in prep). Additionally, the total baryonic mass density in these detected filaments is consistent with the  $(2.5 \pm 0.4)\%$  deficiency between CMB measurements (Bennett et al. 2003) and previous density measurements of stars and gas (see also Nicastro et al. 2005a, and references therein).

Since most galaxies are expected to trace the same cosmic overdensities as the web of IGM filaments, it would be no surprise if the Galaxy itself resided in such a filament. Indeed, X-ray spectra of several quasars show likely  $z = 0$  O VII absorption, e.g. PKS 2155–304 (Nicastro et al. 2002), 3C 273 (Fang et al. 2003), and Mkn 279 (Williams, Rodriguez et al., in preparation). The upper limit found for O VII emission implies that O VII *absorption* systems most likely arise in an extragalactic medium (Rasmussen et al. 2003); however, the analysis is complicated by  $z = 0$  O VI absorption observed with *FUSE* along many quasar

lines of sight (Wakker et al. 2003). The strongest O VI absorption component, typically within  $v_{\text{LSR}} = \pm 100 \text{ km s}^{-1}$  (hereafter denoted O VI<sub>LV</sub>), is due to gas in the halo and thick disk of the Galaxy (Savage et al. 2003). Of the 102 sightlines studied, 84 show at least one additional O VI high-velocity component (HVC), typically weaker than the O VI<sub>LV</sub>.

The origin and location of the O VI HVCs is controversial: while some may be spatially and kinematically associated with known Galactic structure (such as the Magellanic stream and H I high-velocity clouds, though this association is in many cases uncertain), others appear to be completely isolated. Sembach (2003) summarizes the evidence in favor of a Galactic origin for the O VI HVCs. In such a scenario, the absorption could arise at the interface between infalling cooler gas clouds and very hot ( $T > 10^6 \text{ K}$ ) gas in an extended Galactic corona. The observed gas stripping and orbital deflection of the Magellanic clouds also lends credence to such a low-density corona. Furthermore, lower-ionization species such as Si IV and C IV are seen toward some sightlines. Thus, there is some evidence for a collisionally-ionized, high-density Galactic medium.

On the other hand, there is also evidence that the isolated O VI HVCs trace the Local Group medium and thus are associated with the  $z = 0$  O VII and O VIII X-ray absorption. The most compelling evidence for this interpretation is the velocity segregation of the O VI HVCs: Nicastro et al. (2003) report that the mean velocity vector of the O VI HVCs is highest in the local standard of rest and lowest in the Local Group rest frame, implying an extragalactic, Local Group origin. The presence of lower-ionization lines does not rule out a WHIM origin for the O VI HVCs since the medium is likely inhomogeneous and may thus consist of phases of different temperatures and densities (such as the intervening WHIM absorbers found by Danforth & Shull 2005). Furthermore, isolated high-velocity O VI (which is not associated with O I and other low-ionization lines) has not been detected toward high latitude Galactic sources out to 10 kpc (Danforth et al. 2002; Howk et al. 2003; Zsargó et al. 2003). The low-ionization line profiles often differ substantially from the O VI HVCs, implying that they may arise in different components (Collins et al. 2005).

The key to understanding the O VI absorption is higher-quality X-ray data, since the O VII and O VIII along high-latitude quasar sightlines are the most likely to trace the WHIM (i.e., least subject to possible contamination by hot Galactic gas). X-ray measurements by themselves provide great insight into the properties of the local WHIM, including its mass and extent, thereby yielding valuable constraints for models of galaxy formation and the Local Group (e.g., Kravtsov et al. 2002). However, knowing whether the O VI HVCs are also associated with the WHIM provides even stronger diagnostics. Unfortunately, existing X-ray data have not been of sufficiently high quality to resolve this ambiguity: even at large column densities ( $N_i \sim 10^{15} \text{ cm}^{-2}$ ), X-ray lines are quite weak, and several thousand counts

per resolution element in a typical *Chandra* grating spectrum are required to accurately measure these lines.

Through our program of observing nearby blazars in outburst phases, we have obtained high-quality *Chandra* and *FUSE* spectra of Mkn 421, sufficient to study in detail the local WHIM (and Galactic halo/thick disk) absorption. Here we report on these observations, and the inferred properties of the local absorption.

## 2. Observations and Data Preparation

### 2.1. *Chandra*

A full description of the *Chandra* observations, data reduction, and continuum fitting can be found in Nicastro et al. (2005a); a brief summary follows. Mkn 421 was observed during two exceptionally high outburst phases for 100 ks each as part of our *Chandra*–AO4 observing program: one at  $f_{0.5-2\text{keV}} = 1.2 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$  with the Low Energy Transmission Grating (LETG) combined with the Advanced CCD Imaging Spectrometer–Spectroscopic (ACIS-S; Garmire et al. 2003) array, and another at  $f_{0.5-2\text{keV}} = 0.8 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$  with the High Resolution Camera–Spectroscopic (HRC-S; Murray & Chappell 1985) array and LETG. Each of these observations contains  $\sim 2500$  counts per resolution element at 21.6 Å. Additionally, another short observation of Mkn 421 was taken with HRC/LETG (29 May 2004), providing another 170 counts per resolution element. These three spectra were combined over the 10–60 Å range to improve the signal-to-noise ratio (S/N  $\sim 55$  at 21 Å with 0.0125 Å binning). The final coadded spectrum of Mkn 421 is one of the best ever taken with *Chandra*: it contains over  $10^6$  total counts with  $\sim 6000$  counts per resolution element at 21.6 Å, providing a  $3\sigma$  detection threshold of  $W_\lambda \sim 2 \text{ mÅ}$  ( $N_{\text{OVII}} = 8 \times 10^{14} \text{ cm}^{-2}$  for an unsaturated line).

Effective area files (ARFs) for each observation were built using CIAO<sup>1</sup> v3.0.2 and CALDB<sup>2</sup> v2.2.6. Those pertaining to the ACIS/LETG observations were corrected for the ACIS quantum efficiency degradation<sup>3</sup> (Marshall et al. 2003). For the HRC/LETG observations, the standard ARFs were used. Each ARF was then convolved with the relevant standard redistribution matrix file (RMF), and the convolved RMFs were weighted by ex-

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<sup>1</sup><http://cxc.harvard.edu/ciao/>

<sup>2</sup><http://cxc.harvard.edu/caldb/>

<sup>3</sup>See also <http://cxc.harvard.edu/ciao/why/acisqedeg.html>

posure time, rebinned to the same energy scale, and averaged to provide a response file for the coadded spectrum.

Using the CIAO fitting package *Sherpa*<sup>4</sup>, we initially modeled the continuum of Mkn 421 as a simple power law and a Galactic absorbing column density of  $N_H = 1.4 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990), excluding the 48–57 Å HRC chip gap region. Metal abundances for the Galactic gas were then artificially adjusted to provide a better fit around the O I and C I K-edges near 23 Å and 43 Å respectively. This is *not* intended to represent actual changes to the absorber composition, but rather to correct uncertainties in the instrument calibration. These adjustments affect the continuum mostly near the carbon, oxygen, and neon edges, but individual narrow absorption lines are unaffected. After this fit there were still some systematic uncertainties in the best-fit continuum model; these were corrected with broad (FWHM = 0.15 – 5 Å) Gaussian emission and absorption components until the modeled continuum appeared to match the data upon inspection. Indeed, the residuals of the spectrum to the final continuum model have a nearly Gaussian distribution, with a negative tail indicating the presence of narrow absorption lines (see Nicastro et al. 2005a, Figure 8).

## 2.2. FUSE

Mkn 421 was also observed with *FUSE* as part of our Director’s Discretionary Time observing program on 19–21 January 2003 for a total of 62.8 ks. An additional 21.8 ks observation from 1 December 2000 was also available in the archive. We used the time-tagged, calibrated data from only the LiF1A detector, since inclusion of the LiF2B data provides a small ( $\sim 20\%$ ) increase in S/N but degrades the overall spectral resolution.<sup>5</sup> These two observing programs consist of four observations, which in turn contain a total of 29 individual exposures. The wavelength scales of each observation’s constituent exposures were cross-correlated and shifted (typically by 1–2 pixels) to account for slight uncertainties in the wavelength calibration. The exposures for each observation were checked for consistency and coadded, weighted by exposure time. The resulting four spectra were then cross-correlated against each other, coadded (with a  $\sim 10\%$  downward shift in flux applied to the 2000 observation due to source variability), and binned by 5 pixels (0.034 Å, or one-half of the nominal  $20 \text{ km s}^{-1}$  resolution) providing a S/N of 17 near 1032 Å.

To check the absolute wavelength calibration we followed the method of Wakker et al.

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<sup>4</sup><http://cxc.harvard.edu/sherpa/>

<sup>5</sup>See the *FUSE* Data Analysis Cookbook v1.0, <http://fuse.pha.jhu.edu/analysis/analysis.html>

(2003), using their 4–component fit to the Murphy et al. (1996) Green Bank H I–21 cm data as a velocity reference. They find four main components of H I emission with an  $N_H$ –weighted average velocity of  $-31.7 \text{ km s}^{-1}$ . In the *FUSE* spectrum, the Si II  $\lambda 1020.699 \text{ \AA}$  and Ar I  $\lambda 1048.220 \text{ \AA}$  lines are expected to trace the same gas as the H I emission. Each UV line was fit with two Gaussian components in *Sherpa*, giving average velocity offsets of  $-30.9$  and  $-34.9 \text{ km s}^{-1}$  respectively. These agree well with the H I data, though the slight difference between the Ar I and Si II measurements suggest at least a  $\sim 4 \text{ km s}^{-1}$  intrinsic wavelength uncertainty.

### 3. Line Measurements

To find and identify narrow absorption lines in the *Chandra* spectrum of Mkn 421, we visually inspected small (2–5  $\text{\AA}$ ) regions of the spectrum, beginning around the rest wavelength of O VII $_{K\alpha}$  (21.602  $\text{\AA}$ ) since this tends to be the strongest  $z = 0$  X-ray absorption line (e.g. Nicastro et al. 2002; Fang et al. 2003; Chen et al. 2003). Three O VII $_{K\alpha}$  (Figure 1) absorption features were found: one at  $z = 0$ , one at  $z = 0.011$ , and one at  $z = 0.027$  (with typical redshift errors of 0.001). There is also a strong feature which is  $\sim 3\sigma$  from the O V $_{K\alpha}$  rest wavelength, but is more likely O VII $_{K\alpha}$  at  $v \sim +900 \text{ km s}^{-1}$  relative to the blazar. A close pair of lines consistent with Ly $\alpha$  at this velocity has been observed (Shull et al. 1996; Penton et al. 2000), so this may be indicative of an inflow to Mkn 421 or uncertainty in the blazar redshift (based on rather old spectrophotometric measurements by Margon et al. 1978). A weak O VI $_{K\alpha}$  line is seen at the rest wavelength of 22.02  $\text{\AA}$ . Other regions of the spectrum were then searched for lines corresponding to these systems, with particular emphasis paid to strong transitions of the most abundant elements (C, N, O, and Ne). All in all there were 13 lines marginally or strongly detected at  $z \sim 0$  (including the N VII, O V, and Ar XV upper limits), 3 at  $z = 0.011$ , and 7 at  $z = 0.027$ . The latter two systems are the subject of other papers (Nicastro et al. 2004a,b) and thus will not be discussed further here.

