Probing Warm-Hot Intergalactic Medium Associated with the Virgo Cluster
Using an Oxygen Absorption Line

Ryuichi FUJIMOTO, Yoh TAKEI, Takayuki TAMURA, Kazuhisa MITSUDA, and Noriko Y. YAMASAKI
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510
fujimoto@astro.isas.jaxa.jp

Ryo SHIBATA
Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602
Takaya OHASHI and Naomi OTA*

UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
Michael D. AUDLEY

Richard L. KELLEY and Caroline A. KILBOURNE
NASA Goddard Space Flight Center, Greenbelt MD 20771, USA

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Abstract

To detect a warm-hot intergalactic medium (WHIM) associated with the large-scale structure of the universe, we observed a quasar behind the Virgo cluster with XMM-Newton. With 54 ks exposure, we marginally detected an O VIII Kα absorption line at 650.9+0.8−0.9 eV in the RGS spectra, with a statistical confidence of 96.4%. The observed line center energy is consistent with the redshift of M 87, and hence the absorber is associated with the Virgo cluster. From the curve of growth, the O VIII column density was estimated to be $\gtrsim 7 \times 10^{16}$ cm$^{-2}$. In the EPIC spectra, excess emission was found after evaluating the hot ICM in the Virgo cluster and various background components. We inspected the RASS map of the diffuse soft X-ray background, and confirmed that the level of the north and west regions just outside of the Virgo cluster is consistent with the background model that we used, while that of the east side is significantly higher and the enhancement is comparable with the excess emission found in the EPIC data. We consider a significant portion of the excess emission to be associated with the Virgo cluster, although a possible contribution from the North Polar Spur cannot be excluded. Using the column density and the emission measure and assuming an oxygen abundance of 0.1 and an ionization fraction of 0.4, we estimate that the mean electron density and the line-of-sight distance of the warm-hot gas are $\lesssim 6 \times 10^{-3}$ cm$^{-3}$ and $\gtrsim 9$ Mpc. These strongly suggest detection of a WHIM in a filament associated with the Virgo cluster.

Key words: cosmology: large-scale structure of universe — cosmology: observations — galaxies: clusters: individual (Virgo) — galaxies: intergalactic medium — galaxies: quasars: absorption lines

1. Introduction

From several independent measurements — cosmic microwave background anisotropy analysis (Spergel et al. 2003), primordial deuterium-to-hydrogen ratio (Burles et al. 2001), and Lyα forest absorption at high redshift ($z \sim 3$) (Rauch et al. 1997) — the cosmic baryon density is now converging to $\Omega_b \approx 0.04 h_{70}^{-2}$, where $h_{70} = H_0/70$ km s$^{-1}$ Mpc$^{-1}$ and $H_0$ is the Hubble constant. The local baryon density appears, however, to be far lower than these indications (e.g., Fukugita et al. 1998; Bristow, Phillipps 1994; Persic, Salucci 1992). Recent large-scale galaxy formation simulations predict that most of the baryons ($\sim 50\%$) at the present time reside in a warm-hot intergalactic medium (WHIM) with temperatures of $10^5$–$10^7$ K, and form filamentary structures associated with clusters and groups of galaxies (e.g., Cen, Ostriker 1999). This warm-hot gas is heated primarily by shock heating of gas accreting onto the large-scale structure (Davé et al. 2001), and its fraction is increasing with time. Therefore, detecting those warm-hot baryons is very important, not only for settling the ‘missing baryon’ problem, but also for understanding the formation of large-scale cosmological structure.

