WARM-HOT INTERGALACTIC MEDIUM ASSOCIATED WITH THE COMA CLUSTER

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Received 2006 March 13; accepted 2006 October 12

1. INTRODUCTION

Our current understanding of the state of cluster gas (e.g., Voit 2004; Borgani et al. 2005) requires some combination of preheating and radiative cooling of the ambient gas, which is then further heated by the accretion shock as the gas falls into the cluster along with additional cooling and nongravitational heating afterward. However, our direct observational knowledge of the state of the gas before it is accreted onto the cluster is limited. Star formation, active galactic nucleus (AGN) activity, and accretion shocks onto large-scale structures are all possible for the energy source of the preheating (see reviews in, e.g., Borgani et al. 2002; Dos Santos & Dore’ 2002). Furthermore, the material that will later become the cluster gas is thought to be related to the missing low-redshift baryons, most of which are suggested from recent numerical simulations (e.g., Cen & Ostriker 1999; Davé et al. 2001) to reside in a warm-hot intergalactic medium (WHIM) with temperatures of $10^5$–$10^7$ K. Therefore, detecting warm-hot gas around clusters of galaxies is crucial for understanding their formation as well as for settling the missing baryon problem.

The soft X-ray excess above the harder intracluster medium (ICM) emission reported for some clusters (Soltan et al. 1996; Lieu et al. 1996; Bowyer et al. 1999; Bonamente et al. 2002; Finoguenov et al. 2003; Kaastra et al. 2003) may be signaling a fortunate orientation of a filament containing WHIM at those clusters. In particular, Finoguenov et al. (2003) determined the WHIM density, temperature, and abundance of heavy elements by assuming that the soft excess in the EPIC (European Photon Imaging Camera) spectra of the Coma Cluster outskirts is due to a filament extending $\sim 20$ Mpc along the line of sight, correspond-

...ing to the excess galaxies in front of Coma. The conclusions are, however, strongly dependent on that assumption.

An additional uncertainty common to all studies of low-redshift cluster soft excess is the presence of emission lines in the Milky Way and even interplanetary foreground (McCammon et al. 2002; Wargelin et al. 2004; Snowden et al. 2004) that are not easily separable from cluster emission given the spectral resolution of a CCD. Therefore, a confirmation of cosmological origin of the soft components in clusters is required.

A direct way to confirm the existence of the warm-hot gas in cluster outskirts is to detect absorption lines in X-ray spectra of background quasars with a high-resolution grating spectrometer. The spectral resolution of these instruments is sufficient to separate absorption by cluster WHIM from that of foreground contamination due to the interstellar medium (ISM) in our Galaxy or the interplanetary medium of our solar system (Futamoto et al. 2004; Yao & Wang 2005). Given the expected temperatures of this gas and the cosmic abundances of the elements, the strongest lines should be the resonance lines of hydrogen-like and helium-like oxygen and neon. Additional information is available by combining absorption and emission measurements, particularly from the same ion. We can measure the density of the gas, as well as constrain the geometry of the emitting zone directly (Krolik & Raymond 1988; Sarazin 1989).

However desirable these measurements are, they are at the limit of current instrumentation (Kravtsov et al. 2002; Viel et al. 2003), and detecting the WHIM will only be possible in special circumstances. The simulations mentioned above indicate that the WHIM near clusters of galaxies should be denser than average. Therefore, we expect a higher absorption signal from it compared to that along random sight lines. One example is a marginal detection of the O vii absorption line by Fujimoto et al. (2004) toward the Virgo Cluster. It is possible to detect the average-density WHIM in the X-ray spectra of extraordinarily bright background sources such as blazars, particularly when
with standard parameters. We checked the data from a source-free region of CCD 9 for background flares. The regions were CHIPX = 2–341, CHIPY = 2–38 and 87–127 for RGS1 and CHIPX = 2–284, CHIPY = 2–37 and 87–127 for RGS2. We accumulated the signal photons only when the count rates in these regions were less than 0.1 s$^{-1}$ (in pulse-height invariant [PI] range 80–3000) for both RGS1 and RGS2. This rather severe threshold was determined empirically to yield the highest signal-to-noise ratio background-subtracted source spectrum. The net exposure time was about 60% of the total exposure and is summarized in Table 2.

