AN X-RAY WHIM METAL ABSORBER FROM A Mpc-SCALE EMPTY REGION OF SPACE

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ABSTRACT

We report a detection of an absorption line at $\sim$44.8 Å in a $>500$ ks Chandra HRC-S/LETG X-ray grating spectrum of the blazar H 2356-309. This line can be identified as intervening C v–Kα absorption, at $z \approx 0.112$, produced by a warm ($\log T = 5.1$ K) intergalactic absorber. The feature is significant at a $2.9\sigma$ level (accounting for the number of independent redshift trials). We estimate an equivalent hydrogen column density of $N_{\odot} = 19.05(Z/Z_\odot)^{-1} \text{cm}^{-2}$. Unlike other previously reported FUV/X-ray metal detections of warm–hot intergalactic medium (WHIM), this C v absorber lies in a region with locally low galaxy density, at $\sim 2.2$ Mpc from the closest galaxy at that redshift, and therefore is unlikely to be associated with an extended galactic halo. We instead tentatively identify this absorber with an intervening WHIM filament possibly permeating a large-scale, 30 Mpc extended, structure of galaxies whose redshift centroid, within a cylinder of 7.5 Mpc radius centered on the line of sight to H 2356-309, is marginally consistent (at a 1.8σ level) with the redshift of the absorber.

Key words: BL Lacertae objects: individual (H 2356-309) – intergalactic medium – large-scale structure of universe – quasars: absorption lines – techniques: spectroscopic – X-rays: galaxies: clusters

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1. INTRODUCTION

Cosmological simulations predict that during the process of structure formation, the high-redshift diffuse cold photoionized intergalactic baryonic phase responsible for the Lyα forest undergoes a substantial transformation. Baryons in these filaments are predicted to fuel structure formation by accreting toward the large-scale dark matter Cosmic Web, populated by galaxies and, by doing so, to undergo shocks that heat them up to temperatures of $T \approx 10^{5}–10^{6}$ K (Cen & Ostriker 1999; Davé et al. 2001). This new collisionally ionized baryonic phase is dubbed warm–hot intergalactic medium (WHIM) and is supposed to exist in filamentary structures at very low densities (5–100 times the mean baryonic density of the universe) and to account for the majority of the baryons in the local universe ($z < 1$) that are currently still undetected (Fukugita & Peebles 2004).

The range of density and temperature of the WHIM are theoretically well established within the context of a Λ-CDM universe. On the contrary, the effects of AGNs and galaxy wind feedback, as well as that of galaxy mergers, on WHIM filaments, both in the immediate surrounding of structures and at larger scales, are not yet well understood and therefore their physics is difficult to implement in simulations. This feedback may significantly affect the metal content of the WHIM (e.g., Cen & Ostriker 2006) and therefore its detectability. At WHIM temperatures and densities, the gas is so highly ionized and tenuous that it can only weakly emit in the soft X-rays through Bremsstrahlung and weakly interact with radiation in the far-ultraviolet (FUV) and soft X-ray bands through electronic transitions of relatively light metals in their highest ionization states, therefore emitting or absorbing photons at these wavelengths. Uncertainties on the intergalactic medium (IGM)-galaxy feedback processes reflect negatively into the accuracy of hydrodynamic simulation predictions and so, in turn, on feasibility studies of WHIM observations and the prospects for accurate studies of this important baryon phase and its interplay with galaxies at large scales.

Despite the few claims of broadband X-ray imaging detection (Zappacosta et al. 2002, 2005; Werner et al. 2008), the best way to currently detect and study the WHIM still relies on the identification of absorption lines (mainly O vi, O vii, C v, H i-Lyα) from intervening medium in the FUV/X-ray spectrum of bright background extragalactic sources.