Considering the elemental abundance and the ionization fraction, O VII and O VIII absorption lines are the best tracers for probing the warm-hot gas at $10^6$–$10^7$ K (Perna, Loeb 2001), and their fraction is increasing with time. Therefore, detecting those warm-hot baryons is very important, not only for settling the ‘missing baryon’ problem, but also for understanding the formation of large-scale cosmological structure.
interstellar matter in our Galaxy is not trivial (Futamoto et al. 2004). On the other hand, soft X-ray emission in clusters of galaxies has been studied (e.g., Kaasstra et al. 2003; Finoguenov et al. 2003). These authors claimed the detection of a warm-hot component with $kT\sim0.2$ keV. However, since the energy band below 0.5 keV is significantly contaminated by emission from the Milky Way halo and the Local Hot Bubble, a precise determination of the quantities of the warm-hot gas is very difficult with the limited energy resolution of proportional counters and X-ray CCDs.

In searching for a breakthrough, we decided to probe the warm-hot gas associated with nearby clusters of galaxies through absorption lines by observing a quasar behind the Virgo cluster with the Reflection Grating Spectrometer (RGS; den Herder et al. 2001) onboard XMM-Newton (Jansen et al. 2003). These authors claimed the detection of a warm-hot gas in clusters of galaxies has been studied (e.g., Kaastra et al. 2003; Finoguenov et al. 2004). On the other hand, soft X-ray emission in clusters of galaxies has been studied (e.g., Kaastra et al. 2003; Finoguenov et al. 2004). On the other hand, soft X-ray emission in clusters of galaxies has been studied (e.g., Kaastra et al.

### Table 1. Observation mode and net exposure time.

| Instrument | Mode | Filter | Net exposure |
|------------|------|--------|--------------|
| RGS        | Spectrum + Q | ⋯     | 53.8 ks      |
| EPIC pn    | Full frame  | Thin1  | 44.9 ks      |
| EPIC MOS   | Full frame  | Medium | 56.9 ks      |

summarized in table 1. Note that, although 100 ks was scheduled, the net observation time was only $\sim50$ ks due to background flares.

### 3. Data Analysis and Results

#### 3.1. Absorption Line

The observation data file (ODF) was divided into two files. We performed data reduction using the XMM-Newton Science Analysis System (SAS), version 5.4.1, with standard parameters. For the RGS, we checked the data from a source-free region of CCD 9 for background flares, and accumulated the signal photons only when the count rates in this region were less than 0.15 cps for both RGS1 and 2. The net exposure time was 8.8 ks for the first file and 45.0 ks for the second. The background spectra were produced using the same data sets. All of the spectra were binned in four-channel bins (0.042 Å), and the first and second halves were summed.

There was no sign of an O VII absorption line at around 21.6 Å, where only the RGS1 operates. The 99.7% upper limit of the equivalent width was 2.8 eV at 21.69 Å (571.6 eV). Therefore, we concentrated on the O VIII region. Figure 2 shows the spectra obtained with the RGS1 and 2, between 18 Å and 20 Å. There is an absorption-line feature at around 19.1 Å in both RGS1 and 2. We fitted the spectra with a power law and a negative Gaussian, multiplied by the Galactic absorption ($NH = 2.15 \times 10^{20}$ cm$^{-2}$), using XSPEC version 11.2. Since the number of photons, especially near the absorption line, is small, we used the C-statistic (maximum-likelihood) method. When this method is used, a background spectrum cannot be subtracted from the data. Therefore we estimated the background level by fitting the background spectra of RGS1 and 2 simultaneously with a constant model, and included it in the fitting model. The results are summarized in table 2; the best-fit model is shown in figure 2. The line shape was consistent with a narrow line, with a 90% upper limit on a width of $\sigma < 5.1$ eV. Hence, the line width was fixed at 0.1 eV, which is small compared with the detector resolution ($\Delta\lambda \sim 0.06–0.07$ Å or $\Delta E \sim 2$ eV FWHM). When we calculated the errors of the absorption-line parameters, we also fixed the photon index of the power-law component. The observed line center energy and equivalent width were 650.9$^{+1.0}_{-0.8}$ eV and 2.8$^{+1.3}_{-1.2}$ eV, respectively. If we assume that this is an O VIII absorption line, the energy shift from the rest frame is $2.7^{+0.8}_{-1.5}$ eV, which corresponds to $cz = 1253^{+81}_{-369}$ km s$^{-1}$. This is consistent with that of M 87 ($cz = 1307$ km s$^{-1}$). Note that the systematic error in the absolute energy scale of the RGS is 8 mÅ (rms) or 0.3 eV at 650 eV (den Herder et al. 2001), which is much smaller than the statistical errors.