The spectra were extracted after merging the five data sets and then binned by a factor of 4, resulting in a final bin width of 0.035 Å at 11.5 Å and 0.046 Å at 23 Å. These bin widths are about half of the average FWHM wavelength resolution of the RGS (0.067 Å). This wavelength resolution corresponds to the redshift shift width of 0.0058 for 11.5 Å and 0.046 Å for 23 Å. The background spectra were similarly produced from the same data sets using the pixels outside the region where source photons were dispersed. The background spectra were then scaled to account for the different areas used to extract source and background photons. Since the number of photons is small, we used the C-statistic (maximum likelihood) method for model fitting. Rasmussen et al. (2007) pointed out that merging different observations may introduce artificial absorption features in RGS spectra. However, their suggested features have about 1 order of magnitude smaller equivalent widths than those we discuss below. They are smaller than our statistical errors. We tried the procedure to search for bad columns that may cause artificial absorptions according to their Appendix C. It showed no apparent artificial features within our statistics.

### 3.1. Detection of Absorption Features and Their Equivalent Widths

Figure 2 shows the RGS spectra of X Com in the Ne region (11.5–16.0 Å) and the O region (18.0–22.7 Å). We calculated the ratio of the data to a continuum-only model in order to estimate the statistical significance of possible absorption features at the wavelengths of Ne ix, Ne x, O vii, and O viii K$\alpha$ resonance lines.

### TABLE 2

| Date         | Duration (ks) | Net Exposure (ks) | Flux (RGS 0.3–2.0 keV) |
|--------------|---------------|-------------------|------------------------|
|              | RGS | EPIC | pn | EPIC | pn | Medium | Thin | Range | 10$^{-12}$ | 10$^{-12}$ |
| 2004 Jun 6... | 102.6 | 71.5 | 60.1 | 1.92 | 1.92 |
| 2004 Jun 18.. | 108.3 | 54.7 | 46.2 | 1.48 | 1.48 |
| 2004 Jul 12.. | 104.2 | 45.6 | 39.5 | 1.36 | 1.36 |
| 2005 Jun 27.. | 55.9 | 23.9 | 20.3 | 1.02 | 1.02 |
| 2005 Jun 28.. | 80.8 | 62.5 | 57.6 | 1.46 | 1.46 |
| Total......... | 451.8 | 258.2 | 232.7 | 1.66 | 1.66 | 10$^{-12}$ | 10$^{-12}$ |

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**Fig. 1.**—Image of the Coma Cluster in the 0.5–2.0 keV band from Finoguenov et al. (2003). The coordinate grid is in R.A., decl. (J2000.0).
of the Coma redshift \( (z = 0.0231) \) in a model-independent way. That is, we calculated

\[
\text{Ratio} = \frac{(\text{source + background data}) - (\text{background data})}{(\text{source + background model}) - (\text{background model})}.
\]

(1)

This procedure is called the “ratio method” in what follows.

The source model is a broken power law multiplied by the Galactic absorption of \( N_H = 9.3 \times 10^{19} \) cm\(^{-2} \) (Dickey & Lockman 1990). The background model is a different broken power law without Galactic absorption. In order to determine the continuum model, we fitted the source plus background and background spectra of RGS1 and RGS2 simultaneously using XSPEC, version 11.3, in the wavelength region \( 11.5 \)–\( 22.7 \) Å. Regions around the Ne \( {\text{ix}}, \text{Ne} {\text{x}}, \text{O} {\text{vii}}, \) and \( \text{O} {\text{viii}} \) \( \text{K}\alpha \) lines, which are defined as \( z_{\text{Coma}} - 3\sigma_{\text{gal}} < z < z_{\text{Coma}} + 3\sigma_{\text{gal}} \), were excluded from the fit.

The best-fit model and parameters are shown in Figure 2 and in Table 3, respectively. The ratios around the Ne \( {\text{ix}}, \text{Ne} {\text{x}}, \text{O} {\text{vii}}, \) and \( \text{O} {\text{viii}} \) lines versus \( z \) are shown in Figure 3. The FWHM wavelength resolution of RGS is also shown as a horizontal line. We summed the RGS1 and RGS2 data where both were available. Since the mapping from wavelength to redshift is a function of wavelength, we interpolated the counts to a common redshift bin size for all four lines.

The three vertical dashed lines in Figure 3 indicate \( z_{\text{Coma}} \) and \( z_{\text{Coma}} \pm 2.5\sigma_{\text{gal}} \). We defined redshifts within \( z_{\text{Coma}} \pm 2.5\sigma_{\text{gal}} \) as absorption and the remainder in Figure 3 as continuum, and then calculated the error-weighted average of the absorption and continuum ratios. The results are shown in Table 4. When the absorption redshift region was defined, we fixed its center to the a priori known \( z_{\text{Coma}} \) and chose its width to maximize the Ne \( {\text{ix}} \) plus \( \text{O} {\text{viii}} \) signal from among 2, 4, 6, or 8 binned-by-four pixels; i.e., the region was determined after a four-trial optimization.

