THE LACK OF STRONG O-LINE EXCESS IN THE COMA CLUSTER OUTSKIRTS FROM SUZAKU

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ABSTRACT

About half of the baryons in the local universe are thought to reside in the so-called warm-hot intergalactic medium (WHIM) at temperatures of 0.1–10 MK. Thermal soft excess emission in the spectrum of some cluster outskirts that contains O vii and/or O viii emission lines is regarded as evidence of the WHIM, although the origin of the lines is controversial due to strong Galactic and solar system foreground emission. We observed the Coma-11 field, where the most prominent thermal soft excess has been reported, with Suzaku XIS in order to clarify the origin of the excess. We did not confirm O vii or O viii excess emission. The O vii and O viii intensity in Coma-11 is more than 5 \sigma below that reported before, and we obtained 2 \sigma upper limits of 2.8 and 2.9 photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) for O vii and O viii, respectively. The intensities are consistent with those in another field (Coma-7) that we measured, and with other measurements in the Coma outskirts (Coma-7 and X Com field with XMM-Newton). We did not confirm the spatial variation within Coma outskirts. The strong oxygen emission lines previously reported are likely due to solar wind charge exchange.

Subject headings: galaxies; clusters; individual (Coma) — intergalactic medium — large-scale structure of universe

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1. INTRODUCTION

Based on N-body simulations of cosmological large-scale structure formation (e.g., Cen & Ostriker 2006), a significant (30%–50%) fraction of baryons are thought to reside in a "warm-hot" gaseous phase (\( T = 10^5\)–10\(^7\) K), which is difficult to detect with the instruments currently in operation. This warm-hot gas, whose density is 10\(^{-6}\) to 10\(^{-4}\) cm\(^{-3}\), is called the warm-hot intergalactic medium (WHIM). Firm detection of the WHIM is important because it is the most promising candidate for the "missing baryons"; i.e., it is thought to explain the discrepancy between the baryon density observed in the local universe (Fukugita et al. 1998) and that in the distant universe (Rauch et al. 1997) or that calculated from the observed fluctuations of the cosmic microwave background (Spergel et al. 2007). Although \(~10\%\) of the baryons have been resolved as the WHIM in the temperature range \( T = 10^5\)–10\(^6\) K through O vi absorption features observed with FUSE and HST (Danforth & Shull 2008), more baryons are thought to reside in a hotter phase at \( T = 10^6\)–10\(^7\) K. The WHIM of this temperature may be detected via emission or absorption lines from highly ionized elements in X-ray spectra, such as O vii and O viii.

Despite many observations so far, the existence of the WHIM in the hotter phase has not yet been confirmed (see review of Bregman 2007 and references therein). Studies of the WHIM using absorption lines have only led to one disputed detection toward Mrk 421 (Nicastro et al. 2005), a result that was not later confirmed and has thus been questioned (Rasmussen et al. 2007; Kaastra et al. 2006). Possible detections of emission from the WHIM have been reported in cluster outskirts, as a soft X-ray (\( E \lesssim 0.5 \text{ keV} \)) excess containing O vii and O viii lines (Kaastra et al. 2003; Finoguenov et al. 2003). The origin of O-line emission is, however, controversial due to strong Galactic and solar system foreground emission, which has a spectral shape similar to the WHIM (Bonamente et al. 2005; Bregman & Lloyd-Davies 2006). In particular, X-rays induced by solar wind charge exchange (SWCX) could produce serious contamination because of its high variability (e.g., Cravens 2000; Fujimoto et al. 2007). Note that there has been no detection of redshifted emission lines from the WHIM so far.

The most prominent thermal soft excess ever reported is in the Coma outskirts, especially in the Coma-11 field (Finoguenov et al. 2003 hereafter FBH03). FBH03 also observed spatial variation within the Coma outskirts; Coma-7 shows roughly 5 times smaller intensity than Coma-11. Not only O lines, but also an EUV excess (Bonamente et al. 2003) and marginal detection of Ne ix emission and absorption lines (Takei et al. 2007 hereafter T07) have been reported in the Coma outskirts. These results may support the existence of the WHIM.