![Fig. 1. ROSAT PSPC image around M 87. The target, LBQS 1228+1116, is located 83′3 south of M 87.](image-url)
reasonable oscillator strength at \( z = 0 \), the cluster redshift, or structures other than that at 19.05 Å. However, none of them can be identified with the absorption line in the observed spectra, and actually found seven such structures in the simulation spectra. We searched for such structures for detecting such an absorption line at the very wavelength region used in the fits and the choice of the continuum model. For this purpose, we changed the width of the wavelength band for fits from 1.0 to 2.8 Å and added a fifth-order polynomial to the continuum. We found that, as long as the width of the fitting region is wider than 1.6 Å, the variation of the equivalent width on the wavelength region fixed at 0.1 eV.

We evaluated the statistical significance of the absorption line in the following way. The best-fit model without an absorption line gives a C-statistic of 181.76. When we include an absorption line, but fix the center and the width to the absorption line gives a C-statistic of 177.02. Thus, the improvement, \( \Delta C \), is 4.33. The value of \( \Delta C \) approximately follows the \( \chi^2 \) statistic for 1 degree of freedom if the absorption line is just a statistical fluctuation (Cash 1979). In order to evaluate the statistical confidence of the line detection, we produced 10 000 simulation spectra using the continuum model shown in table 2 and the background without the absorption line. We then fitted the spectra with and without a Gaussian absorption or emission line model. We obtained \( \Delta C \gtrsim 4.33 \) for 3.6% of the simulation spectra. This is consistent with the value expected from the \( \chi^2 \) distribution (3.7%). We thus conclude that the chance probability for detecting such an absorption line at the very wavelength corresponding to O VIII \( \alpha \) at the cluster redshift is 3.6%; in other words, the statistical confidence of the absorption line is 96.4%.

The width of the wavelength range where both the RGS1 and 2 operate is \( \sim 15.6 \) Å. Because the wavelength resolution is \( \sim 0.06 \) Å, there are about 260 independent wavelength bins. The probability for detecting an emission/absorption structure of \( \Delta C \gtrsim 4.33 \) at some wavelength is almost unity with an expected occurrence of 9.4. We searched for such structures in the observed spectra, and actually found seven such structures other than that at 19.05 Å. However, none of them can be identified with an atomic emission/absorption line with a reasonable oscillator strength at \( z = 0 \), the cluster redshift, or the quasar redshift. Thus, these are all considered to be statistical fluctuations, and only the 19.05 Å feature can be real at a statistical confidence of 96.4%.

We then investigated the systematic errors. First, we checked the RGS spectra of bright X-ray sources in the archival data to ensure that there is no instrumental feature at that wavelength. Then, since the estimation of an absorption line could be influenced by the determination of the continuum, we examined the dependence of the equivalent width on the wavelength region used in the fits and the choice of the continuum model. For this purpose, we changed the width of the wavelength band for fits from 1.0 to 2.8 Å and added a fifth-order polynomial to the continuum. We found that, as long as the width of the fitting region is wider than 1.6 Å, the variation of the equivalent width is smaller than 0.2 eV. When the fitting region is too narrow, the continuum level is not well constrained, and is strongly coupled to the equivalent width of the line.