Ne \( {\text{ix}} \) is the ion with the deepest absorption, and \( \text{O} {\text{viii}} \) has the second deepest. The absorption ratio is below 1 for the Ne \( {\text{ix}} \) and \( \text{O} {\text{viii}} \) lines as well, although they are not very significant. The continuum is always consistent with 1. This situation of strong Ne \( {\text{ix}} \) absorption and weak absorption by the other three lines is often observed at much higher signal-to-noise ratio in interstellar medium features in the spectra of Galactic X-ray sources (e.g., Yao & Wang 2005).

To improve the signal-to-noise ratio, we made a grand error-weighted average of the ratios for the Ne \( {\text{ix}} \) and \( \text{O} {\text{viii}} \) lines and calculated the combined significance. The result is shown in Figure 4, where the band around unity shows the range \( +0.7\% \) to \( -1.0\% \), the 1 \( \sigma \) error of the model normalization with power-law indices fixed at their best-fit values. The average of the grand-averaged ratio are also given in Table 4.

Since the number of counts in each bin is not very high (20–30 counts bin\(^{-1} \)), we investigated the significance of the absorption using Monte Carlo simulations. We made 1000 simulated spectra with no absorption, which have the same statistics and the same response function as the actual data, and then calculated the ratios with the same procedure as above. That is, we calculated the ratio for the Ne \( {\text{ix}}, \text{Ne} {\text{x}}, \text{O} {\text{vii}}, \) and \( \text{O} {\text{viii}} \) lines and grand error-weighted average of the ratios of Ne \( {\text{ix}} \) and \( \text{O} {\text{viii}} \). This calculation was done for 2, 4, 6, and 8 binned-by-four pixels around \( z_{\text{Coma}} \), and then we chose the most significant grand average among the four trials. The significance of

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**TABLE 3**

**RESULTS OF FITTING THE RGS SPECTRA OF X COM WITH BROKEN POWER-LAW MODELS**

| Component          | Value                      |
|--------------------|----------------------------|
| \( N_H \) (cm\(^{-2} \)) | \( 9.3 \times 10^{19} \) (fixed) |
| Source \( \Gamma^* \) (\( E < 0.75 \) keV) | \( 1.74 \pm 0.15 \) |
| Source \( \Gamma^* \) (\( E > 0.75 \) keV) | \( 2.41 \pm 0.25 \) |
| Source normalization\(^a\) | \( 6.88 \pm 0.74 \times 10^{-4} \) |
| Background \( \Gamma^* \) (\( E < 0.75 \) keV) | \( 3.73 \pm 0.18 \) |
| Background \( \Gamma^* \) (\( E > 0.75 \) keV) | \( 1.96 \pm 0.23 \) |
| Background normalization\(^a\) | \( 0.79 \pm 0.08 \times 10^{-4} \) |
| C-statistic         | 708.63                     |
| Free parameters     | 6                          |
| Degrees of freedom  | 628                        |

\(^a\) Photon index.

\(^b\) In units of photons keV\(^{-1} \) cm\(^{-2} \) s\(^{-1} \) at 1 keV.
the absorption in our observed RGS data can be estimated as the probability that the simulated spectra without absorption yield a smaller discrepancy from unity. The significance for the grand error-weighted average was 99.7%. We conclude that we have detected absorption by material associated with the Coma Cluster with a significance of 99.7%. This significance is equivalent to 3.0 $\sigma$ of a Gaussian distribution. The significance of Ne ix and O viii was 98.0% (2.3 $\sigma$) and 94.1% (1.9 $\sigma$), respectively.

The equivalent width (EW) of the absorption lines can be calculated from the ratios as $(1 - \text{ratio})\Delta E$, where $\Delta E$ is the energy corresponding to the width of six bins we used to calculate the ratios. The EWs for the four lines are also shown in Table 4.