Cross-correlation studies of WHIM metal and H i systems over the entire WHIM temperature/density distribution intervals, and their surrounding galaxy environments, are critical to progress in this field. These, however, are hampered mostly by the small number of WHIM metal detections, particularly in the regime of temperatures $T \bigg\approx 10^{5.5}$ K (where the majority of these baryons should be found), accessible only in the X-ray band where so far only few mostly controversial results have been obtained even when targeting sightlines crossing known galaxy-traced superstructures (Nicastro et al. 2005; Fang et al. 2010; Zappacosta et al. 2010). At lower temperatures ($T \approx 10^{5}–10^{5.5}$ K), the WHIM can be also identified in the FUV band, through the detection of, possibly paired, O vi doublet and thermally broadened H i absorbers (BLAs; see Richter et al. 2008 for a review). These are found to constitute $<25\%$ of the predicted baryon mass, in the local universe (e.g., Shull et al. 2011), and are supposed to be tracers of collisionally ionized IGM (the WHIM), at $T \bigg\approx 10^{5}$ K. Cross-correlation studies of this cool tail of the WHIM-mass distribution with the surrounding galaxy environment tentatively suggest that while O vi absorbers (or O vi and BLA pairs) lie relatively close ($\lesssim 800 h_{70}^{-1}$ kpc) to bright $L^*$ galaxies (Stocke et al. 2006), BLA-only absorbers are found at larger distances from their nearest $L^*$ galaxy neighbor ($0.75–2.9 h_{70}^{-1}$ Mpc; Danforth et al. 2010, hereafter DSS10). This tentative evidence (based on a small number of systems) would suggest that “warm” metals ($T \lesssim 10^{5.5}$) are limited to the surrounding of large galaxy halos.
which probably contributed to their enrichment, while the more diffuse "metal-poor" gas (at least in the $T \approx 10^5-10^6$ temperature range) traces more distant regions.

Here, we present the first evidence for possible C v (40.27 Å) IGM absorption in the X-rays, at $z = 0.112$, found to lie in a relatively underdense region of the local universe, with the nearest galaxy at $\sim 2.2$ Mpc distance, but still within a large-scale filamentary structure of galaxies. The paper is organized as follows: we briefly present the data and their reduction in Section 2, then we describe the spectral analysis in Section 3, and finally in Section 4 we discuss and interpret our findings.

Reported errors are $1\sigma$ unless otherwise specified.

2. DATA REDUCTION

H2356-309 has been observed twice with Chandra with the HRC-S/LETG grating configuration for a total of $\sim 600$ ks. The first observation was performed in 2008 October (96.49 ks). The second observation (496.4 ks) consists in 10 pointings with exposures ranging from 15 ks to 100 ks and was carried out during the last four months of 2009. H 2356-309 was also observed with XMM-Newton for 130 ks. However, the XMM-Newton gratings (RGSs) do not cover the $\lambda \gtrsim 38$ Å spectral band, which we focus on in this paper. We therefore do not use the XMM-Newton data of H 2356-306 in this paper. The Chandra data have been previously analyzed and presented by Fang et al. (2010) and Zappacosta et al. (2010). In this paper, we make use of the data reduced by Zappacosta et al. (2010; see their Section 3.1; for details on the data reduction). In order to maximize the signal-to-noise ratio ($S/N$) of the single Chandra observations, for each observation we co-add the HRC-LETG positive and negative order source and background spectra. Given the nonlinearity of the HRC-LETG effective dispersion relation, this procedure may introduce additional uncertainties ($\sigma_{\text{cal}}$) in the wavelength calibration scale (currently calibrated to 0.01 mÅ). Since the corrections leading to these calibrations are obtained at the rest-frame position of strong X-ray metal electronic transitions and the interpolation to redshifted transitions may not be strictly valid, we assumed throughout the spectral range a conservative increased uncertainty of $\sigma_{\text{cal}} = 0.02$ Å. This uncertainty will in turn increase to $\sigma_{\text{cal}} \approx 0.04$ Å when we will co-add the spectra of all the observations to maximize the $S/N$. In this case the final uncertainty is obtained by propagating the single spectra uncertainties but weighting each term by the relative contribution in counts of each observation in the 0.5–2 keV band. In the following we will always quote the statistical errors only, unless differently specified.