Assuming that the absorption line is not saturated, the equivalent width is related to the ion column density in the following way:

\[
EW = \frac{\pi h e^2}{m_e c} f_{\text{ion}} \frac{N_{\text{ion}}}{1 + z},
\]

where \( N_{\text{ion}} \) is the column density of the ion and \( f_{\text{ion}} \) is the oscillator strength of the transition (Sarazin 1989). We used \( f_{\text{ion}} = 0.70 \) for the O VII resonance absorption line and \( f_{\text{ion}} = 0.42 \) for that of O VIII (Verner et al. 1996). Then, the O VIII column density was \( (6.2 \pm 3.3) \times 10^{16} \) cm\(^{-2}\), while the 99.7% upper limit on the O VII column density was \( 3.7 \times 10^{16} \) cm\(^{-2}\).

### 3.2 Excess Emission

We also analyzed the EPIC data, and searched for diffuse emission. Since we are mostly interested in the low-energy band, the pn detector is suitable for our analysis. Hence, we describe the results obtained from the pn data here. We confirmed that the MOS data gave similar results, but with larger errors.

The number of events above 10 keV is regarded as a good indicator of the internal background. Thus, we discarded the data where the rate of pattern 0 events in this energy range was larger than 0.7 cps. Then, we excluded LBQS 1228 + 1116 and other point sources using SAS edetect_chain, and accumulated photons from the diffuse emission in the 0.3–3 keV band over the field of view. To remove any contribution from the internal background, we subtracted data taken with the filter wheel in

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**Table 2.** Best-fit parameters of the absorption line.

| Parameter | Value |
|-----------|-------|
| Energy    | 650.9^{+0.8}_{-1.9} eV |
| Width (\( \sigma \)) | < 5.1 eV (90%) |
| Normalization | (3.9^{+2.0}_{-2.8}) \times 10^{-6} \text{ photons cm}^{-2} \text{s}^{-1} |
| C-statistic | 177.02 |
| d.o.f. | 167 |

† For all fits except for the determination of the statistical error for this parameter, it was fixed at 0.1 eV.  
† In units of photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.

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Image: Spectra around the O VIII \( \alpha \) line obtained with RGS1 and 2. The cross and circle symbols represent the data points of RGS1 and 2, respectively. The thick and thin solid histograms show the best-fit models for RGS1 and 2. The backgrounds were not subtracted, but were instead simultaneously fitted with a constant model. The background levels are shown with dotted curves. For illustrative purposes, channels with flickering pixels were masked.

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**Fig. 2.** Spectra around the O VIII \( \alpha \) line obtained with RGS1 and 2. The cross and circle symbols represent the data points of RGS1 and 2, respectively. The thick and thin solid histograms show the best-fit models for RGS1 and 2. The backgrounds were not subtracted, but were instead simultaneously fitted with a constant model. The background levels are shown with dotted curves. For illustrative purposes, channels with flickering pixels were masked.
evaluate its effect, we inspected the RASS 3 excess emission depends on the normalization, abundance, and of the background components. The normalization of the errors given in table 3 do not contain the uncertainties table 3, and the best-fit models are shown in figure 3. Note A here, we assumed A 1. The results are summarized in figure 4 shows a 25° × 25° image centered at LBQS 1228+1116. The lower panel is a projection of the 0.5 × 50° region shown in the upper panel. The levels of the background components (MWH, LHB, CXB) estimated from the data obtained by Lumb et al. (2002) and of the warm-hot emission plus LHB and CXB estimated from the present EPIC pn data are also shown in the panel with a dashed line and a solid line, respectively. The level of the west side of the Virgo cluster (≤ 3°) is consistent with that of Lumb et al. (2002), while that of the east side (∼ ± 4°) is significantly higher and comparable with the level of the warm-hot emission plus LHB and CXB at LBQS 1228+1116.