Assuming that the absorption lines are not saturated, the column density $N_{\text{ion}}$ is calculated from EW as (Sarazin 1989)

$$N_{\text{ion}} = \frac{m_e c (1 + z)}{\pi \hbar^2} \frac{\text{EW}}{f_{\text{os}}},$$

or

$$N_{\text{ion}} = \left(9.11 \times 10^{15} \text{ cm}^{-2}\right) \left(1 + z\right) \frac{\text{EW}}{1 \text{ eV}},$$

TABLE 4  
RATIO FOR CONTINUUM AND ABSORPTION SPECTRAL REGIONS

| Line    | Continuum Region$^a$ | Absorption Region$^{ab}$ | EW$^c$ (eV) |
|---------|----------------------|--------------------------|-------------|
| Ne ix   | 1.027 ± 0.058        | 0.782 ± 0.071 (98.0%)    | 3.3 ± 1.8   |
| Ne x    | 1.011 ± 0.073        | 0.950 ± 0.092 (42.7%)    | 0.8 (<3.9)  |
| O vii   | 0.908 ± 0.080        | 0.927 ± 0.103 (50.0%)    | 0.7 (<2.6)  |
| O viii  | 0.963 ± 0.054        | 0.845 ± 0.071 (94.1%)    | 1.7 ± 1.3   |
| Average of Ne ix and O viii | 0.993 ± 0.039 | 0.813 ± 0.050 (99.7%)    | ...         |

$^a$ Errors are quoted at 68% confidence level.

$^b$ Probability that a simulated spectrum without absorption yields a smaller discrepancy from unity.

$^c$ Errors are quoted at 90% confidence level, while upper limits are 2 $\sigma$. 

Fig. 3.—Ratios of the data to the continuum model (as defined in eq. [1]) vs. $z$ for Ne ix, Ne x, O vii, and O viii (from top to bottom). Vertical dashed lines indicate $z_{\text{Coma}}$ and $z_{\text{Coma}} \pm 2.5\sigma_{\text{gal}}$. The two horizontal lines show the ±1 $\sigma$ error of the model continuum normalization with power-law indices fixed at their best-fit values. The average of the ratio in the six bins between the left and right vertical lines is 0.813 ± 0.050. The significance of this absorption is 99.7% according to Monte Carlo simulations. The average of the remaining 10 continuum bins is 0.993 ± 0.039, which is consistent with unity. The FWHM averaged wavelength resolution of RGS is also shown as a horizontal line at the lower right.

Fig. 4.—Error-weighted average ratio of the data to the continuum model (as defined in eq. [1]) vs. $z$ for the Ne ix and O viii lines. Vertical dashed lines indicate $z_{\text{Coma}}$ and $z_{\text{Coma}} \pm 2.5\sigma_{\text{gal}}$. The two horizontal lines show the ±1 $\sigma$ error of the model continuum normalization with power-law indices fixed at their best-fit values. The average of the ratio in the six bins between the left and right vertical lines is 0.813 ± 0.050. The significance of this absorption is 99.7% according to Monte Carlo simulations. The average of the remaining 10 continuum bins is 0.993 ± 0.039, which is consistent with unity. The FWHM averaged wavelength resolution of RGS is also shown as a horizontal line at the lower right.
TABLE 5
RESULTS OF FITTING THE RGS SPECTRA OF X COM WITH BROKEN POWER
LAW PLUS BOXCAR ABSORPTION MODELS

| Component | Value |
|-----------|-------|
| Continuum |       |
| \(N_{\text{H}}\) (cm\(^{-2}\)) | \(9.3 \times 10^{21}\) (fixed) |
| Source \(\Gamma\) \((E < 0.75\text{ keV})\) | \(1.71^{+0.21}_{-0.36}\) |
| Source \(\Gamma\) \((E > 0.75\text{ keV})\) | \(2.35 \pm 0.24\) |
| Source normalization\(^a\) | \(6.92^{+0.62}_{-0.33} \times 10^{-4}\) |
| Background \(\Gamma\) \((E > 0.75\text{ keV})\) | \(3.64^{+0.11}_{-0.19}\) |
| Background \(\Gamma\) \((E < 0.75\text{ keV})\) | \(2.01 \pm 0.21\) |
| Background normalization\(^b\) | \((0.82 \pm 0.07) \times 10^{-4}\) |

\(\text{Ne}\)\(^{ix}\) \(\lambda = 13.447\)

| \(\lambda_{\text{notch}}\) \(^b\) | \(0.0231\) (fixed) |
| \(W_{\text{notch}}\) \(^b\) | \(9.79 \times 10^{-3}\) |
| \(F\) | 0.41 |
| \(\text{EW}\) \(^c\) (eV) | \(3.7^{+2.0}_{-2.2}\) |
| \(N_{\text{neutral}}\) \(^e\) (cm\(^{-2}\)) | \(4.7^{+2.6}_{-2.9} \times 10^{16}\) |