We observed the Coma-11 and Coma-7 fields with the XIS (Koyama et al. 2007) on board Suzaku (Mitsuda et al. 2007), in order to clarify the origin of the excess. The XIS is an ideal instrument to study the emission lines from the WHIM, because it does not show a large low-energy tail in the pulse-height distribution function, even in the very soft (\( E \lesssim 0.5 \text{ keV} \)) band.

We assume a Hubble constant of 70 km s\(^{-1}\) Mpc\(^{-1}\) or \( h_0 = 1 \), and \( \Omega_m = 0.3 \), \( \Omega_L = 0.7 \). The solar metal abundance is given by Lodders (2003). Unless otherwise stated, errors and upper limits are at the 68\% confidence level in the figures, and at the 90\% confidence level in the text and tables. The emission line intensities
are quoted in line units (LU), defined as photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). One LU corresponds to \(8.46 \times 10^{-8}\) photons cm\(^{-2}\) s\(^{-1}\) arcmin\(^{-2}\).

2. OBSERVATIONS AND DATA REDUCTION

We observed three fields from 2007 June 19 to June 22; two of them are in the Coma outskirt, namely Coma-11 and Coma-7, which FBH03 observed with XMM-Newton, and the other is an offset observation (hereafter we call it ComaBKG) of 5.0' distance from the Coma center (NGC 4874). The coordinates and net exposure times are summarized in Table 1. The XIS was operated in the normal mode and with the spaced-row charge injection (SCI). We analyzed the clean-event data of Ver 2.0 processing with standard parameters, but with the latest gain calibration (Ver 2.6.1.16).

We excluded the regions where point sources are found or which are irradiated by the 55Fe calibration sources. The point sources were identified using the XMM-Newton Serendipitous Source Catalogue (2XMM; M. Watson et al. 2008, in preparation), as well as by examining the XIS images by eyes. Response files were created using Suzaku FTOOLS \texttt{xissimarfgen} and \texttt{addrmf}, and \texttt{marfrmf}, and \texttt{xissimarfgen} version 2007-09-22 with CALDB release 2008-01-14. We assumed uniform emission from the sky. The spectra and response files of the two XIS-FIs (XIS0 and 3) were added using FTOOLS \texttt{mathpha}, \texttt{marfrmf}, and \texttt{addrmf}. X-ray spectra are analyzed with XSPEC 12.4.0.

### Table 1

| Source       | R.A. (J2000.0) | Decl. (J2000.0) | Exposure* (ks) |
|--------------|----------------|----------------|----------------|
| Coma-11      | 12 58 31.7     | 28 24 13.2     | 53.02          |
| Coma-7       | 12 57 22.9     | 28 08 58.1     | 25.26          |
| ComaBKG      | 13 15 00.0     | 31 39 28.0     | 30.78          |

*After screening as described in the text.

3. SPECTRAL ANALYSIS

3.1. ComaBKG Field

ComaBKG is observed in order to precisely determine the foreground and background emission, in particular O and Ne line intensities around the Coma Cluster. The instrumental background, estimated using a FTOOL \texttt{xisnxbgen} version 2007-11-23 with COR2 as the sorting parameter (Tawa et al. 2008), were subtracted from the ComaBKG spectra.

We modeled the spectra with a sum of two thin thermal plasma models (APEC in XSPEC) and a power law to represent emission from the local hot bubble (LHB), Milky Way halo (MWH), and extragalactic cosmic X-ray background (CXB), respectively. MWH and CXB were convolved with absorption in the Galaxy (WABS in XSPEC). We fitted the spectra in the energy range 0.5-5.0 keV for the XIS-FI and 0.35-5.0 keV for XIS1 (XIS-BI). The spectra of XIS-FI and XIS-BI were fitted simultaneously. We ignored 1.40-1.55 keV, where a relatively large uncertainty exists in the instrument background (Tawa et al. 2008). The redshift and abundance of the two thermal plasma models were fixed to 0 and 1.0 solar, respectively. The temperature of the LHB was also fixed to 0.07 keV, while the temperature of the MWH was allowed to vary. The column density of the Galactic hydrogen gas was fixed to 1.0 \times 10^{20} cm\(^{-2}\) (Kalberla et al. 2005). Figure 1 and Table 2 show the best-fit model.