3. SPECTRAL ANALYSIS

For the spectral analysis we use the fitting package Sherpa (Freeman et al. 2001), in CIAO 4.2. We perform all our fits using the data weighted $\chi^2$ with the Gehrels variance function and adopting a Nelder–Mead simplex optimization method.

The analysis is mainly focused on the 44–48 Å spectral region, not considered in Fang et al. (2010) and Zappacosta et al. (2010). In our spectral analysis and fitting procedure, we use two different approaches to the data: (1) in order to maximize the $S/N$ per resolution element, we first co-add all the 11 HRC-LETG spectra together (see Zappacosta et al. 2010 for details) and analyze the total 568.8 ks spectrum; (2) then, to check the reliability of our findings against possible systematics introduced by co-adding the single spectra, we also repeat the fitting procedures simultaneously to 6 HRC-LETG spectra, extracted from the 11 observations in such a way that the resulting 6 spectra have all homogeneous $S/N$ per resolution element: the exposures of these 6 spectra vary between 90 and 110 ks each.

All spectra are binned to half the HRC-S/LETG FWHM (0.025 Å).

3.1. Single Line Analysis

Figure 1 shows two portions of the total HRC-LETG spectrum of H 2356-309, where the redshifted C v $K\alpha$ (top panel) and OVII $K\alpha$ (bottom panel) lines are expected ($\lambda = 44–48.5$ Å, top panel, and $\lambda = 23–28$ Å, bottom panel), together with the local best-fitting continuum models (magenta curves in both panels), and the intervening absorber models (red and blue curves; Section 3.2), folded through the HRC-LETG response. In these two spectral intervals, the total spectrum has $\sim 230–280$ net source counts per resolution element ($S/N \sim 12$) and so is sensitive to the detection of absorption line equivalent widths $EW \gtrsim 12$ mÅ at $\gtrsim 3\sigma$.

A visual inspection of the $\lambda = 44–48.5$ Å portion of the spectrum (Figure 1, top panel) reveals the presence of two

\footnote{The $\lambda = 23–28$ Å best-fitting continuum includes also two negative Gaussians to model atomic O i absorption both at $z = 0$ and at the redshift of H 2356-309.}
negative (compared to the best-fitting continuum) line-like features at $\sim 44.75$ Å and $\sim 47$ Å. We modeled these features by adding two negative Gaussians to our best-fitting local continuum model. The two resulting best-fitting absorption lines have line centroids $\lambda = 44.76 \pm 0.02$ Å and $\lambda = 47.00 \pm 0.02$ Å, $\text{EW} = 22 \pm 5$ mÅ and $\text{EW} = 16 \pm 6$ mÅ, and single line statistical significances (i.e., estimated by dividing the best-fitting Gaussian normalizations by their $1\sigma$ errors) of $4.2\sigma$ and $2.7\sigma$, respectively.

To check the actual statistical significance of these features against possible systematics introduced by co-adding the 11 observations, we performed the same analysis simultaneously on the $\lambda = 44–48.5$ Å portion of the 6 homegeneous S/N spectra extracted from the 11 observations. For each of the six spectra, our local continuum model includes a power law with spectral index and normalizations free to vary independently. We then include two negative Gaussians for each of the six spectra, with common line centroids, common EWs, and line widths frozen to a common unresolved HRC-LETG value, and fit the six data sets simultaneously. The best-fit model gives line positions and equivalent widths consistent with the ones derived from the fit to the co-added spectrum, although with larger uncertainties due to the larger number of free parameters in the joint fit.