\(\text{Ne}\) \(\lambda = 12.134\)

| \(\lambda_{\text{notch}}\) \(^b\) | \(0.0231\) (fixed) |
| \(W_{\text{notch}}\) \(^b\) | \(9.79 \times 10^{-3}\) (fixed to the Ne \(\text{ix}\) value) |
| \(F\) | 0.09 |
| \(\text{EW}\) \(^c\) (eV) | \(0.8 (<4.7)\) |
| \(N_{\text{neutral}}\) \(^e\) (cm\(^{-2}\)) | \(1.9 (<10.5) \times 10^{16}\) |
| \(\text{EW}/\text{EW}_{\text{Ne}\text{ix}}\) | \(0.2 (<1.3)\) |
| \(N_{\text{neutral}}/N_{\text{Ne}\text{ix}}\) | \(0.4 (<2.3)\) |

\(\text{O}\)\(^{vii}\) \(\lambda = 21.602\)

| \(\lambda_{\text{notch}}\) \(^b\) | \(0.0231\) (fixed) |
| \(W_{\text{notch}}\) \(^b\) | \(9.79 \times 10^{-3}\) (fixed to the Ne \(\text{ix}\) value) |
| \(F\) | 0.04 |
| \(\text{EW}\) \(^c\) (eV) | \(0.2 (<2.2)\) |
| \(N_{\text{neutral}}\) \(^e\) (cm\(^{-2}\)) | \(0.3 (<2.9) \times 10^{16}\) |
| \(\text{EW}/\text{EW}_{\text{Ne}\text{ix}}\) | \(0.06 (<0.59)\) |
| \(N_{\text{neutral}}/N_{\text{Ne}\text{ix}}\) | \(0.06 (<0.63)\) |

\(\text{O}\)\(^{viii}\) \(\lambda = 18.969\)

| \(\lambda_{\text{notch}}\) \(^b\) | \(0.0231\) (fixed) |
| \(W_{\text{notch}}\) \(^b\) | \(9.79 \times 10^{-3}\) (fixed to the Ne \(\text{ix}\) value) |
| \(F\) | 0.06 |
| \(\text{EW}\) \(^c\) (eV) | \(0.4 (<2.2)\) |
| \(N_{\text{neutral}}\) \(^e\) (cm\(^{-2}\)) | \(0.8 (<4.9) \times 10^{16}\) |
| \(\text{EW}/\text{EW}_{\text{Ne}\text{ix}}\) | \(0.10 (<0.59)\) |
| \(N_{\text{neutral}}/N_{\text{Ne}\text{ix}}\) | \(0.2 (<1.0)\) |

Statistics

| C-statistic | 834.33 |
| Free parameters | 11 |
| Degrees of freedom | 745 |

\(^a\) In units of photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.
\(^b\) Wavelength converted to redshift.
\(^c\) Errors include covariance of \(W_{\text{notch}}\) and \(F\).
\(^d\) Upper limit is at 2 \(\sigma\) confidence.

where \(f_{\text{os}}\) is the oscillator strength of the transition and the other symbols have their usual meanings. We used \(f_{\text{os}} = 0.724\) for \(\text{Ne}\)\(^{ix}\), \(f_{\text{os}} = 0.696\) for \(\text{O}\)\(^{vii}\), and \(f_{\text{os}} = 0.416\) for \(\text{O}\)\(^{viii}\) (Verner et al. 1996). The column densities of the four lines are then \(N_{\text{Ne}\text{ix}} = (4.3 \pm 2.3) \times 10^{16}\) cm\(^{-2}\), \(N_{\text{Ne}\text{x}} = 1.9 < (8.8) \times 10^{16}\) cm\(^{-2}\), \(N_{\text{O}\text{vii}} = 0.9 < (3.5) \times 10^{16}\) cm\(^{-2}\), and \(N_{\text{O}\text{viii}} = (3.7 \pm 2.8) \times 10^{16}\) cm\(^{-2}\).

![Graph](image-url)

Fig. 5.—Contour plot of \(\Delta C\) as a function of \(W_{\text{notch}}\) (converted to redshift) and \(F\) for the Ne \(\text{ix}\) line. The equivalent width is \(W_{\text{notch}}F\). The four contours are at \(\Delta C = 1.0, 2.71, 4.0,\) and 6.6 corresponding to 68%, 90%, 95%, and 99% confidence for one interesting parameter, respectively. These would also correspond to 1, 1.6, 2, and 2.6 \(\sigma\), respectively, if the data were Gaussian distributed.