These 13  $z = 0$  X-ray lines were fitted in *Sherpa* with narrow Gaussian features superposed on the fitted continuum described in §2.1 (see Figure 1). We are excluding the strong O I (23.51  $\text{\AA}$ ) line since it arises in the neutral ISM and is not of interest here, as well as the O $_2$  (23.34  $\text{\AA}$ ) absorption since it coincides with a strong instrumental feature and cannot be accurately measured. Due to the FWHM = 0.04  $\text{\AA}$  ( $\sim 600 \text{ km s}^{-1}$ ) LETG resolution the lines are all unresolved, so only the position and equivalent width of each line are measured. Errors are calculated using the “projection” command in *Sherpa*, allowing the overall continuum normalization to vary along with all parameters for each line. The resulting line parameter estimates are presented in Table 1. The  $\sim 0.02 \text{ \AA}$  systematic wavelength

uncertainty of the LETG<sup>6</sup> is in most cases larger than the statistical uncertainty of the line centroid; thus, Table 1 lists whichever is greater. Additionally, a meaningful upper error bar on the C VI equivalent width could not be calculated with *Sherpa*. In this case, the FWHM was frozen at the instrumental resolution and the error was recalculated; a visual inspection confirms the new limit to be more reasonable. Upper limits for the O V, N VII, Ar XV, and Ne X lines were calculated with both the position and FWHM frozen.

The *FUSE* spectrum (Figure 2) shows a strong, broad low-velocity O VI 1032 Å absorption line at  $z \sim 0$  due to gas in the Galactic thick disk and halo (Savage et al. 2003). An asymmetric wing on the red side of this line is evident, possibly a kinematically distinct HVC. We fitted the O VI 1032 Å line in *Sherpa* using a constant local continuum (in a  $\pm 2$  Å window) and two Gaussian absorption components: one for the  $v \sim 0$  O VI<sub>LV</sub> line, and one at  $v \sim 100 \text{ km s}^{-1}$  for the HVC. No H<sub>2</sub> contamination is seen at the O VI 1032 Å wavelength when absorption templates are fit to the other H<sub>2</sub> lines seen in the spectrum. The 1037 Å line is somewhat blended with a single H<sub>2</sub> absorption line; this is taken into account with another narrow Gaussian. From this fit, we find equivalent widths of  $18.6 \pm 5.6 \text{ mÅ}$  for the 1032 Å HVC and  $270.7 \pm 7.9 \text{ mÅ}$  for the Galactic component. The best-fit model for the HVC is fairly robust and not sensitive to variations in the initial parameters; however, the derived equivalent width of  $18.5 \pm 5.6 \text{ mÅ}$  is lower than the  $37 \pm 11 \pm 29 \text{ mÅ}$  (errors are statistical and systematic, respectively) measured by Wakker et al. (2003) in the initial 21.8 ks observation. They employed a direct integration method which may not have taken into account the substantial blending of the Galactic O VI<sub>LV</sub> with the HVC. Our total O VI equivalent width (LV+HVC =  $279 \pm 10 \text{ mÅ}$ ) is in good agreement with their value of  $285 \pm 20 \text{ mÅ}$ .

Deblending the O VI 1037 Å line is less certain due to the presence of adjacent Galactic C II and H<sub>2</sub> absorption. A flat continuum was again employed from 1035 – 1040 Å and single Gaussian components were used to fit the C II, O VI, and H<sub>2</sub> absorption lines. The HVC on the 1032 Å O VI line should also appear at  $\sim 1038 \text{ Å}$  with  $W_\lambda = 0.50 \times W_\lambda(1032 \text{ Å})$ . Although this component is too weak to be detected directly, it could cause the measurement of the Galactic LV–O VI 1037 Å line to be systematically high. Another absorption Gaussian with one-half of the 1032 Å HVC equivalent width (and with the same FWHM and velocity offset) was included in the 1037 Å O VI line fit to account for this. Table 1 lists the measured properties of the O VI<sub>LV</sub> and HVC absorption lines.

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<sup>6</sup><http://cxc.harvard.edu/cal/>

## 4. Absorption Line Diagnostics

### 4.1. Doppler Parameters

To convert the measured equivalent widths to ionic column densities, we calculated curves of growth for each absorption line over a grid of Doppler parameters ( $b = 10 - 100 \text{ km s}^{-1}$ ) and column densities ( $\log N_H/\text{cm}^{-2} = 12.0 - 18.0$ ), assuming a Voigt line profile. Since the X-ray lines are unresolved,  $b$  cannot be measured directly. It can, however, be inferred from the relative strengths of the three measured O VII K-series lines. These lines are produced by the same ionic species, so in an unsaturated medium  $W_\lambda \propto f_{lu}\lambda^2$  where  $f_{lu}$  is the oscillator strength. The expected equivalent width ratio of O VII K $\beta$  to K $\alpha$  is then  $W_\lambda(\text{K}\beta)/W_\lambda(\text{K}\alpha) = 0.156$ , so the measured value of  $0.49 \pm 0.09$  indicates that the K $\alpha$  line is saturated. On the other hand, the measured O VII K $\gamma$ /K $\beta$  ratio is  $0.43 \pm 0.16$ , in agreement with the predicted (unsaturated) value of 0.34.

These line ratios by themselves are insufficient to determine the physical state of the O VII-absorbing medium since  $b$  and  $N_{\text{OVII}}$  are degenerate: the K $\alpha$  line saturation could be due to high column density, low  $b$ , or a combination of both. However, given an absorption line with a measured equivalent width and known  $f_{lu}\lambda^2$  value, the inferred column density as a function of the Doppler parameter can be calculated. The measured equivalent width (and errors) for each transition thus defines a region in the  $N_{\text{OVII}} - b$  plane. Since the actual value of  $N_{\text{OVII}}$  is fixed,  $b$  and  $N_{\text{OVII}}$  can be determined by the region over which the contours “overlap;” i.e. the range of Doppler parameters for which the different transitions provide consistent  $N_{\text{OVII}}$  measurements.

Figure 3 shows such  $1\sigma$  contours for the three measured O VII transitions. As expected, the inferred  $N_{\text{OVII}}$  is nearly constant in the unsaturated regime (large  $b$ ), and rises sharply at low  $b$  as the lines begin to saturate. At each value of  $b$ , the differences  $\Delta(\log N_{\alpha\beta}) = \log(N_{K\alpha}) - \log(N_{K\beta})$  and  $\Delta(\log N_{\alpha\gamma}) = \log(N_{K\alpha}) - \log(N_{K\gamma})$  were calculated, along with the errors on each  $\Delta(\log N)$ . The quantity  $\Delta(\log N_{\alpha\beta})$  is consistent with zero at the  $1\sigma$  and  $2\sigma$  levels for  $15 < b < 46 \text{ km s}^{-1}$  and  $13 < b < 55 \text{ km s}^{-1}$  respectively, while  $\Delta(\log N_{\alpha\gamma})$  provides limits of  $31 < b < 50 \text{ km s}^{-1}$  and  $24 < b < 76 \text{ km s}^{-1}$  respectively. Since  $\Delta(\log N_{\alpha\gamma})$  provides a more stringent lower limit on  $b$  while  $\Delta(\log N_{\alpha\beta})$  better constrains the upper limit, we thus assume a  $1\sigma$  range of  $31 < b < 46 \text{ km s}^{-1}$ , and a  $2\sigma$  range of  $24 < b < 55 \text{ km s}^{-1}$ . It should be noted that Figure 3 also shows some overlap between the  $K_\alpha$  and  $K_\gamma$  at  $b \lesssim 12 \text{ km s}^{-1}$ ; however, this solution is unlikely given the lower limit provided by the  $K_\beta$  line. Moreover,  $b = 12 \text{ km s}^{-1}$  implies a maximum temperature (assuming purely thermal motion) of  $T_{\text{max}} = 1.3 \times 10^5 \text{ K}$ ; such a low temperature is unlikely to produce the observed strong high-ionization lines.

A similar analysis is not as effective when applied to the strong O VI<sub>LV</sub> UV doublet (from the thick disk), since these lines are only slightly saturated: the measured  $W_\lambda$  ratio is  $0.61 \pm 0.04$ , compared to the expected unsaturated value of 0.50. When the inferred  $N_{\text{OVI}}$  is calculated as a function of  $b$  for both lines of the O VI<sub>LV</sub> doublet, the predicted  $N_{\text{OVI}}$  values are consistent over  $b = 34 - 112 \text{ km s}^{-1}$  (at the  $2\sigma$  level; see Figure 4). Since the O VI<sub>LV</sub> 1032 Å line is fully resolved by *FUSE* ( $\sim 15$  resolution elements across the line profile) and relatively unblended, its Doppler parameter can be estimated much more accurately using the measured line width and strength. In an unsaturated absorption line,  $\text{FWHM} = 2(\ln 2)^{1/2}b$ ; however, the measured FWHM increases if the line is saturated. We compensated for this by calculating Voigt profile FWHMs on a grid of  $N_{\text{OVI}}$  and  $b$ , and determining the region consistent with the O VI<sub>LV</sub> 1032 Å FWHM measurement of  $152 \pm 7 \text{ km s}^{-1}$  (or  $b = 91 \pm 4 \text{ km s}^{-1}$  assuming no saturation).

When the FWHM–derived contour is overlaid on the  $N_{\text{OVI}} - b$  contour inferred from the equivalent width measurement of the LV–O VI 1032 Å line, the two regions overlap nearly orthogonally (Figure 4) leading to a constraint of  $b(\text{O VI}_{\text{LV}}) = 80.6 \pm 4.2 \text{ km s}^{-1}$ . This is  $\sim 2\sigma$  lower than the unsaturated FWHM, once again confirming that the O VI<sub>LV</sub> is only weakly saturated. At this  $b$  the inferred column densities from the two lines of the O VI<sub>LV</sub> doublet differ by  $1.3\sigma$  but this is only a minor discrepancy and likely due to errors introduced by the blending of the 1037 Å line; thus, we will only consider results from the more reliable 1032 Å line measurement. However, at no value of the Doppler parameter do the 1032 Å, 1037 Å, and O VI<sub>K $\alpha$</sub>  lines all produce a consistent  $N_{\text{OVI}}$  measurement; in fact, the O VI<sub>K $\alpha$</sub>  column density is a factor of  $\sim 4$  higher than that inferred from the UV data. This discrepancy is discussed further in §5.1.1.