We also fitted the spectra with another model in order to determine O vii, O viii, Ne ix and Ne x intensity more precisely. Four Gaussians were added to represent the four line emissions, while O and Ne abundance of the LHB and MWH were fixed to zero. The energies of the Gaussians were allowed to vary by \(\pm 35\) eV around the resonance line energy (0.574 keV for O vii, 0.653 keV for O viii, 0.922 keV for Ne ix, and 1.022 keV for Ne x) in order to compensate for the uncertainty in the energy-scale calibration, while we fixed the line width to zero. The intensities of the four lines are also shown in Table 2. The relatively large \(\chi^2\) value may be due to incorrect calibration of the energy resolution. The \(\chi^2\) improved to 128.18 when we added 50 eV (FWHM) additional width into the model with lines. The best-fit parameters were not sensitive to this calibration uncertainty; they stay the same within the error at 90% confidence level. We confirmed that the fitting is not improved when we allow \(N_{\text{HI}}\) to vary.

3.2. Coma-11 and Coma-7 Fields

The background and foreground emission of Coma-11 and Coma-7 were corrected by subtracting the ComaBKG spectra.
that were extracted from the same region as Coma-11 or Coma-7 in the detector coordinates. We then fitted the spectra (0.5–7.5 keV for XIS-FI and 0.35–7.5 keV for XIS-BI) by the emission of the intracluster medium (ICM), i.e., a thin thermal plasma model (APEC) convolved with Galactic absorption (WABS). The spectra of XIS-FI and XIS-BI were again fitted together. The spectra and the best-fit models are shown in Figure 2, and the best-fit parameters are in Table 3. We did not see a soft excess, i.e., emission from the WHIM. Next, we added four Gaussians to the model, corresponding to lines of O vii, O viii, Ne ix, and Ne x at the cluster redshift, in order to investigate possible contributions of the WHIM. The central energy of each line was fixed to that of the resonance lines at redshift z = 0.0231, and the width of the line was fixed to zero. The results are shown in Table 3. The fit is slightly improved ($\Delta \chi^2 \sim 10$) by adding the lines. However, the significance of each line is less than 3 $\sigma$. The fitting without FI also gave the same results within the statistical errors, which excludes the possible systematic bias due to the low statistics of the FI data below 1 keV. We also tried to fit the spectra with two thin thermal plasma models, i.e., one for the intracluster medium and one for the WHIM. This did not improve the fit. To obtain robust upper limits of line intensities, we consider systematic uncertainties in calibration: the centroid energy ($\pm 35$ eV), the energy resolution (10–80 eV FWHM), energy scale ($\pm 50$ eV), and the contamination thickness ($\pm 5 \times 10^{-17}$ cm$^{-2}$). The 2 $\sigma$ upper limits we obtained for O vii, O viii, Ne ix, and Ne x are 1.4, 2.7, 0.5, and 0.9 LU for Coma-11 and 2.6, 3.7, 1.2, and 1.1 LU for Coma-7, respectively. The uncertainty in Galactic O intensity should also be taken into account. From the variation among background fields in T07, we adopted $\pm 1.2$ LU for O vii and $\pm 0.6$ LU for O viii as 1 $\sigma$. Then, O vii and O viii 2 $\sigma$ upper limits are 2.8 and 2.9 LU for Coma-11 and 3.5 and 3.9 LU for Coma-7, respectively.

| Parameter       | Coma-11       | Coma-7       |
|-----------------|---------------|--------------|
| Galactic $N_H$ (cm$^{-2}$) | $1.0 \times 10^{20}$ (fixed) | $1.0 \times 10^{20}$ (fixed) |
| Temperature (keV) | $6.7^{+0.4}_{-0.3}$ | $8.3^{+0.8}_{-0.6}$ |
| Abundance (solar) | $0.36 \pm 0.11$ | $0.21 \pm 0.15$ |
| Redshift         | 0.0231 (fixed) | 0.0231 (fixed) |
| EM (pc cm$^{-6}$) | $0.100 \pm 0.002$ | $0.110 \pm 0.002$ |
| $\chi^2$/dof without lines | 307.51/275 = 1.12 | 295.40/281 = 1.05 |
| O vii intensity (LU) | $0.0 (<0.9)$ | $0.2 (<2.1)$ |
| O viii intensity (LU) | $1.1 \pm 0.8$ | $1.7 \pm 1.1$ |
| Ne ix intensity (LU) | $0.1 (<0.4)$ | $0.4 (<0.8)$ |
| Ne x intensity (LU) | $0.3 \pm 0.2$ | $0.3 (<0.6)$ |
| $\chi^2$/dof with lines | 297.71/271 = 1.10 | 284.92/277 = 1.03 |

4. DISCUSSION

We measured the spectra of Coma-11 and Coma-7 with the Suzaku XIS. The spectra were fitted with a single thin thermal plasma model, and the emission from the WHIM was not confirmed. Here we compare our results with previous XMM-Newton observations. We do not discuss the lower energy excess ($E < 0.5$ keV) observed with ROSAT and EUVE, because the XIS is not sensitive in that energy band.