3.2. Fitting the Absorption Features and Their Equivalent Widths

Next we derived the equivalent widths of the four lines by another method: using model fitting of the spectra. We adopted the same continuum model as that in §3.1 and a boxcar profile to describe the absorption (NOTCH model in XSPEC). This absorption model multiplies the continuum by a factor of

\[
\left\{ \begin{array}{ll}
(1 - F) & \text{for } \lambda_{\text{notch}} - W_{\text{notch}}/2 < \lambda < \lambda_{\text{notch}} + W_{\text{notch}}/2, \\
1 & \text{for all others},
\end{array} \right.
\]

where \(\lambda_{\text{notch}}\), \(W_{\text{notch}}\), and \(F\) are the central wavelength, width, and absorption factor, respectively. The equivalent width is given by \(\text{EW} = W_{\text{notch}}F\). We fixed \(\lambda_{\text{notch}}\) to be the value corresponding the redshift of the Coma Cluster. Since the significances of the absorption features were low, except for Ne \(\text{ix}\), we fitted the Ne \(\text{ix}\) absorption first and then fitted the other lines with \(W_{\text{notch}}\) fixed to the best-fit Ne \(\text{ix}\) value (in \(z\), not wavelength). All together the free parameters were the power-law indices and normalizations of the source and background continua, \(W_{\text{notch}}\) and \(F\) for the Ne \(\text{ix}\) absorption, and \(F\) for the other species. Data between 11.5 and 22.7 Å were used in the fit.

The best-fit parameters are shown in Table 5, where \(\lambda_{\text{notch}}\) and \(W_{\text{notch}}\) are converted to redshift. The equivalent widths and their errors were determined taking into account the covariance between \(W_{\text{notch}}\) and \(F\), as shown in Figure 5 for Ne \(\text{ix}\). Figure 5 indicates that this analysis is not sensitive to \(F\) or \(W_{\text{notch}}\) because the wavelength resolution of RGS is comparable to the width of the absorption. Figure 6 compares the best-fit (red line) boxcar absorption model and the model with \(F = 1.0\) and \(W_{\text{notch}} = 3.1 \times 10^{-3}\) (green line). There is little difference between them. Note that we can estimate the EW, the product of \(F\) and \(W_{\text{notch}}\), more precisely than either \(F\) or \(W_{\text{notch}}\). From Figure 6, the equivalent width of Ne \(\text{ix}\) is estimated to be \(3.7^{+0.3}_{-0.2}\) keV (90% confidence errors). Best-fit values and 2 \(\sigma\) upper limits are also given in Table 5 for the Ne \(\text{x}\), O \(\text{vii}\), and O \(\text{viii}\) absorption lines. The column density \(N_{\text{ion}}\) of each ion, estimated from the EWs, are tabulated in Table 5 as well. The derived equivalent widths are...
consistent within the errors with those obtained from the ratio of the data to the continuum model described in §3.1.

The significance of the line was again calculated using Monte Carlo simulations. The C-statistic was improved by 7.57 when we added the Ne ix absorption line. The probability that the simulated data shows less improvement of the C-statistic was 99.2%, equivalent to 2.7σ compared to <EW> = 3.1 ± 1.0 calend. Vertical dashed lines indicate zComa and zComa ± 2.5σgal.

4. EMISSION LINES IN THE EPIC SPECTRA

We cleaned the EPIC X Com data of flares as described by Finoguenov et al. (2003). This procedure yielded 223.7 ks of clean EPIC pn (Strüder et al. 2001) data. This exposure is among the longest ever made of a cluster with XMM-Newton. We analyzed the entire X Com field, as well as dividing it into five concentric sectors of annuli, approximately centered on the center of the cluster.

Determining a reliable background is crucial for this work because the temperatures of the WHIM and the Milky Way interstellar medium are similar and the soft emission in the X Com field is not very bright. Many previous attempts to measure the soft emission from the Coma Cluster (e.g., Finoguenov et al. 2003; Kaasstra et al. 2003) used ROSAT (Röntgensatellit) All-Sky Survey (RASS) data to obtain the values of the components of a Galactic background model. The resulting background subtraction is only as good as the model. Since then there have been several XMM-Newton observations serendipitously located around the Coma Cluster, as we show in Figure 7. Those observations provide a true background measured with the same instrument as for our data and are therefore preferable for our analysis. We have examined the RASS data at the location of these fields to determine whether they are representative of the general background around the Coma Cluster. One of them, HD 111812 (ObsID 0008220201), was located on an unusually bright spot of the RASS maps and has been omitted from the analysis. Some properties of the four remaining fields are shown in Table 6.