Figure 2 shows the smoothed residuals of the 44–48.5 Å portion of the six spectra (top panel) and the co-added spectrum (bottom panel) to their respective best-fitting continuum models (obtained by folding the residual histograms through the HRC-LETG line spread function), re-normalized after smoothing to comply with Poisson statistics. The $\lambda = 44.76 \pm 0.02$ Å line is visible in four out of the six best-fitting continuum residuals and appears prominent in the best-fitting continuum residuals to the co-added spectrum. The second absorption feature is only visible in the best-fitting continuum residuals to the co-added spectrum.

In the following analysis, we focus exclusively on the co-added spectrum of H 2356-309, and tentatively identify the two absorption features at $\lambda = 44.76 \pm 0.02$ Å and $\lambda = 47.00 \pm 0.02$ Å, as redshifted C v Kα lines at $z = 0.1117 \pm 0.0005$ and $0.1671 \pm 0.0005$ (only marginally consistent at a 3σ level with the systemic redshift of H 2356-309: $z = 0.1654 \pm 0.0002$; Jones et al. 2009).

### 3.2. Global Analysis and Characterization of the Absorber

To test the validity of our tentative C v identifications at $z = 0.1117 \pm 0.0005$ and $0.1671 \pm 0.0005$, we used our hybrid-ionization WHIM spectral model (adapted from PHASE; Krongold et al. 2003) to check for compatibility between the data and the presence or absence of associated absorption from other ions of the same or different metals. The model includes more than 3000 electronic transitions from H to Ca and predicts the opacity of each transition for given H equivalent column densities ($N_H$), and temperatures ($T$), for collisionally ionized plasma undergoing the additional photoionizing contribution by UV and X-ray metagalactic photons at a given redshift and baryon density ($n_b$).

We proceeded as follows: we first modeled local continua separately in four different key spectral bands of the co-added HRC-LETG spectrum of H 2356-309: 23.0–28.0 Å, 31.0–36.0 Å, 36.0–41.0 Å, and 44.0–48.5 Å. We chose these four spectral bands because these are the regions where transitions from other abundant ions associated with C v in plasma in collisional ionization, photoionization, or hybrid-ionization equilibrium are expected to produce significant opacity. To model the local continua we used simple power laws and, in the 23–28 Å spectral range, we also included two negative Gaussians to model the atomic O i transitions at $z = 0$ and at blazar redshift (Figure 1, bottom panel, magenta curves). Then we added two hybrid-ionization components, at the redshift of our tentative C v identifications. The model parameters are: temperature, equivalent H column density and volume baryon density of the gas, the redshift of the absorber, and its internal turbulence velocity. The baryon volume density is used to define the relative contribution of photoionization: lower the volume density, higher the photo-ionization contribution from the surrounding metagalactic photons. This contribution is highly degenerate with the temperature of the plasma and cannot be constrained independently in such quality data. We therefore fixed this parameter to a typical WHIM value of $n_b = 10^{-5}$ cm$^{-3}$ (overdensity of $\sim 50$, compared to the average universe density), for both absorbers. We also froze the turbulent velocity to $v_{\text{turb}} = 100$ km s$^{-1}$ (that of an unresolved line in HRC-LETG data). Of the remaining three parameters, the temperature and equivalent H column density of the absorbers were left free to vary in the fit, but linked to a common value in all the four spectral regions. Finally, the redshifts of the two absorbers were set to their best-fit values determined in previous section and left free to vary within $\pm 0.005$ and linked to a common narrow spectral interval in each of the four bands. The best-fitting absorber models confirm our tentative identifications of the two lines as C v Kα absorbers. Figure 1 shows the best-fitting absorption models (blue and red curves) in the only two bands where relatively strong opacities from C v Kα (top panel) and O iv–vii Kα (bottom panel) lines are predicted. For both best-fitting absorber models the strongest opacity contribution by far is given by C v Kα. The additional opacity produced by O iv–vii Kα lines...
is fully consistent with the data (bottom panel, blue and red curves). The best-fitting parameters of the possible intervening absorbers are: \( z = 0.1117 \pm 0.0005 \), \( T = 5.10^{+0.13}_{-0.17} \) K, \( N H = 19.05^{+0.15}_{-0.25} (Z/Z_{\odot})^{-1} \text{cm}^{-2} \) and \( z = 0.1671 \pm 0.0005 \), \( T \gtrsim 4.6 \) K, \( N H \gtrsim 18.5 (Z/Z_{\odot})^{-1} \text{cm}^{-2} \) (90% upper limits). For the intervening absorber the small upper and lower error bars in temperature are set by the lack of strong O viii Kα and O iv Kα absorption in the data, respectively.