## 4.2. Column Densities

The Doppler parameters measured for the O VII ( $31 \text{ km s}^{-1} < b < 46 \text{ km s}^{-1}$ ) and O VI<sub>LV</sub> ( $b = 80.6 \pm 4.2 \text{ km s}^{-1}$ ) absorption are inconsistent at the  $\sim 3\sigma$  level, indicating the presence of at least two distinct components: the Galactic thick–disk gas traced by broad  $v \sim 0$  O VI<sub>LV</sub> absorption, and another lower– $b$  phase, possibly of extragalactic origin, traced by the O VII absorption lines. It cannot be assumed *a priori* that any given line (other than those used to determine  $b$ ) originates in one phase or another; moreover, the uncertainty in the calculated column density depends not only on the equivalent width error but also the error in  $b$ . To take this into account, for each ion the derived column density  $\log N_i$  and its  $\pm 1\sigma$  limits were averaged over the  $\pm 1\sigma$  ranges of both measured Doppler parameters. As it turns out, the choice of  $b$  does not make a significant difference since all other lines

(besides the O VII and O VI<sub>LV</sub> absorption) are essentially unsaturated; i.e., the difference in  $N_i$  calculated with the O VI<sub>LV</sub> and O VII Doppler parameters is small compared to the  $1\sigma$  error on the equivalent width measurements. Even so, to avoid possible systematic errors, we assumed  $b = 80.6 \pm 4.2 \text{ km s}^{-1}$  for those lines *likely* to originate in the Galactic thick disk (O VI<sub>LV</sub>, O V, and C V), and  $b = 31 - 46 \text{ km s}^{-1}$  for all other species. The derived ionic column densities are listed in Table 1

### 4.3. Temperature and Density Constraints

At densities such as those found in the Galactic interstellar medium (ISM;  $n_e \sim 1 \text{ cm}^{-3}$ ), photoionization is unimportant because thermal collisions are by far the dominant ionization source. This is also the case for very high temperatures ( $T \gtrsim 10^7 \text{ K}$ ) even at low densities, since the collisional rate is greater than the photoionization rate. However, at the low densities typically found in the intergalactic medium ( $n_e = 10^{-6} - 10^{-4} \text{ cm}^{-3}$ ), photoionization from the diffuse UV/X-ray background begins to play a greater role by enriching the abundances of highly-ionized elements at typical WHIM temperatures ( $\log T(\text{K}) \sim 5 - 7$ ) relative to those expected from pure collisional ionization (Nicastro et al. 2002; Mathur et al. 2003). It is thus imperative that the ionizing background be taken into account in order to accurately predict ionic abundances in the WHIM.

Version 90.04 of the ionization balance code *Cloudy* (Ferland 1996) was used to compute collisional- plus photoionization hybrid models for the absorbing medium. Relative ionic abundances were computed over a grid of  $\log T(\text{K}) = 4.5 - 7.4$  and  $\log n_e(\text{cm}^{-3}) = -7 - 0$ , with a step size of 0.1 dex in both  $\log n_e$  and  $\log T$ . Initially, a rigid scaling of  $[Z/H] = -1$  for all metals was assumed. For the ionizing background we employed the Sternberg et al. (2002) fit to the metagalactic radiation field:

$$J_\nu = \begin{cases} J_{\nu_0} \left(\frac{\nu}{\nu_0}\right)^{-3.13} & 1 < \frac{\nu}{\nu_0} < 4 \\ 2.512 \times 10^{-2} J_{\nu_0} \left(\frac{\nu}{\nu_0}\right)^{-0.46} & \frac{\nu}{\nu_0} > 4 \end{cases} \quad (1)$$

where here  $J_{\nu_0} = 2 \times 10^{-23} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$  and  $\nu_0 = 13.6 \text{ eV}$ . The total flux of ionizing photons is then given by  $f_\gamma = 4\pi \int_{\nu_0}^{\infty} (J_\nu/h\nu) d\nu = 1.3 \times 10^4 \text{ photons s}^{-1} \text{ cm}^{-2}$ , and the ionization parameter is  $\log U = \log(f_\gamma/c) - \log n_e = -6.36 - \log(n_e)$  where  $n_e$  is the electron density in  $\text{cm}^{-3}$ .

Using the ionic abundances calculated with *Cloudy*, we derived expected abundance ratios for all observed ions at each point in the  $\log n_e - \log T$  plane. Since any given density and temperature uniquely determines a set of abundance ratios ( $N_a/N_b$  for all ions  $a$  and

b), the problem can be inverted: any value of  $N_a/N_b$  defines a curve in the  $\log n_e - \log T$  plane, i.e. a set of temperatures and densities which can produce the measured ratio. When the errors on  $N_a/N_b$  are taken into account, the curves become contours, and the overlap between two or more contours defines the temperatures and densities for which the measured ratios are consistent. This is analogous to the method used in §4.1 to determine Doppler parameters for O VI<sub>LIV</sub> and O VII.

The most powerful diagnostics are those using ratios between different ions of the same element, since these ratios are independent of the relative metal abundances. Unfortunately the N VII/N VI and Ne X/Ne IX upper limits are not stringent enough to place meaningful constraints on the temperature and density. Figure 5 shows the  $\log n_e - \log T$  contours for ratios between the X-ray O VI<sub>K $\alpha$</sub> , O VII, and O VIII lines as well as the O VI<sub>HVC</sub>/O VII ratio. The X-ray line ratios are inconsistent with a high-density ( $n_e \gtrsim 10^{-3} \text{cm}^{-3}$ ), high-temperature ( $\log T > 6.2$ ) medium, and instead converge on a partially photoionized plasma with  $n_e = 10^{-4.7} - 10^{-3.9} \text{cm}^{-3}$  (from the overlap between the O VI<sub>K $\alpha$</sub> /O VII and O VIII/O VII contours) and  $T = 10^{5.5-5.7} \text{K}$  (from the limits provided by O VI<sub>K $\alpha$</sub> /O VII in this density range). These ranges of temperatures and densities are in line with those expected from WHIM gas (Davé et al. 2001). Of course, this is all contingent on the O VI<sub>K $\alpha$</sub>  line being a reliable tracer of  $N_{\text{OVI}}$ ; this caveat is discussed in detail in §5.

On the other hand, the O VI<sub>HVC</sub>/O VII ratio overpredicts the temperature by at least an order of magnitude for all values of  $\log n_e$ —in order to be consistent with the O VIII/O VII ratio, the O VI<sub>HVC</sub>/O VII ratio would need to be stronger by a factor of  $\sim 2.5$  (or  $\sim 3.5\sigma$ ). It is possible that the HVC is not a physically distinct component, but is instead the result of some systematic error (such as fixed pattern noise or an unexpected anomaly in the Galactic O VI<sub>LIV</sub> velocity distribution). In this case, the O VI associated with the O VII and O VIII may be completely blended with the thick-disk O VI<sub>LIV</sub> and thus unmeasurable. Consistency with the O VIII/O VII ratio (in the collisional ionization regime) requires  $\log(N_{\text{OVI}}/N_{\text{OVII}}) \sim -2.5$ , or roughly 20% of the Galactic UV O VI absorption. Although it appears that the O VI HVC as measured cannot originate in the same medium as the O VII absorption, we suspect that additional atomic physics may be at work here and could in principle reconcile this disagreement (see §5.1.1).

While the O VI<sub>K $\alpha$</sub> /O VII and O VIII/O VII ratios provide strong constraints, it is important to consider other ion ratios as well (particularly since the O VI<sub>K $\alpha$</sub>  and 1032 Å O VI column densities disagree). Figure 6 shows the  $\log n_e - \log T$  contours for several different ion ratios, all calculated relative to O VII since the error on  $N_{\text{OVII}}$  is small. With a rigid metallicity shift relative to Solar, the Ne IX/O VII, O VIII/O VII, and O VI<sub>K $\alpha$</sub> /O VII ratios are not all consistent with each other for any combination of temperature and density;

however, the consistency can be improved with adjustments to the [Ne/O] ratio (see §5.1.3). Both the C VI/O VII and N VII/O VII measurements are consistent with a high- or low-density medium at solar abundances.

Limits on the temperature of the Galactic thick-disk absorption can be derived in a similar fashion, although it is not the primary focus of this work and there are far fewer measured lines to work with. The most accurately-measured line is the O VI<sub>LV</sub>; additionally, C V and N VI X-ray lines are measured, and upper limits have been determined for O V and N VII. Figure 7 shows the temperature constraints derived for this Galactic absorption, assuming pure collisional ionization. The O V/O VI<sub>LV</sub> and N VII/N VI upper limits provide metallicity-independent constraints of  $\log T > 5.39$  and  $\log T < 6.64$  respectively. A more stringent upper limit on temperature of  $\log T < 6.03$  is provided by the N VII/O VI<sub>LV</sub> ratio, but this is somewhat dependent on [N/O]. Within this range the C V/O VI<sub>LV</sub> ratio provides an even stricter limit of  $5.3 < \log T < 5.7$ , but again this depends on [C/O]. At these temperatures the expected O VII column density is at most an order of magnitude less than measured; thus, the O VI<sub>LV</sub>, O VII, and O VIII cannot all originate in the same phase assuming pure collisional ionization (see also Mathur et al. 2003).

## 5. Discussion

Our *Chandra* and *FUSE* observations have provided a wealth of data on absorption near the Galaxy, constraining the temperature and density tightly ( $\log T(\text{K}) = 5.5 - 5.7$  and  $n_e = 10^{-4.7} - 10^{-3.9} \text{ cm}^{-3}$  when the O VI<sub>K $\alpha$</sub>  measurement is included), which are conditions suggestive of the local group intergalactic medium and require supersolar [Ne/O]. Here we first examine the assumptions that have led us to these results (§5.1), and then we discuss their implications for the location of the absorbing gas (§5.2), subject to these caveats.

### 5.1. Potential Caveats

#### 5.1.1. The O VI Discrepancy

The interpretation of the UV and X-ray data are particularly important, since (as Figure 5 shows) the combined O VIII/O VII and O VI/O VII ratios can provide tight constraints on the absorber temperature and density simultaneously (see also Figure 5 in Mathur et al. 2003). However, in this case the O VI column density inferred from the O VI<sub>K $\alpha$</sub>  is a factor of  $\sim 4$  higher than the combined 1032 Å low- and high-velocity components. Since both the X-ray and UV transitions trace the same atomic state, the inferred column densities

should match. A similar disagreement has been seen in intrinsic AGN absorption systems (see Krongold et al. 2003; Arav et al. 2003); however, in these cases it is typically attributed to saturation or a velocity–dependent covering factor, neither of which is relevant to this  $z \sim 0$  absorption.

On the other hand, our O VI $_{K\alpha}$  measurement provides a test for these attributions; the local absorption, after all, is likely a dramatically different physical system than an AGN outflow, yet the same conflict arises. A macroscopic explanation does not adequately describe how this discrepancy is seen in both physical systems, so the actual reason may lie in the atomic physics of highly ionized plasmas. For example, some fraction of the O VI may be excited through collisions or recombination from O VII, and thus unable to produce 1032 Å absorption while still absorbing O VI $_{K\alpha}$  photons. While a scenario that produces significant depopulation of the O VI ground state is difficult to envisage in such a low density plasma, we are investigating further the statistical equilibrium of O VI including photoexcitation and recombination in order to study such effects in more detail. However, it should be emphasized that this is not an isolated case so there must be a physical explanation for the O VI discrepancy, and the resolution of this paradox is crucial to our understanding of O VI UV and X-ray absorption and how it relates to the O VII.