4. Discussion

Our results suggest the existence of a red-shifted O VIII resonance absorption line with a statistical confidence of 96.4% due to limited statistics. The velocity shift is 1253 ± 881 km s⁻¹, which is consistent with that of M 87 (cz = 1307 km s⁻¹). Thus, we claim detection of the WHIM associated with the Virgo cluster. The equivalent width of the O VIII Kα line is 2.8 ± 1.3 eV. This is much larger than those reported for WHIM in the local group (EW = 0.1–0.4 eV; e.g., Rasmussen et al. 2003; Fang et al. 2002). The intrinsic width of the line was not resolved, with an upper limit of σ < 5.1 eV (90%). This corresponds to a Doppler b parameter of < 3300 km s⁻¹. Because the Virgo cluster is thought to be elongated along the line of sight by 12–30 Mpc (Yasuda et al. 1997), a velocity difference of 800–2100 km s⁻¹ is expected due to cosmological expansion. On the other hand, a turbulent velocity of a few hundred km s⁻¹ is expected for WHIM from simulations (e.g., Cen, Ostriker 1999). From the curve of growth of the O VIII Kα absorption line (see Futamoto et al. 2004), the O VIII column density, N_{O VIII}, is estimated to be 6.8 × 10^{16}, 9.6 × 10^{16}, and 2.4 × 10^{17} cm⁻², respectively, for b = 2100, 800, and 400 km s⁻¹ with EW = 2.8 eV. N_{O VIII} ∼ 1 × 10^{17} cm⁻² is close to the maximum column density predicted by Fang and Canizares.
kT > f further assume collisional ionization equilibrium, this implies the multi-component model is consistent with the RASS diffuse soft X-ray background map in the north and the west regions just outside of the Virgo cluster. This strongly suggests that the excess emission is associated with the Virgo cluster. However, a possible contribution by emission from the North Polar Spur cannot be excluded completely. We thus take the emission intensity as the upper limit for the emission from the WHIM around the Virgo cluster. The O VIII column density is related to the average electron density, ne, and the line-of-sight length, L, of the WHIM as NO VIII = fA Z⊙ n_e L, where f is the ionization fraction, A is the oxygen abundance relative to the solar value, and Z⊙ is the solar abundance of the oxygen. On the other hand, if we assume a uniform distribution of the WHIM, the emission measure, EM, of the plasma is EM = n_e^2 L S, where S is the geometrical area that we observed, and is 7.3 x 10^3 kpc^2 for the present data. Then, the electron density and the line-of-sight distance are constrained to

\[ n_e \lesssim 6 \times 10^{-5} \text{ cm}^{-3} \left( \frac{N}{1.5 \times 10^{-3}} \right) \left( \frac{A}{0.1} \right) \left( \frac{f}{0.4} \right) \times \left( \frac{N_{\text{O VIII}}}{6.2 \times 10^{16} \text{ cm}^{-2}} \right)^{-1}, \]

\[ L \gtrsim 9 \text{ Mpc} \left( \frac{N}{1.5 \times 10^{-3}} \right)^{-1} \left( \frac{A}{0.1} \right)^{-2} \left( \frac{f}{0.4} \right)^{-2} \times \left( \frac{N_{\text{O VIII}}}{6.2 \times 10^{16} \text{ cm}^{-2}} \right)^2, \]

where N is the normalization of the excess emission (see table 3), and 0.4 is the ionization fraction for kT = 0.21 keV. The derived density corresponds to a baryon overdensity of δ ≳ 250. The depth of δ ≳ 9 Mpc is much larger than the linear dimensions of the Virgo cluster in the sky, but is consistent with the elongation of 12–30 Mpc suggested by Yasuda, Fukugita, and Okamura (1997), which is understood as being a filament of the large-scale hierarchical structure along the line of sight. Note that the line broadening due to the Hubble flow of the 9 Mpc line-of-sight distance corresponds to about 1.4 eV. This is much smaller than the 90% upper limit of the line width obtained from the present data. However, it could be resolved if the statistics were good enough, since it is comparable to the energy resolution of the RGS (≈ 2 eV FWHM).

In summary, the present results strongly suggest the presence of the WHIM in a filament associated with the Virgo cluster at the 96.4% confidence level. To further constrain the physical parameters of the WHIM, a precise determination of the absorption line profile is an important next step. Future high-resolution spectroscopic observations of the emission are also strongly desirable for resolving the Galactic and extragalactic components.

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