We also checked whether the detected absorption feature at 44.76 Å could be due to a different transition from a cooler ion of C, at redshift lower than \( z = 0.112 \). Possible candidates are inner-shell Kα transitions from lithium-like C (C iv) all the way down to neutral C (C i). However, unlike C v which is helium-like and so highly stable and practically the only ion of C over a wide range of temperatures (from \( log T = 4.8-6 \) K), lower ionization ions are much less stable and contribute together to the total C fraction, in a mixture that depends upon the exact gas temperature. Typically, at temperatures of \( log T \sim 3-4 \) K, C iii and C iv contribute most, while at lower temperature C i and C ii are the dominant ions. In other words, while He-like metals can be found isolated in absorption or emission spectra, for a wide interval of temperatures, lower ionization ions produce equally strong opacities in groups of two to three ions. We checked the data for their compatibility with the presence of any of these low-ionization transitions and found no possible solution. If the detected absorber at \( \lambda = 44.76 \) Å was due, e.g., to the C iv Kα transition at \( \lambda = 41.39 \) Å (which would place the absorber at \( z \sim 0.081 \)), in order to reproduce the spectral features at \( \lambda = 44.76 \) Å, the absorber should have either a temperature \( log T < 4 \) K and \( log NH \sim 19 (Z/Z_{\odot})^{-1} \text{cm}^{-2} \) or higher temperatures but extremely high column densities \( log NH \gtrsim 20 (Z/Z_{\odot})^{-1} \text{cm}^{-2} \). In both cases the models predict similar, or even higher, opacities at other transitions (i.e., C iii at \( \sim 45.55 \) Å and O iv, O vi in the range 24–25 Å) whose presence is not consistent with the data. Similar considerations hold for the possible identification of the \( \lambda = 44.76 \) Å feature with the main transitions from lower ionization ions. We therefore exclude the identification of the \( \lambda = 44.76 \) Å feature with intervening cool medium at \( z < 0.112 \) and conclude that a C v Kα absorber at \( z = 0.1117 \pm 0.0005 \) is the most likely identification for the observed feature.

Our best-fitting model for the \( z = 0.1117 \pm 0.0005 \) absorber predicts an O vi column of \( \sim 1.3 \times 10^{14} \text{cm}^{-2} \). O vi has its strongest outer-shell doublet transitions in the FUV, at 1031.93, 1037.62 Å. We checked for the presence of these lines in the low S/N (<1.5 ks) archival Far-Ultraviolet Spectroscopic Explorer observation of H 2356-309. Unfortunately, however, in the relevant spectral region (\( \lambda = 1147-1154 \) Å) these data are only sensitive to column densities of \( >(1-2) \times 10^{14} \text{cm}^{-2} \) (for line Doppler parameters in the range \( b = 50-100 \text{ km s}^{-1} \)) at a 3σ level, so fully consistent with the presence of the predicted line, but not of sufficient quality to uncontroversially set the issue.