There is also the possibility that the line was misidentified as O VI $_{K\alpha}$ , and is actually another intervening O VII absorption line at  $z = 0.0195$ . This latter explanation is unlikely since no other absorption lines at this redshift are seen in the *FUSE* or *Chandra* spectra; additionally, this would require the line to fall exactly on the O VI rest wavelength, which seems like an improbable coincidence. Another possibility is that the theoretical oscillator strength of the O VI $_{K\alpha}$  transition is incorrect, but the value given in Pradhan (2000) would need to be low by a factor of  $\sim 2-4$ , in sharp contrast to the successful calculations of  $f_{lu}$  for inner shell transitions in other ions in the same paper. Nevertheless, due to the discrepancy between the UV and X-ray O VI column density measurements, we present both possibilities: either (a) the O VI $_{K\alpha}$  line measures  $N_{\text{OVI}}$ , or (b) it does not and is thus ignored.

### 5.1.2. Absorption Components

The Doppler parameter measurements indicate the existence of two distinct components along the Mkn 421 line of sight: one seen in the thick–disk O VI $_{LV}$  1032 Å absorption with  $b_{LV} = 80.6 \pm 4.2 \text{ km s}^{-1}$ , and the O VII absorber with  $b_{\text{OVII}} = 31 - 46 \text{ km s}^{-1}$  ( $1\sigma$  limits). The O VI HVC may represent a third phase (if case (b) above is correct) with  $b_{\text{HVC}} = 35^{+18}_{-10} \text{ km s}^{-1}$  (from the FWHM measurement). This agrees surprisingly well with the O VII  $b$  measurement, and is consistent with numerical simulations of the nearby IGM (Kravtsov

et al. 2002). However, the extremely low O VI<sub>HVC</sub>/O VII ratio requires a temperature much higher than the upper limit provided by  $b_{\text{OVII}}$ . In order for the HVC to trace the same gas as O VII (case a), then, the aforementioned atomic physics effects would need to be suppressing O VI HVC absorption and not the O VI<sub>LV</sub> line. Sembach et al. (2003) list mean Doppler parameters for a variety of HVCs, both Galactic and probable Local Group; unfortunately, the dispersion in these values and the errors on  $b_{\text{OVII}}$  and  $b_{\text{HVC}}$  measured here are both too large to associate the components presented here to one of their classifications.

It is also important to note that our analysis assumes a single phase origin for the included X-ray lines. This assumption is consistent with the data, given the good agreement between the three O VII lines in the calculated ranges of  $b$  and  $N_{\text{OVI}}$  (Figure 3). Even so, if any of the ionic species arises in more than one phase along the line of sight, our results could be affected. For example, a Galactic, purely collisionally ionized medium can in principle reproduce the observed relative abundances of O VIII, O VII, O VI<sub>K $\alpha$</sub> , and Ne IX if several unresolved components are invoked to explain this absorption. However, the simplest explanation (a single-phase, low-density, partially photoionized extragalactic absorber) is fully consistent with all of these line measurements, and the similarity of the derived absorber properties to expectations for the local WHIM lend further support to this model (see §5.2).

### 5.1.3. Abundances

Due to the uncertainty associated with the O VI<sub>K $\alpha$</sub>  absorption, metal abundances relative to oxygen play a particularly important role in this analysis. By adjusting the metal abundances of the absorbing gas, the consistency of the solutions can in principle be improved with and without the O VI<sub>K $\alpha$</sub>  measurement. Although the  $\log n_e - \log T$  contour plots are useful for finding solutions, they cannot easily be used to determine the effects of changes in elemental abundances; thus, Figure 8 shows  $N_i/N_{\text{OVII}}$  as a function of  $\log T$  for both the  $\log n_e = -3.9$  and  $\log n_e = 0$  cases. In this figure, the  $y$ -ranges given by the measured ratios (thick lines) shift up and down as a result of decreases and increases in the abundances relative to oxygen, respectively; thus different parts of the theoretical curves would be in bold, moving the allowed temperature ranges (shown in the lower panel) to the left or right. Solar abundances here are taken to be the *Cloudy* 90 defaults (Ferland 1996; Grevasse & Anders 1989).

In case (a), i.e. if the O VI<sub>K $\alpha$</sub>  measurement of  $N_{\text{OVI}}$  is correct, then the temperature and density of the absorber are tightly constrained in a metallicity-independent manner, and relative abundances for other elements can be estimated. Under this assumption, the

oxygen ion ratios are consistent within a range of  $n_e = 10^{-4.7} - 10^{-3.9} \text{ cm}^{-3}$ ; however at solar abundances the Ne IX/O VII ratio demands higher temperatures than allowed by the O VI<sub>K $\alpha$</sub> /O VII ratio. Over this range of densities, the permitted abundances of neon, carbon, and nitrogen abundances relative to oxygen (that is, the range of abundances which produce line ratios consistent with both O VI<sub>K $\alpha$</sub> /O VII *and* O VIII/O VII) are then  $0.6 \leq [\text{Ne}/\text{O}] \leq 2.2$ ,  $-0.8 \leq [\text{C}/\text{O}] \leq 0.3$ , and  $[\text{N}/\text{O}] \leq 0.9$ . Note that supersolar [Ne/O] has also been observed in the  $z = 0$  absorber toward PKS2155–304 (Nicastrò et al. 2002). The improvement in the fit from supersolar [Ne/O] is shown in the right panel of Fig 6. Note, however, that in this case the discrepancy between the O VI<sub>K $\alpha$</sub>  and 1032 Å measurements becomes even more severe. Since the bulk of the O VI<sub>LV</sub> cannot be associated with the O VII due to the different Doppler parameters, the UV O VI component associated with the WHIM (hence the O VI<sub>K $\alpha$</sub> ) must be substantially weaker than the Galactic O VI absorption; thus the discrepancy is correspondingly larger.

On the other hand, if (b) the O VI<sub>K $\alpha$</sub>  line is ignored then the relative abundances in the absorber can be adjusted such that the measured line ratios are consistent with either a low- or high-density absorber. As shown in Figure 6, a high-density, collisionally-ionized medium fits the data with Solar abundances. Assuming this is the case, the temperature is then completely constrained by the O VIII/O VII ratio at  $\log T = 10^{6.1-6.2} \text{ K}$ , and the relative abundances consistent with the O VIII/O VII ratio in this temperature range are  $-0.6 \leq [\text{Ne}/\text{O}] \leq 0.6$ ,  $-0.6 \leq [\text{C}/\text{O}] \leq 0.3$ , and  $[\text{N}/\text{O}] \leq 0.4$ .

The requirement that [Ne/O] be supersolar does not affect the viability of the partially-photoionized model: in both the ISM and low- $z$  IGM, [Ne/O] is observed to be significantly larger than the solar value (e.g. Paerels et al. 2001; Nicastrò et al. 2005a). This may be an intrinsic property of the enriched gas ejected into the IGM and ISM, or instead could be due to depletion of C, N, and O onto dust grains in supernova ejecta or quasar winds (Whittet 1992; Elvis et al. 2002). If the dust destruction timescale is long and the IGM is continuously enriched by this latter mechanism, then the observed supersolar [Ne/O] would be expected. All of these enrichment scenarios are quite uncertain, but few (if any) are able to produce  $[\text{Ne}/\text{O}] < 0$ . Indeed, the solar neon abundance itself is quite uncertain since it is inferred from solar wind measurements. The increase in the solar neon abundance proposed by Drake & Testa (2005) is supported by these observations, and may provide another physical argument for the lack of subsolar [Ne/O].

## 5.2. Where does the X-ray absorption originate?

Assuming the O VII absorption system is homogeneous, its radial extent can be estimated by calculating  $r \approx N_H/(\mu n_e)$ , where  $\mu \sim 0.8$ ,  $\log(n_O/n_H) = -3.13$  (solar abundance), and

$$N_H = N_{\text{OVII}} \times \left( \frac{N_{\text{O,tot}}}{N_{\text{OVII}}} \right) \times 10^{3.13 - [\text{O}/\text{H}]} \quad (2)$$

The second term in the equation is approximately unity, since over the range of temperatures and densities implied from the O VIII/O VII ratio, O VII is the dominant ionization state by at least an order of magnitude; thus,  $\log N_H = \log N_{\text{OVII}} + 3.13 - [\text{O}/\text{H}] = \{20.37 - ([\text{O}/\text{H}] + 1)\} \pm 0.11$ . The measurement error on  $N_{\text{OVII}}$  is small compared to the uncertainty range in  $n_e$ , so it can be disregarded. Assuming that (a) the O VI $_{K\alpha}$  line does measure  $N_{\text{OVI}}$ , the  $2\sigma$  range of densities is  $-4.7 \leq \log n_e \leq -3.9$ , resulting in a radial extent of  $r = (0.8 - 4.9) \times 10^{-(\text{O}/\text{H}+1)}$  Mpc. These radial extents are consistent with those expected from a Local Group medium or local filament interpretation for this absorption (Nicastro et al. 2002, 2003) and too large to be confined within a Galactic halo. The absorber extent could be marginally consistent with a Galactic corona if the metallicity is high ( $r = 80 - 490$  kpc,  $2\sigma$  limits at Solar metallicity); however, such a scenario seems implausible, particularly if this corona primarily consists of gas accreted from the metal-poor IGM.

It is unlikely that this absorption system, if extragalactic, is spherically symmetric (particularly in a “local filament” interpretation). The total mass in the O VII system can be written as  $M_{\text{tot}} = f \times (4/3)\pi r^3 (1.4n_H m_H)$ , where  $f$  ( $< 1$ ) parameterizes the departure from spherical symmetry and  $1.4n_H m_H \approx n_H m_H + n_{\text{He}} m_{\text{He}}$ . Replacing  $r$  with  $N_H/(\mu n_e)$  and plugging in relevant values,

$$M_{\text{tot}} = 9.9 \times 10^{12} M_\odot \left( 10^{-3([\text{O}/\text{H}]+1)} \right) \left( \frac{n_e}{10^{-4} \text{ cm}^{-3}} \right)^{-2} f \quad (3)$$

This is several times larger than estimates of the total Local Group binding mass, e.g.  $M_{\text{tot}} = (2.3 \pm 0.6) \times 10^{12} M_\odot$  as calculated by Courteau & van den Bergh (1999). Baryonic matter should only contribute  $\sim 15\%$  of this mass (if the baryon-to-dark matter ratio is equal to the cosmological value), so our estimate appears high. This discrepancy can be easily resolved with different values of  $[\text{O}/\text{H}]$  and  $f$ . For instance, if we assume an oxygen abundance of 0.3 times solar rather than 0.1, then the range of possible masses becomes  $2.0 \times 10^{11} f M_\odot \leq M_{\text{tot}} \leq 7.9 \times 10^{12} f M_\odot$ . Thus, unless  $[\text{O}/\text{H}]$  is very high or  $f \ll 1$ , the O VII absorber almost certainly accounts for a major fraction of the baryonic matter in the Local Group. This sightline may also be probing gas that is not gravitationally bound to the Local Group (i.e., the Local Filament), which may explain why our range of  $M_{\text{tot}}$  extends to such high values. Although Collins et al. (2005) argue that a Local Group origin requires

that the O VII absorbers contain too much mass, we see here that the total mass is in fact consistent with expectations.