We performed the following analysis on these 10 fields. We excised point sources including X Com. We also used a wavelet-based detection algorithm to excise diffuse sources on a spatial scale of 4′′–4′ and with a surface brightness comparable to that of the cluster emission. We extracted a spectrum from each of the 10 fields and subtracted from each the detector background that was estimated by accumulating observations when a filter wheel was closed. We determined the vignetting correction assuming a uniform source surface brightness in each field. We fitted the net vignetting-corrected spectrum with a collisionally

Fig. 6.—Ratios of the data to the continuum model vs. z for Ne ix (the same data as in Fig. 3, top), overlaid with boxcar absorption models. The red line shows the best-fit model, while the green line displays \( F_{\text{W notch}} = 1.0 \times 10^{-3} \). Since the wavelength resolution of the RGS is comparable to the width of the absorption, the fit is not sensitive to \( F \) or \( W_{\text{notch}} \) individually but to the EW, which is proportional to \( F W_{\text{notch}} \). Vertical dashed lines indicate \( z_{\text{Coma}} \) and \( z_{\text{Coma}} \pm 2.5 \sigma_{\text{gal}} \).

Fig. 7.—ROSAT R4 band map (∼0.4–1.0 keV) near the Coma Cluster (Snowden et al. 1997) with analyzed regions of the EPIC overlaid. The R4 band map was smoothed with a two-dimensional Gaussian with \( \sigma = 3 \) pixels.
Ref: 837

### TABLE 6

| Field      | ObsID          | Exposure (ks) | Distance from NGC 4874 (arcmin) | O vii \( I^a \) | O viii \( I^a \) | Ne ix \( I^a \) |
|------------|----------------|---------------|---------------------------------|----------------|----------------|--------------|
| X Com      | ...            | ...           | 26.5                            | 55.6 \pm 2.1   | 15.4 \pm 1.3   | 6.0 \pm 0.9   |
| X Com 1    | ...            | ...           | 17.6                            | 61.7 \pm 12.3  | 12.9 \pm 4.1   | 11.5 \pm 0.4  |
| X Com 2    | ...            | ...           | 20.6                            | 59.7 \pm 38    | 14.8 \pm 32    | 7.7 \pm 2.7   |
| X Com 3    | ...            | ...           | 25.9                            | 54.7 \pm 33    | 15.0 \pm 24    | 5.7 \pm 1.7   |
| X Com 4    | ...            | ...           | 31.8                            | 53.5 \pm 33    | 16.0 \pm 21    | 3.8 \pm 1.4   |
| X Com 5    | ...            | ...           | 38.2                            | 52.2 \pm 41    | 15.6 \pm 27    | 5.2 \pm 1.8   |
| Coma 0     | 0124711501     | 15.4          | 46.2                            | 71.5 \pm 5.1   | 28.1 \pm 3.4   | 4.5 \pm 1.8   |
| 1253+275   | 0058940701     | 10.5          | 71.6                            | 44.9 \pm 6.5   | 15.1 \pm 4.5   | 1.1 \pm 0.4   |
| 3C 284     | 0021740201     | 34.2          | 156.4                           | 62.2 \pm 4.0   | 26.4 \pm 2.5   | 3.7 \pm 1.2   |
| \( \beta \) Com  | 0148680101     | 29.4          | 162.7                           | 70.2 \pm 5.5   | 17.5 \pm 3.2   | 3.7 \pm 1.6   |
| Average background | ... | ... | 109.2                           | 62.2 \pm 9.8   | 21.8 \pm 5.2   | 3.3 \pm 1.2   |
| Average background\( b \) | ... | ... | 130.2                           | 59.1 \pm 12.0  | 19.7 \pm 5.5   | 2.8 \pm 1.4   |
| Weighted average background | ... | ... | 109.2                           | 63.6 \pm 2.5   | 23.1 \pm 1.6   | 3.5 \pm 0.8   |
| Weighted average background\( b \) | ... | ... | 130.2                           | 61.1 \pm 2.9   | 21.8 \pm 1.8   | 3.3 \pm 0.9   |

\( ^a \) Surface brightness in units of \( 10^{-8} \) photons cm\(^{-2} \) s\(^{-1} \) arcmin\(^{-2} \).

\( ^b \) Except for the Coma 0 field, which may have a contribution from emission associated with the cluster.

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The intensity of the \( \text{O vii} \) and \( \text{O viii} \) Gaussian components did not vary in an obvious way as a function of position (see Fig. 9). The two oxygen lines show no enhancement at the position of the cluster: their intensity in the five X Com sectors is the same or even lower than that in the background fields. We thus conclude that all of the oxygen emission comes from the Milky Way soft background and not from material in the Coma Cluster.

