

XMM-NEWTON RGS AND CHANDRA LETGS OBSERVATIONS OF THE WHIM IN 1ES 1028+511

K. C. Steenbrugge, F. Nicastro, and M. Elvis

Harvard-Smithsonian Center for Astrophysics, 60 Garden street, Cambridge, MA 02138, USA

ABSTRACT

We report preliminary results on the detection of the Warm-Hot Intergalactic Medium (WHIM) along the line of sight toward the blazar 1ES 1028+511 ($z = 0.361$). 1ES 1028+511 was observed for 150 ks with the low energy transmission grating in combination with the high resolution camera onboard *Chandra*. An additional 300 ks observation was obtained using the reflection grating spectrometers (RGS) onboard XMM-*Newton*. We report the detection of three absorption lines which can be attributed to the WHIM, and compare the results with theoretical predictions.

Key words: Warm-hot intergalactic medium, blazar: 1ES 1028+511, X-ray spectroscopy.

1. INTRODUCTION

At $z > 2$ the vast majority of the baryons ($> 76\%$, Rauch (1998); Weinberg et al. (1997)) are found in a mildly photoionized (by the metagalactic UV radiation field) phase of the IGM, through a forest of HI Ly α absorption lines in the background O-UV spectra of background quasars. However, at $z < 2$ only $\sim 30\%$ of the baryons are detected in the residual local Ly α forest (Penton et al., 2004), and already-virialized structures account for even a smaller fraction $\sim 12\%$ Fukugita (2003). About 54% of the baryons are eluding detection in the local Universe. Hydrodynamical simulations for the formation of structures in a Λ -CDM Universe, provide a self-consistent solution to this puzzle: about half of the baryons in the local Universe should still be confined in the IGM, but shock-heated to temperatures of about $10^5 - 10^7$ K, during the collapse of density perturbation.

At such high temperatures H is fully ionized and so the gas is transparent to Optical and UV observations. However, electronic transitions from highly ionized metals, can still provide a significant source of opacity. CV-VI, OVII-VIII and NeIX-X K α are the most intense of these transitions, in gas with Solar-like composition. All these transitions fall in the soft X-ray band, and can now be

detected thanks to the high-resolution spectrometers of *Chandra* and XMM-*Newton*.

1ES 1028+511 (Schachter et al. (1993); Elvis et al. (1992)) is at a redshift of 0.361 (Polowski et al., 1997) thus, according to simulations (Fang et al., 2002), we expect to detect 1 system with an O VII column density equal or greater than 10^{16} cm^{-2} .

2. OBSERVATIONS AND DATA REDUCTION

1ES 1028+511 was observed by *Chandra* for 149.86 ks on March 11, 2004, using the Low Energy Transmission Grating in combination with the High Resolution Camera (LETGS). We extracted the LETGS spectrum using the pipeline described by Kaastra et al. (2002), which includes an empirical correction for the known wavelength problem in the LETGS (Kaastra et al., 2002) and fitted it with responses that include the first 10 positive and negative orders.

The XMM-*Newton* observation was split into three separate observations, between June 20 to 24, 2005. The exposure times were 104.2, 95.2 and 101.4 ks. The data were reduced using the SAS version 6.1.0 standard threads.

In all fitting, we fitted the RGS and LETGS spectra (7 spectra) simultaneously. Errors were evaluated at 68% significance level, for one interesting parameter. The data were analyzed using the *spex* package (Kaastra et al., 2002b).

3. ABSORPTION LINES

Three absorption lines are detected with a at least 2σ significance. Table 1 lists the equivalent width (EW) of these absorption features, the most likely identification, and the ionic column densities assuming a velocity broadening of 100 km s^{-1} .

The 28.74 Å line can be identified as an O VII K α line and has a 2.5σ significance. However, this line is only

Table 1. The observed wavelength, EW, ion column density, the redshift and the most likely identifications.