If this absorption does only trace the Local Group medium, then constraints on the extent of the absorber can be derived by assuming  $M_{\text{tot}} = 0.15M_{\text{LG}} \approx 3.5 \times 10^{11}M_{\odot}$ . In this case,  $r^3 f = 3M_{\text{tot}}/(4\pi \times 1.4\mu n_e m_{\text{H}})$ . Taking the  $2\sigma$  upper limit of  $\log n_{\text{H}} = -3.9$ , the  $2\sigma$  lower limit on  $M_{\text{LG}} = 1.1 \times 10^{12}M_{\odot}$ , and assuming  $f = 1$ , we obtain a lower limit of  $r > 0.2$  Mpc for the O VII absorption. Similarly, the upper limit on the radius is  $r < 0.6f^{-1/3}$  Mpc. This seems somewhat small compared to the actual size of the Local Group, but once again is dependent on the geometry of the absorber. A value of  $f \sim 0.1$  brings this upper limit more in line with the Mpc scales expected in the Local Group; this may indicate that the Mkn 421 line of sight probes an extended, filamentary WHIM distribution. This calculation also assumes that the density of the Local Group medium is constant with radius, when the actual density profile is more likely centrally concentrated. These measurements are also affected by the O VI discrepancy: in case (b), only the lower density limit of  $\log(n_e) > -4.7$  (from the  $2\sigma$  O VI  $K\alpha$  upper limit) applies, so the upper radius and mass limits are still valid. Nevertheless, the consistency with the expected Local Group parameters is intriguing.

### 5.3. Comparisons to Other Studies

Kravtsov et al. (2002) used constrained simulations to study the properties of the Local Supercluster region; sky maps produced from this simulation (their Figure 5) show filamentary structures near the Mkn 421 direction, possibly corresponding to the observed absorption. Additionally, they note that a Local Group medium would exhibit a low Doppler parameter ( $b \lesssim 60 \text{ km s}^{-1}$ ) out to distances of  $\sim 7$  Mpc, consistent with our O VII measurement.

The inferred properties of the X-ray absorption along this line of sight also appear similar to other observations: toward 3C 273, for example, Fang et al. (2003) find  $5.36 < \log T < 6.08$  and comparable O VII column density; however, their inferred O VII Doppler parameter is significantly higher than that toward Mkn 421:  $b > 100 \text{ km s}^{-1}$ . On the other hand, the  $z = 0$  absorber toward PKS 2155–304 (Nicastro et al. 2002) exhibits a temperature consistent with the Mkn 421 absorber, yet inferred density about an order of magnitude lower. Compared to the two intervening filaments seen toward Mkn 421 (Nicastro et al. 2005a), the density of the  $z = 0$  absorption agrees with the derived lower limits ( $\log n_e \gtrsim -5$  for both filaments), but the filaments appear to exhibit higher temperatures than that derived for the local absorption. These variations along different lines of sight simply demonstrate the complex nature of the absorption, and the diversity of temperature and density environments produced in the

structure formation process (e.g., Kravtsov et al. 2002).

The detection of X-ray absorption lines toward the Large Magellanic Cloud binary LMC X-3 by Wang et al. (2005) presents an important consideration for these results as well. The measured O VII and Ne IX equivalent widths and upper limits on O VIII and O VII<sub>Kβ</sub> are all consistent with the same lines measured toward Mkn 421 (albeit with much larger statistical errors). Although this detection provides evidence of a hot intervening absorber between the Galaxy and LMC, it certainly does not rule out a primarily extragalactic origin for the Mkn 421 absorber. Any absorption, either Galactic or extragalactic, is likely to be inhomogeneous; thus, it’s entirely plausible that the LMC X-3 sightline probes hot Galactic gas (perhaps enhanced by winds or outflows from both the Galaxy and LMC), while the absorption toward Mkn 421 is primarily due to low-density nearby WHIM gas.

## 6. Summary and Future Work

Through long-duration *Chandra* and *FUSE* observations of Mkn 421 in outburst, we have obtained unprecedented measurements of a variety of  $z \sim 0$  absorption lines, many of which likely arise in extragalactic, partially photoionized gas. A brief summary of our results follows.

1. The relative strengths of the three O VII K-series lines imply  $2\sigma$  Doppler parameter constraints of  $24 < b < 55 \text{ km s}^{-1}$ . This is inconsistent with the value of  $b = 80.6 \pm 4.2 \text{ km s}^{-1}$  derived for the Galactic low-velocity O VI, indicating that the O VI<sub>LV</sub> and O VII likely arise in different phases. The O VII  $b$  value is, however, consistent with the local IGM simulations of Kravtsov et al. (2002) out to distances of several Mpc.
2. A weak high-velocity O VI 1032 Å component also appears in the *FUSE* spectrum. Although its width is consistent with the O VII  $b$  measurement, the O VI<sub>HVC</sub> column density is too low to be associated with the O VII absorption unless  $T \gtrsim 10^7 \text{ K}$  (which itself is ruled out by the upper limit on  $b$ ). The O VI<sub>HVC</sub> may thus represent a distinct third component along this line of sight.
3. The column density inferred from the O VI K<sub>α</sub> line is a factor of  $\sim 4$  higher than that measured from the O VI 1032 Å transition. This may be due to unaccounted-for atomic physics effects, in which case the K<sub>α</sub> line may provide a more accurate measurement of  $N_{\text{OVI}}$  than the 1032 Å line. We consider both cases:
  - (a) If the O VI K<sub>α</sub> line measures  $N_{\text{OVI}}$ , then strong constraints on the temperature, density, and relative abundances of the X-ray absorber can be derived:

$T = 10^{5.5-5.7} \text{ K}$  and  $n_e = 10^{-4.7} - 10^{-3.9} \text{ cm}^{-3}$ , with allowed abundances of  $0.6 \leq [\text{Ne}/\text{O}] \leq 2.2$ ,  $-0.8 \leq [\text{C}/\text{O}] \leq 0.3$ , and  $[\text{N}/\text{O}] \leq 0.9$  (all  $2\sigma$  ranges). This range of densities, combined with  $N_{\text{OVII}}$ , implies a total mass and extent consistent with those expected in the Local Group and/or Local Filament if the gas metallicity is low. However, in this case the O VI UV–X-ray discrepancy becomes worse since (due to the Doppler parameter constraints) only a small portion of the O VI<sub>LV</sub> line can be associated with the extragalactic X-ray lines.

- (b) If, instead, the O VI  $K\alpha$  line does not correctly measure  $N_{\text{OVI}}$ , then the O VI associated with the O VII absorption must be fully blended with the Galactic 1032 Å O VI, and thus not measurable. In this case a lower density limit of  $\log n_e > -4.7$  is found, which is consistent with either a Galactic or extragalactic medium.

Much work remains to be done—both in order to better understand the data presented here, and to determine the true nature of the  $z \sim 0$  X-ray absorption. Higher signal to noise data along the Mkn 421 sightline would be useful to obtain better column density constraints, particularly on O VIII, O VI <sub>$K\alpha$</sub> , and Ne IX, and thus better constrain the effects of photoionization on the absorber. Data of comparable quality along other sightlines would be invaluable as well, both to probe other regions surrounding the Galaxy and to reconfirm the tantalizing O VI results presented herein. Higher-resolution simulations of the Local Group may allow us to determine the ionic column densities expected in the WHIM, and thus whether or not the observed absorption can possibly arise in the WHIM. Finally, more detailed modeling of O VI inner-shell transitions would shed a great deal of light on whether or not the O VI X-ray/UV discrepancy is real, and thus provide an invaluable framework for studying new (and existing) X-ray data.

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Table 1. Observed  $z \sim 0$  lines.

Line ID	$\lambda_{\text{rest}}^{\text{a}}$ (Å)	$\lambda_{\text{obs}}^{\text{b}}$ (Å)	$\Delta v_{\text{FWHM}}$ ( $\text{km s}^{-1}$ )	$v_{\text{obs}}$ ( $\text{km s}^{-1}$ )	$W_{\lambda}^{\text{c}}$ (mÅ)	$\log N_i^{\text{c,d}}$	Note
X-ray:							
Ar XV $_{K\alpha}$	24.737	24.737	...	...	$< 3.09$	$< 15.12$	
C V $_{K\alpha}$	40.268	$40.26 \pm 0.02$	...	$-60 \pm 150$	$11.3^{+3.3}_{-2.6}$	$15.19 \pm 0.15$	
C VI $_{K\alpha}$	33.736	$33.736 \pm 0.02$	...	$0 \pm 180$	$7.2 \pm 1.4$	$15.31 \pm 0.11$	
Ne IX $_{K\alpha}$	13.447	$13.431 \pm 0.02$	...	$-360 \pm 450$	$2.4^{+0.9}_{-0.8}$	$15.48 \pm 0.24$	
Ne X $_{K\alpha}$	12.134	$12.11^{+0.03}_{-0.02}$	...	$-590^{+740}_{-490}$	$< 5.04$	$< 16.21$	1
N VI $_{K\alpha}$	28.787	$28.755 \pm 0.02$	...	$-330 \pm 210$	$4.1 \pm 1.5$	$15.02^{+0.19}_{-0.24}$	
N VII $_{K\alpha}$	24.781	24.781	...	...	$< 2.86$	$< 15.16$	
O V $_{K\alpha}$	22.374	22.374	...	...	$< 2.20$	$< 14.97$	2,3
O VI $_{K\alpha}$	22.019	$22.023 \pm 0.02$	...	$50 \pm 270$	$2.4 \pm 0.9$	$15.07^{+0.17}_{-0.22}$	2
O VII $_{K\alpha}$	21.602	$21.603 \pm 0.02$	...	$10 \pm 280$	$9.4 \pm 1.1$	$16.22 \pm 0.23$	
O VII $_{K\beta}$	18.629	$18.612 \pm 0.02$	...	$-273 \pm 320$	$4.6 \pm 0.7$	$16.28 \pm 0.13$	
O VII $_{K\gamma}$	17.768	$17.762 \pm 0.02$	...	$-100 \pm 340$	$2.0 \pm 0.7$	$16.19^{+0.16}_{-0.21}$	
O VIII $_{K\alpha}$	18.969	$18.974 \pm 0.02$	...	$80 \pm 320$	$1.8 \pm 0.7$	$15.17^{+0.16}_{-0.24}$	
UV:							
O VI $_{1032}$	1031.926	$1031.88 \pm 0.01$	$152.3 \pm 7.0$	$-13.7 \pm 2.6$	$270.9 \pm 7.9$	$14.43 \pm 0.02$	
O VI $_{1032, \text{HVC}}$	1031.926	$1032.30 \pm 0.04$	$59^{+31}_{-17}$	$108 \pm 12$	$18.5 \pm 5.6$	$13.18^{+0.12}_{-0.16}$	
O VI $_{1037}$	1037.617	$1037.59 \pm 0.01$	$145.4 \pm 11.6$	$-9.3 \pm 4.0$	$164.9 \pm 8.4$	$14.47 \pm 0.03$	

<sup>a</sup>From Verner et al. (1996), except O VI and O V which are from Schmidt et al. (2004)

<sup>b</sup>Wavelength uncertainty is measured from fit or intrinsic LETG 0.02 Å error, whichever is greater. For upper limits, the line position was frozen to the rest wavelength.

<sup>c</sup>Error bars are  $1\sigma$ ; upper limits are  $2\sigma$ .