T07 measured O vii, O viii, Ne ix, and Ne x emission line intensities with XMM-Newton in the field of X Com and four background fields whose distance from NGC 4874 is $46.2^\circ$–$162.7^\circ$. The intensities of O vii, O viii, and Ne x lines measured by T07 are $6.6 \pm 0.2$, $1.8 \pm 0.2$, and $0.7 \pm 0.1$ LU in the X Com field and $7.4 \pm 1.2$, $2.6 \pm 0.6$, and $0.4 \pm 0.1$ LU in the (averaged) background fields, respectively. The values of the X Com field shown above contain contributions of the background emission. The intensities of the X Com field are consistent within the 90% confidence range with those of Coma-11 and Coma-7 measured in this work, and those of the background field of T07 are also consistent with those of ComaBKG.

The origin of the large discrepancy in Coma-11 O intensities between this work and FBH03 could be contamination by SWCX emission. The solar wind proton flux observed with ACE (Advanced Composition Explorer$^7$) showed flares both during the

$^7$ See http://www.srl.caltech.edu/ACE/ASC.

Fig. 2.—Spectra of Coma-11 (top) and Coma-7 (bottom). Gray and black data correspond to BI and FI respectively. ComaBKG spectra were subtracted to correct the background emission. [See the electronic edition of the Journal for a color version of this figure.]
Coma-11 observation of FBH03 (2.5 × 10^9 cm^2 s^(-1)) and during the ComaBKG observation of this work (1.5 × 10^9 cm^2 s^(-1)), as shown in Figure 3. Both are ~8 times larger than the quiescent state around each observation time. Hence, two possibilities should be considered: (1) O intensities of Coma-11 in FBH03 are overestimated, or (2) those of ComaBKG in this work are overestimated, and thus those of Coma-11 in this work are underestimated. However, the latter case is not likely because the O-line intensities are consistent with or even smaller than T07 measurements of background fields around the Coma cluster. There is no indication of the geocoronal SWCX emission; the first point in the line of sight (LOS) where the geomagnetic field started to open was always higher than 10 times the Earth radius (Fujimoto et al. 2007; Tsyganenko & Sitnov 2005), and there was no variation in the O vii and O viii flux during the ComaBKG observation. The heliospheric SWCX emission could be weak, since it is faint at solar minimum on the high ecliptic latitude line of sight (Koutroumpa et al. 2007). Moreover, even if the ComaBKG observation were heavily contaminated with the SWCX emission, the 2 σ upper limits of Coma-11 O vii and O viii intensity would be no larger than 4.8 and 3.5 LU, respectively, which are still lower than values of FBH03. These values are calculated by assuming the lower limits of O vii and O viii intensities as the LHB contribution without any MWH contribution, measured toward a molecular cloud MBM 12 (3.5 and 0 LU, respectively; Smith et al. 2007). On the other hand, it is more likely that the FBH03 observation suffered heliospheric SWCX contamination, since a similar solar wind flare during XMM-Newton observation of the Hubble deep field north increased the O vii and O viii flux by 6.25 ± 0.67 and 5.53 ± 2.87 LU, respectively (Snowden et al. 2004; Koutroumpa et al. 2007). The solar cycle at the observations, the position of the Earth and the LOS, which also affects the X-ray flux induced by SWCX, are similar in the two observations. Note that the observation of FBH03 was performed at solar maximum, while our observation was at solar minimum. The field-to-field variation of O vii and O viii flux reported by FBH03 might also be due to the variation of the SWCX flux.

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8 Calculated using the software GEOPACK-2005 and T96 magnetic field model (http://geo.phys.spbu.ru/~tsyganenko/modeling.html), with CDAWeb solar-wind parameters (http://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys/).

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