4. DISCUSSION

4.1. On the Significance of the Intervening C v Line

In Section 3.1 we estimated the significance of the intervening C v Kα line, as a single-line significance of 4.2σ. However, in doing so we did not account for the number of redshift trials, i.e., for the lack of a prior on the expected redshift of the line (see, e.g., Kaasstra et al. 2006). A blind search for intervening C v Kα line exploits the entire redshift range available, from \( z = 0 \) to the redshift of the background blazar. The number of resolution elements of the spectrometers between the rest-frame position of the C v Kα line (\( \lambda_{C,v} \)) and the position of the line at the redshift \( z_{bl} \) of the blazar represents the number of independent redshift trials \( N \). In our case: \( N = \lambda_{C,v} \star z_{bl}/0.05 = 133 \). The probability of chance detection of an intervening \( z \leq z_{bl} \) C v Kα line seen at a single-line significance of 4.2σ is given by the binomial distribution formula

\[
P = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n},
\]

where \( N = 133, n = 1, \) and \( p = 1.34 \times 10^{-5} \) is the one-sided Gaussian probability corresponding to 4.2σ. This gives a chance detection probability of \( P = 1.8 \times 10^{-3} \) (0.2%), corresponding to an effective line significance of 2.9σ, after accounting for the number of redshift trials.

4.2. Possible Galactic/Super-galactic Identification of the Absorber

The low temperature estimated for the intervening C v absorber at \( z = 0.1117 \pm 0.0005 \) suggests it to be the X-ray counterpart of the O vi intergalactic absorbers commonly found in the FUV spectra of extragalactic sources, at \( z \lesssim 0.5 \) (Danforth & Shull 2005; Tripp et al. 2008). However, unlike O vi, which can be efficiently produced in both photoionized and collisionally ionized gas, C v is an He-like ion, and as such much more stable and abundant in collisionally ionized gas (or WHIM) than in gas purely photoionized by the metagalactic radiation field.

Indeed, only a relatively small fraction of the O vi absorbers are found to originate in shock-heated (e.g., collisionally ionized) gas at low-temperature end of the WHIM mass distribution and therefore associated with BLAs, while the rest is possibly imprinted by the residual local photoionized Lyα forest (e.g., Danforth & Shull 2005; Tripp et al. 2008). The C v absorber that we find here belongs probably to the class of O vi-BLA associations, which are still limited in number.

In a recent work on BLA detections along the line of sight to seven AGNs, DSS10 report a marginal evidence for BLA-O vi detections in well-surveyed galaxy fields (four in their sample) to be closer to \( L^* \) galaxies (\(< 0.5 \text{ Mpc from their closest galaxy} \)) than isolated BLAs with O vi non-detections (four in their sample; 0.75 Mpc < \( d < 2.9 \) Mpc from the closest galaxy). This limited number statistic evidence suggests that metals in the local universe (at least at such moderately low temperatures) are not uniformly spread in the IGM, but they concentrate around structures, possibly in extended halos of galaxies.

However, these searches are limited to nearest-galaxy versus absorber correlations and do not investigate on the spatial distributions of galaxies around a given absorber. WHIM filaments embedding a large number of galaxies could be enriched differently, and at different levels, from extended galaxy halos in relatively sub-dense galaxy regions.

The evidence regarding metals at higher temperatures that can be traced in the X-rays is much sparser. Nicastro et al. (2005) and Fang et al. (2010) have obtained so far the most convincing, although still debated (e.g., Kaasstra et al. 2006; Yao et al. 2012, respectively) detections from this hotter phase. They have found absorptions from warm-hot material at \( z = 0.027 \) and \( z = 0.03 \), both coincident with extended filaments of galaxies (Williams...
distribution of the galaxies relative to the C\textsuperscript{v} absorption line is detected at a distance $\Delta v \approx 1117$ km s\textsuperscript{-1} from the absorber. We tentatively identify this absorber with an intervening WHIM absorber embedding a large-scale filament of galaxies extending for $\sim 30$ Mpc and connecting clusters and groups of galaxies at its extremes, and we rule out its possible association with the extended halo of a bright single galaxy at a distance lower than 2 Mpc from the absorber.