<sup>d</sup>Column densities are calculated using curve-of-growth analysis with  $b = 80.6 \pm 4.2 \text{ km s}^{-1}$  for C V, N VI, and O V, and the O VII Doppler parameter of  $b = 31 - 46 \text{ km s}^{-1}$  ( $1\sigma$  range) for all other lines.

Note. — (1) The Ne X line lies within a detector feature, so only an upper limit on its equivalent width is given. (2) The O VI and O V  $\lambda_{\text{rest}}$  values are from laboratory measurements by Schmidt et al. (2004); theoretical oscillator strengths are taken from Pradhan et al. (2003). (3) There is an absorption line at  $-760 \text{ km s}^{-1}$  from the O V rest wavelength, but this is more likely O VII associated with Mkn 421.

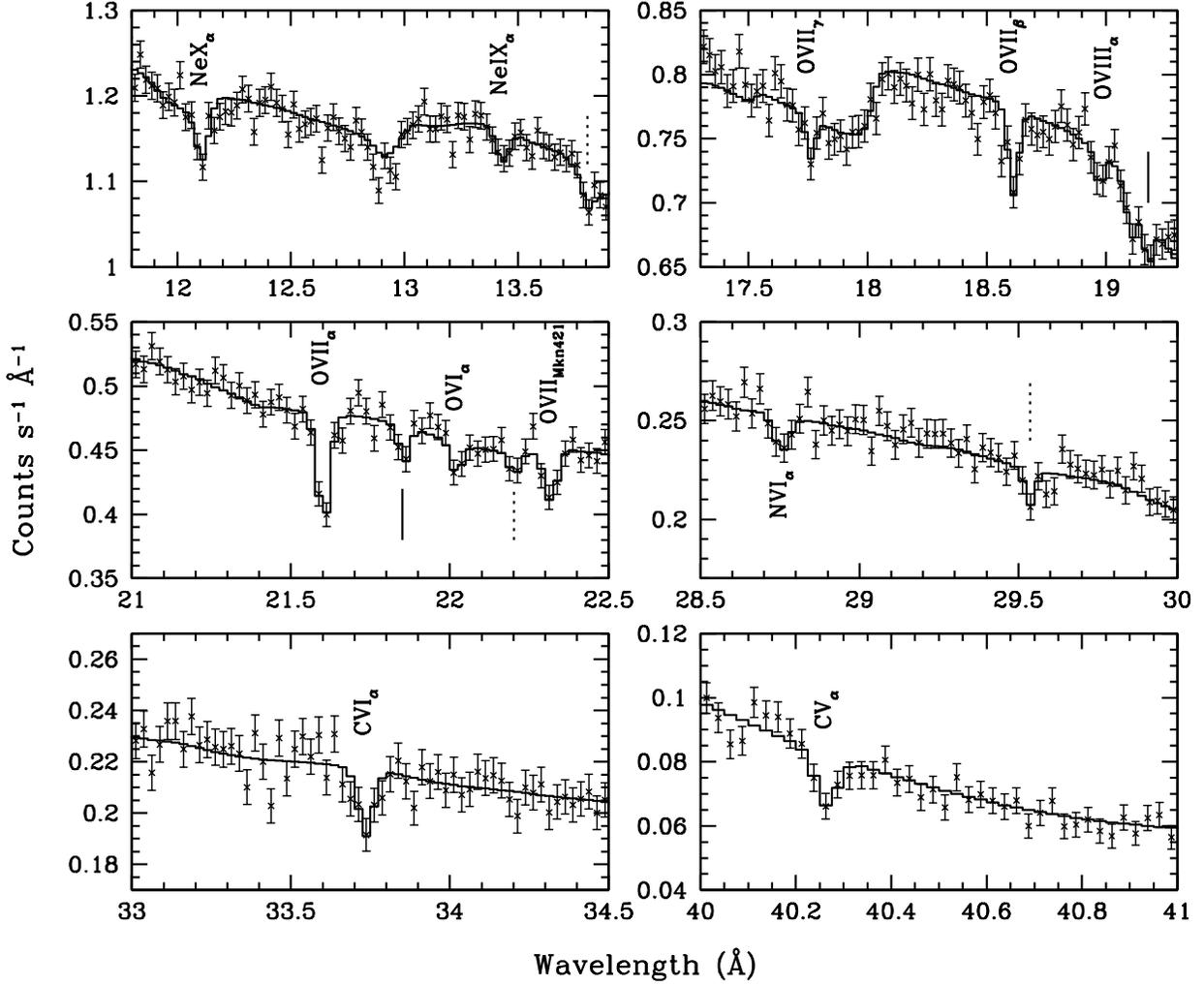


Fig. 1.— Portions of the Mkn 421 *Chandra* LETG spectrum (points) and the best-fitting model (histogram). Absorption lines at  $z \sim 0$  are labeled, and vertical tick marks indicate absorption from the  $z = 0.011$  (solid) and  $z = 0.027$  (dotted) intervening WHIM filaments (Nicastro et al. 2005a).

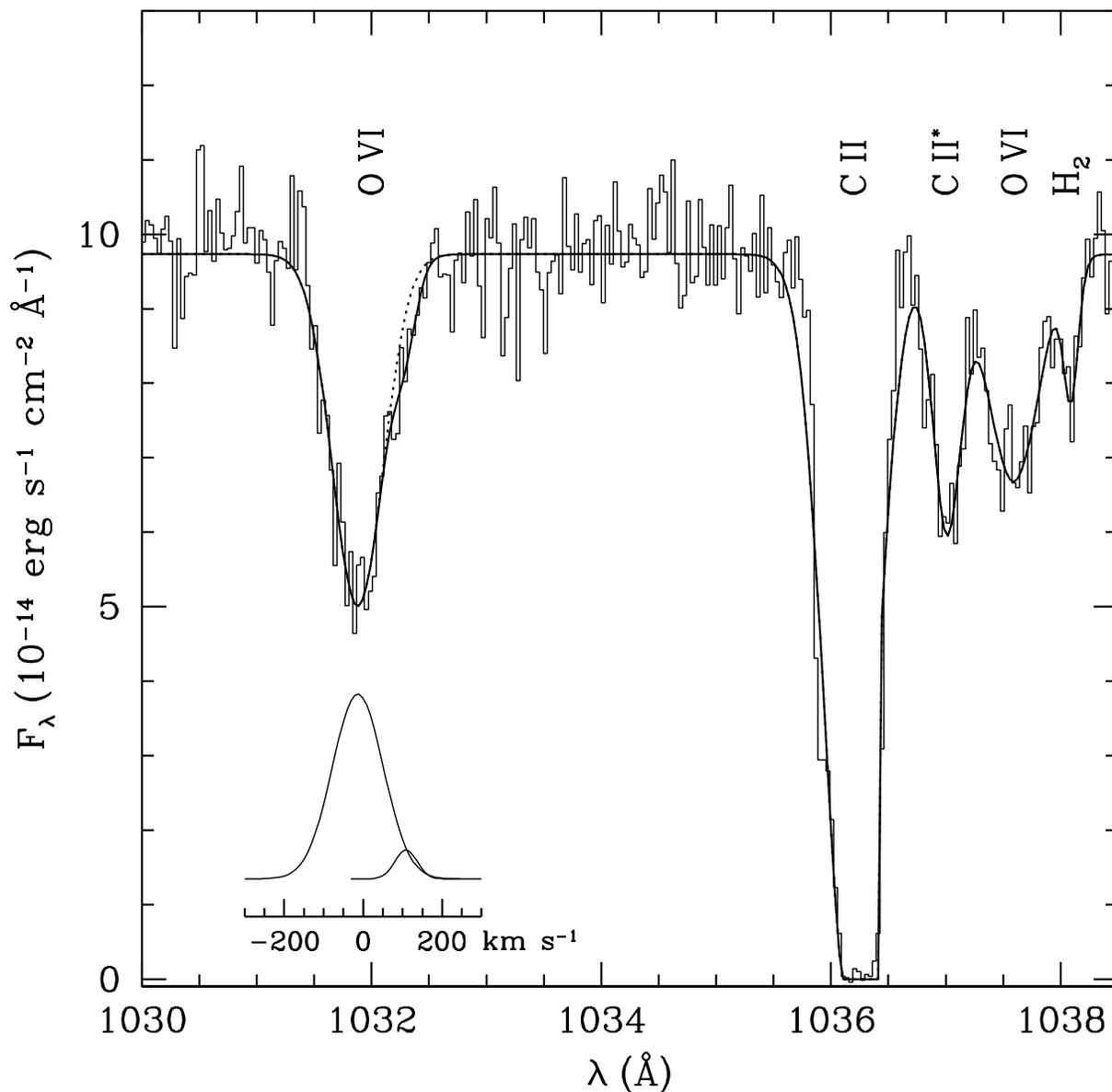


Fig. 2.— *FUSE* spectrum of Mkn 421 around the O VI $\lambda$ 1032, 1037  $\text{\AA}$  absorption doublet (histogram). The dark curve shows the best-fit model with (solid line) and without (dotted line) the 1032  $\text{\AA}$  HVC included. The inset plot shows the best-fitting Galactic (large Gaussian) and high-velocity (small Gaussian) components for the 1032  $\text{\AA}$  line, plotted against velocity relative to the O VI rest wavelength.