λ_{obs} Å	EW mÅ	$\log N_i$ cm^{-2}	redshift	iden.
28.74	34 ± 12	15.7 ± 0.4	0.33	O VII $K\alpha$
46.25	24 ± 7	15.6 ± 0.2	0.15	C V $K\alpha$
			0.12	C IV $K\alpha$
48.80	32 ± 10	15.8 ± 0.2	0.21	C V $K\alpha$
			0.18	C IV $K\alpha$

Table 2. The 1σ upper limits for the O VII and O VIII column density.

redshift	N_{OVII} $\log \text{cm}^{-2}$	N_{OVIII} $\log \text{cm}^{-2}$
0.15	> 15.5	> 15.9
0.21	> 15.3	> 15.9

seen in the positive order of the LETGS and has a full width half maximum of 500 km s^{-1} . The line falls on an instrumental feature in the RGS spectra. An alternative, but unlikely identification is $z=0$ N VI $K\alpha$. Therefore it should be considered as a possible detection of O VII $K\alpha$.

The 46.25 Å and 48.80 Å lines can be either identified as C V or C IV lines. The significance of the lines is 3.4 and 3.2 σ respectively. Table 2 lists the OVII–OVIII column density 1-sigma upper limit at the redshifts of the CV identifications. If the lines are C IV, they are probably imprinted by mildly photoionized gas at temperatures of about 10^4 K, and so are not tracking WHIM filaments. For both redshifts the C IV 1549 Å line is redshifted out the HST STIS spectrum.

4. COMPARISON WITH SIMULATION

Fig. 1 shows the expected number of WHIM absorbing systems per unit redshift versus O VII column density (Fang et al., 2002). The the Gehrels upper limit (square), the measured column density for O VII (circle), and the measured column density for Mrk 421 (star). The box indicates the expected number of O VII lines and column densities from the detected C V lines. All data points are consistent with the expectation of hydrodynamical simulations by Fang et al. (2002).

5. ACKNOWLEDGEMENTS

K. C. S. and F. N. acknowledges support from the Chandra grant G04-5101X. F. N. acknowledges support from the XMM grant NNN046D836.

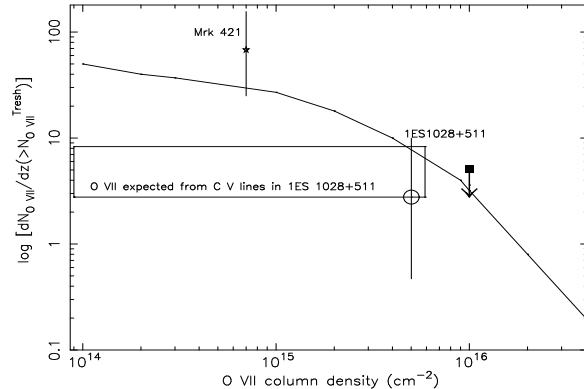


Figure 1. The predicted number of intervening WHIM absorbers per redshift versus the O VII column density (solid line) (Fang et al., 2002). The result for the Mrk 421 spectra (Nicastro et al., 2005) (star), the Gehrels upper limit (square), and assuming we detect O VII (circle). The box indicates the expected number of O VII absorption lines and their column density calculated from the C V detections in the 1ES 1028+511 spectra.

REFERENCES

- Elvis, M., Plummer, D., Schachter, J., & Fabbiano, G. 1992, ApJS, 80, 257
- Fang, T., Bryan, G. L., & Canizares, C. R. 2002, ApJ, 564, 604
- Fukugita, M. 2003, Cosmic Matter Distribution: Cosmic Baryon Budget Revisited
- Kaastra, J. S., Mewe, R., & Raassen, A. J. J. 2002b, Proc. Symp. New Visions of the X-ray Universe in the XMM-Newton and Chandra era
- Kaastra, J. S., Steenbrugge, K. C., Raassen, A. J. J., et al. 2002, A&A, 386, 427
- Nicastro, F., Mathur, S., Elvis, M., et al. 2005, ApJ, 629, 700
- Penton, S. V., Stocke, J. T., & Shull, J. M. 2004, American Astronomical Society Meeting Abstracts, 204,
- Polomski, E., Vennes, S., Thorstensen, J. R., Mathioudakis, M., & Falco, E. E. 1997, ApJ, 486, 179
- Rauch, M. 1998, ARA&A, 36, 267
- Schachter, J. F., Stocke, J. T., Perlman, E., et al. 1993, ApJ, 412, 541
- Weinberg, D. H., Miralda-Escude, J., Hernquist, L., & Katz, N. 1997, ApJ, 490, 564