Future FUV studies with \textit{HST}-COS coupled with further deeper and redshift-complete optical spectroscopic observations of the local galaxy field will certainly help in shedding further light on the origin of the absorber, its metallicity, and physical properties.

5. SUMMARY AND CONCLUSIONS

We reported on a strong intervening C\textsuperscript{v} Ka absorber at $z = 0.1117 \pm 0.0005$, serendipitously detected in the $\sim 600$ ks \textit{Chandra} HRC-S/LETG spectrum of the blazar H2356-309. The C\textsuperscript{v} Ka absorption line is detected at a $\sim 2.9 \sigma$ confidence level (accounting for the number of independent redshift trials).

We tentatively identify this absorber with an intervening WHIM absorber embedding a large-scale filament of galaxies extending for $\sim 30$ Mpc and connecting clusters and groups of galaxies at its extremes, and we rule out its possible association with the extended halo of a bright single galaxy at a distance lower than 2 Mpc from the absorber.

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REFERENCES

Buote, D. A., Zappacosta, L., Fang, T., et al. 2009, ApJ, 695, 1351
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Cen, R., & Ostriker, J. P. 2006, ApJ, 650, 560
Colless, M., Peterson, B. A., Jackson, C., et al. 2003, arXiv:astro-ph/0306581
Danforth, C. W., & Shull, J. M. 2005, ApJ, 624, 555
Danforth, C. W., Stocke, J. T., & Shull, J. M. 2010, ApJ, 710, 613
Davé, R., Cen, R., Ostriker, J. P., et al. 2001, ApJ, 552, 473
Falomo, R., Scarpa, R., Treves, A., & Urry, C. M. 2000, ApJ, 542, 731
Fang, T., Buote, D. A., Humphrey, P. J., et al. 2010, ApJ, 714, 1715
Freeman, P., Doe, S., & Siemiginowska, A. 2001, Proc. SPIE, 4477, 76
Fukugita, M., & Peebles, P. J. E. 2004, ApJ, 616, 643
Giroletti, M., Giovannini, G., Taylor, G. B., & Falomo, R. 2004, ApJ, 613, 752

Jones, D. H., Read, M. A., Saunders, W., et al. 2009, MNRAS, 399, 683
Kaasstra, J. S., Werner, N., Herder, J. W. A. den., et al. 2006, ApJ, 652, 189
Krongold, Y., Nicastro, F., Brickhouse, N. S., et al. 2003, ApJ, 597, 832
Nicastro, F., Mathur, S., Elvis, M., et al. 2005, Nature, 433, 495
Pointecouteau, E., Arnaud, M., & Pratt, G. W. 2005, A&A, 435, 1
Richter, P., Puerels, F. B. S., & Kaasstra, J. S. 2008, Space Sci. Rev., 134, 25
Shull, J. M., Smith, B. D., & Danforth, C. W. 2011, arXiv:1112.2706
Stocke, J. T., Penton, S. V., Danforth, C. W., et al. 2006, ApJ, 641, 217
Tripp, T. M., Sembach, K. R., Bowen, D. V., et al. 2008, ApJS, 177, 39
Werner, N., Finoguenov, A., Kaasstra, J. S., et al. 2008, A&A, 482, L29
Williams, R. J., Mulchaey, J. S., Kollmeier, J. A., & Cox, T. J. 2010, ApJ, 724, L25
Yao, Y., Shull, J. M., Wang, Q. D., & Cash, W. 2012, ApJ, 746, 166
Zappacosta, L., Mannucci, F., Maiolino, R., et al. 2002, A&A, 394, 7
Zappacosta, L., Maiolino, R., Mannucci, F., Gilli, R., & Schuecker, P. 2005, MNRAS, 357, 929
Zappacosta, L., Nicastro, F., Maiolino, R., et al. 2010, ApJ, 717, 74