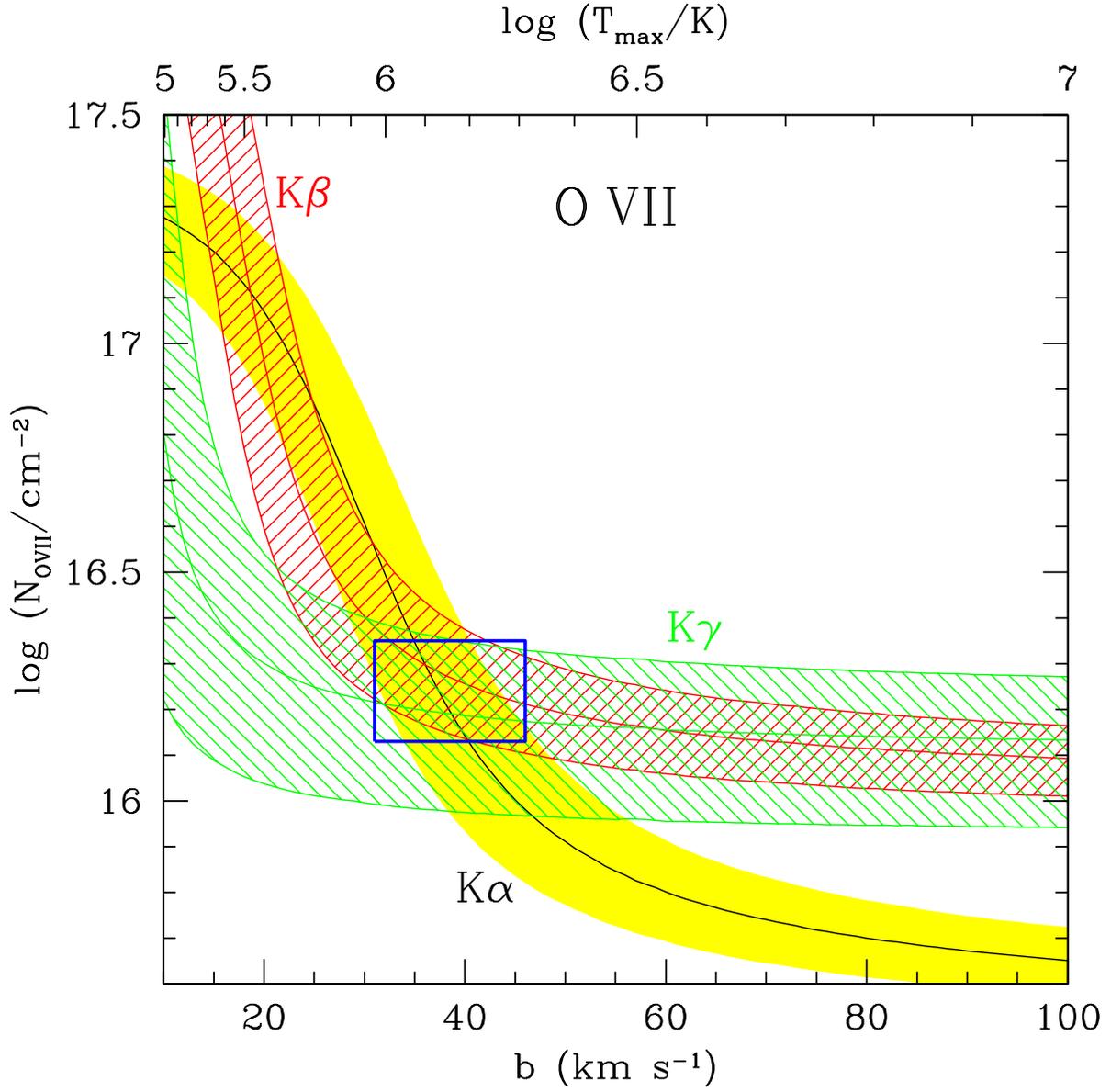


Fig. 3.— Contours of allowed  $N_{\text{OVII}}$  and  $b$  for the O VII  $K_\alpha$  (yellow),  $K_\beta$  (red), and  $K_\gamma$  lines. Shaded regions depict the  $1\sigma$  errors on  $W_\lambda$ , with the best-fit  $W_\lambda$  line in the center of each region. The overlap between the  $K_\alpha$  and  $K_\gamma$  region provides a  $2\sigma$  lower limit of  $b > 24 \text{ km s}^{-1}$ , and the  $K_\alpha - K_\beta$  overlap implies  $b < 55 \text{ km s}^{-1}$ . The weighted average O VII column density of the three transitions over the  $1\sigma$   $b$  range is  $\log(N_{\text{OVII}}) = 16.24 \pm 0.11$ . The blue box depicts the  $1\sigma$  ranges in  $\log(N_{\text{OVII}})$  and  $b$ . Also labeled on the top axis is  $\log T_{\text{max}} = \log(mb^2/2k)$ , the temperature inferred from a given Doppler parameter assuming purely thermal motion.

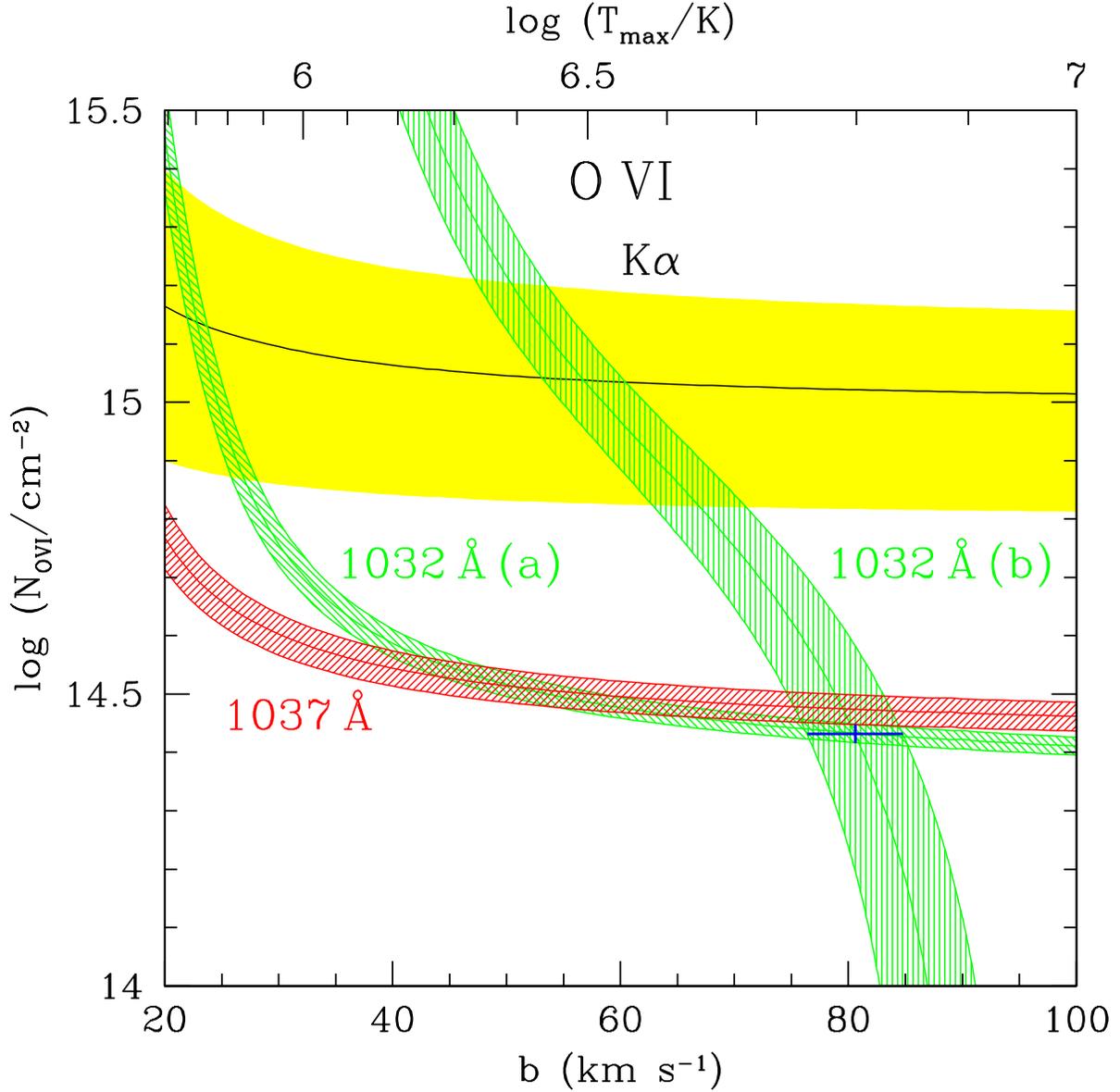


Fig. 4.— Contours of allowed  $N_{\text{OVI}}$  and  $b$  for the O VI 1032 Å (green), 1037 Å (red), and putative  $K\alpha$  22 Å (yellow) lines. Contour (a) is derived from the 1032 Å O VI<sub>L</sub>V equivalent width while (b) is from the measured FWHM; the intersection between the two green contours provides a tight constraint of  $b = 80.6 \pm 4.2 \text{ km s}^{-1}$  and  $\log N_{\text{OVI}}(\text{cm}^{-2}) = 14.432 \pm 0.016$  for the O VI<sub>L</sub>V (shown as the blue cross). Note that the O VI  $K\alpha$  transition predicts  $N_{\text{OVI}}$  about 0.5 dex higher than the UV line, and this discrepancy cannot be explained by saturation.

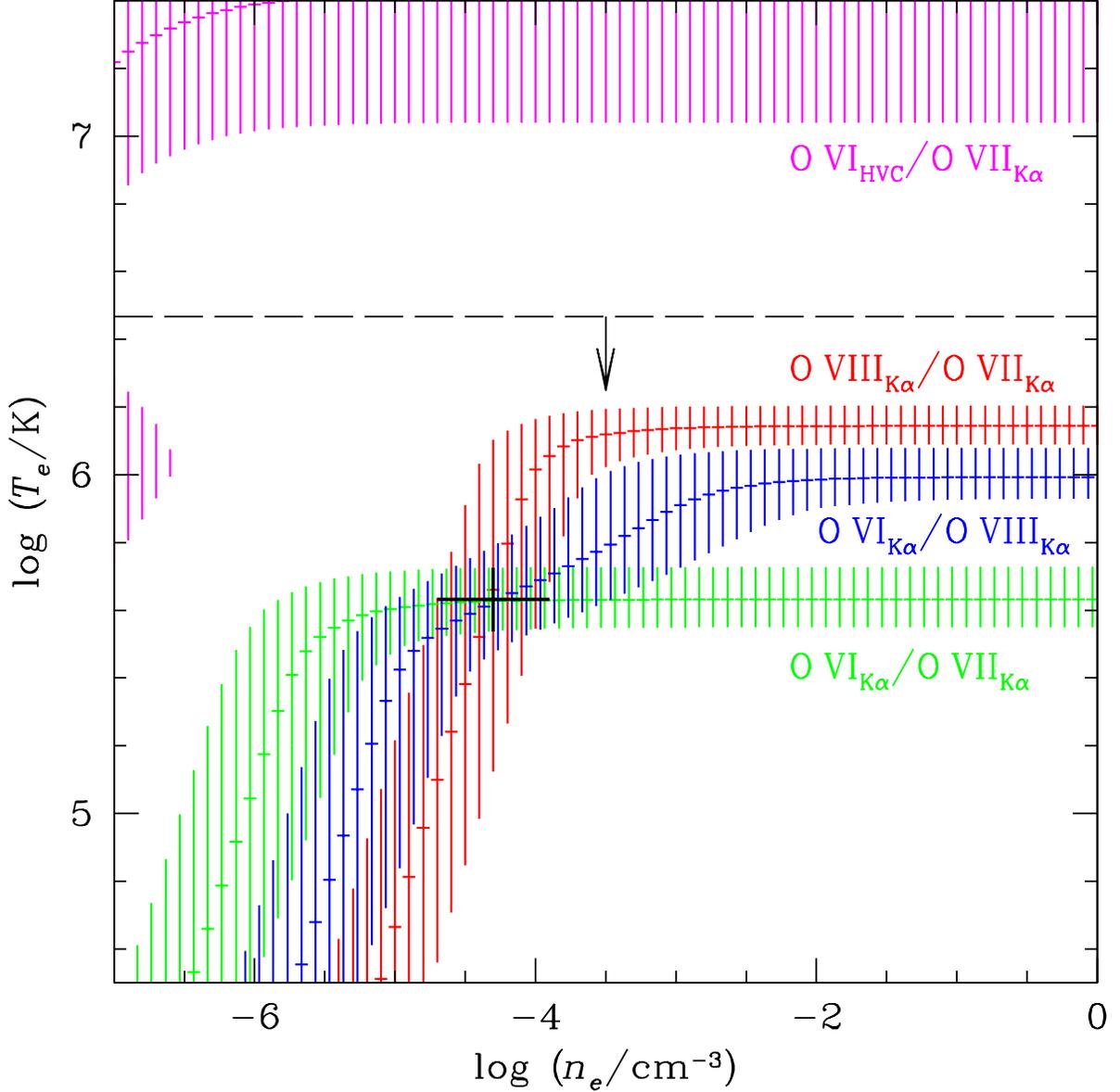


Fig. 5.— Contours of constant abundance ratios for X-ray and UV oxygen absorption lines. Vertical bars denote the  $2\sigma$  range of temperatures inferred from the abundance ratio at each step in  $\log n_e$ . The horizontal dashed line is the  $2\sigma$  upper limit on the temperature of the O VII absorber from the Doppler parameter measurement. While the X-ray line ratios predict significantly different temperatures in the collisional ionization regime ( $\log n_e \gtrsim -3$ ), they are consistent with  $\log n_e(\text{cm}^{-3}) = -4.7$  to  $-3.9$  and  $\log T(K) \sim 5.5 - 5.7$  (denoted by the black cross). Note that the O VI<sub>HVC</sub>/O VII ratio predicts a temperature far higher than the other derived limits, and thus the HVC is unlikely to be associated with the O VII absorption.

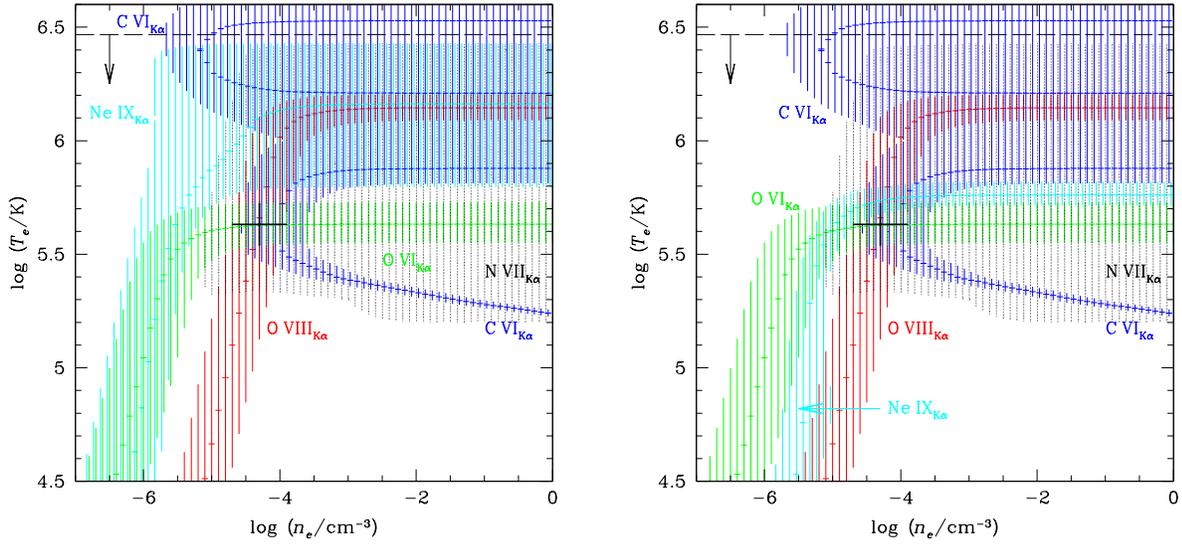


Fig. 6.— Same as Figure 5, but for ratios of several different ion abundances to O VII: O VI<sub>Kα</sub> (green), O VIII (red), C VI (blue), Ne IX (cyan), and N VII (dotted black region). The black cross shows the range of  $\log T$  and  $\log n_e$  derived from the O VIII/O VII and O VI<sub>Kα</sub>/O VII ratios. Assuming solar abundances (left panel), the O VI<sub>Kα</sub> and Ne IX contours are inconsistent for  $\log n_e \gtrsim -5$ , while all other ratios (except O VI<sub>Kα</sub>/O VII) are consistent at  $\log n_e \gtrsim -4.5$ . The right panel shows how a neon abundance shift of  $[\text{Ne}/\text{O}]=1$  produces better agreement in the low-density regime. High-density models agree with the data only if the O VI<sub>Kα</sub> measurement is disregarded.

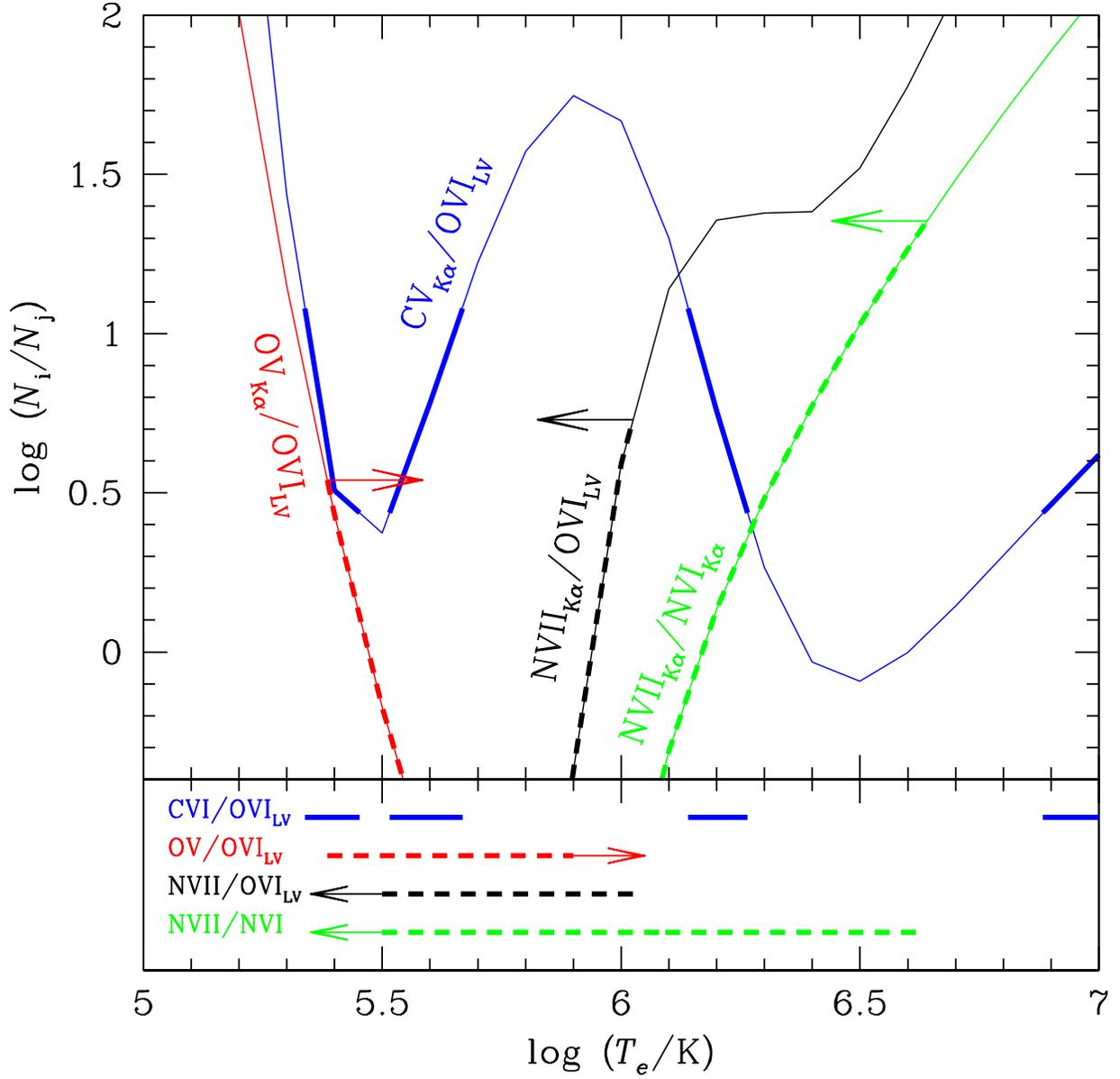


Fig. 7.— Models of ionic column density ratios for ions likely to arise in the Galactic ISM (assuming pure collisional ionization). Calculated ratios are shown as thin lines with  $\pm 2\sigma$  ratio measurements overplotted (thick segments). Upper limits are shown as dashed lines, and the temperature ranges derived from the different ion ratios are shown in the lower panel. The same-element ratios in this case provide strong constraints of  $\log T > 5.4$  (O V/O VI) and  $\log T < 6.6$  (N VII/N VI).

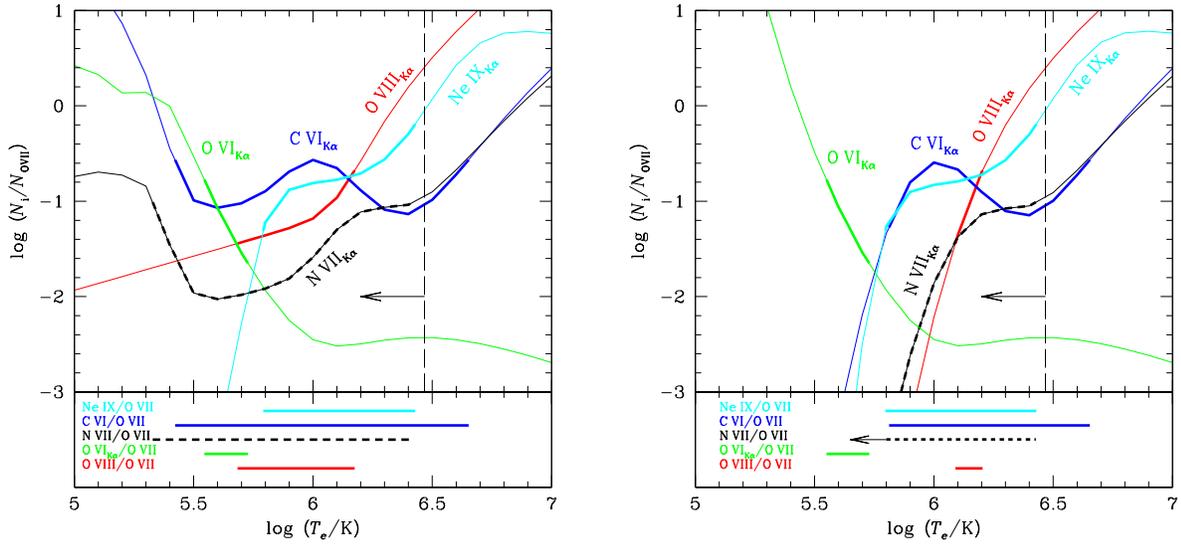


Fig. 8.— Same as Figure 7, for the ions likely originating in an extragalactic medium, with  $\log n_e = -3.9$  (left) and  $\log n_e = 0$  (right). Solar abundances relative to oxygen are assumed, and all calculated ratios are relative to  $N_{\text{O VII}}$ . The low-density case produces a consistent temperature solution of  $T \sim 10^{5.7}$  K (from the overlap between the O VIII and O VI $_{K\alpha}$  bold regions), and [Ne/O] must be supersolar. The high-density case, on the other hand, provides a consistent solution with Solar abundances but the temperatures implied by the O VIII/O VII and O VI $_{K\alpha}$ /O VII ratios are inconsistent.