The intensity of the \( \text{O vii} \) and \( \text{O viii} \) lines has a large scatter from one background field to another. The intensity in one of them (the 1253+275 field) is consistent with the soft X-ray background measured by McCammon et al. [2002; \( 40.6 \pm 10.9 \times 10^{-8} \) and \( 13.5 \pm 5.4 \times 10^{-8} \) photons cm\(^{-2} \) s\(^{-1} \) arcmin\(^{-2} \) for \( \text{O vii} \) and \( \text{O viii} \), respectively], while the intensity levels in the other fields are larger than their values. On the other hand, the scatter of the Ne ix intensity among the background fields is not as large, and the average is consistent with the upper limit of McCammon et al. [2002; \( <5.4 \times 10^{-8} \) photons cm\(^{-2} \) s\(^{-1} \) arcmin\(^{-2} \), from their Fig. 13].

Do we expect not to be able to detect Coma Cluster oxygen emission given the strength of the cluster neon line? The \( \text{O vii} \) surface brightness is 1.67 times that of Ne ix, for a temperature of \( 4 \times 10^8 \) K and a Ne/O number density ratio of 0.14 (see § 5.1.1 for a justification of these values). This expected \( \text{O vii} \) line intensity in the entire X Com field is approximately the dispersion of the other nine measurements (\( 10.0 \times 10^{-8} \) vs. \( 8.0 \times 10^{-8} \) photons cm\(^{-2} \) s\(^{-1} \) arcmin\(^{-2} \), respectively). Thus, the different behavior of the neon and oxygen emission lines is probably due to the much lower Galactic neon background intensity, which allows the Coma neon emission to be detected. The higher Galactic oxygen background intensity masks the Coma oxygen emission in the X Com fields.

In § 5 we need the net Ne ix intensity at the position of X Com. Of course this measurement requires an extrapolation to that position, since the glare from the AGN prevents measurement of emission from the Coma Cluster gas. We give in Table 6 the numerical and error-weighted average of all four background fields and the three fields excluding Coma 0. The numerical average is more appropriate if there are real variations from field to field. Excluding Coma 0 is appropriate if it has a higher intensity. Since none of the four averages are statistically distinguishable, we take for the Ne ix background the weighted average of all background fields because it has the lowest error. We similarly take for the gross intensity the value from the entire X Com field, since it is statistically indistinguishable from the sector closest to X Com but has a lower error. The net intensity is thus \( (2.5 \pm 1.2) \times 10^{-8} \) photons cm\(^{-2} \) s\(^{-1} \) arcmin\(^{-2} \) (90% confidence errors or 3.4 \sigma detection).

The intensity of the Ne ix line is only 9% of the continuum level, as seen in Figure 8. Such a low intensity may mean that its measurement is subject to systematic errors in the continuum. We therefore repeated the entire preceding analysis with six additional continuum models that froze or thawed different components and/or added a soft proton component that was not folded...
through the mirror area. The dispersion in the seven measurements of the net Ne IX intensity was less than the above statistical error. We conclude that the statistical error accurately reflects the uncertainties of the measurement.

5. DISCUSSION

5.1. Properties of the Warm-Hot Gas

We have detected absorption features in the RGS spectra of X Com at the redshift of the Coma Cluster with a combined confidence of 99.7% (equivalent to 3.0 $\sigma$ of a Gaussian distribution) and line emission features in the EPIC pn spectra of diffuse gas at the position of X Com at the 3.4 $\sigma$ confidence level. Although the significance of either one is not very high, the fact that we observed both absorption and emission from Ne IX at the Coma Cluster redshift or position is additional support for the detection of this ion. In this section we give the properties of the warm-hot gas that can be deduced from our observations under the assumption that the absorbing and emitting materials are the same and that material is uniformly distributed in a single phase in collisional ionization equilibrium. Although these assumptions have the virtue that they are simple and are consistent with the observations, it is entirely possible, even likely, that the actual situation is more complicated. In this case the properties we derive are typical of the dominant phase of the material.

5.1.1. Temperature and Ne/O Number Density Ratio

We can constrain the temperature of a plasma in ionization equilibrium from the ratios of absorption EWs between different
ionization states of the same species. On the other hand, we can constrain the number density (or abundance) ratio of different elements from the ratio of absorption EWs between lines of different species.

First, we investigate the allowed temperature and abundance for the boxcar-fitting case. Figure 10 plots the ratio of the theoretically expected EWs of Ne x, O vii, and O viii to Ne ix divided by the observed upper limits to that ratio. The dotted line shows Ne x, while the dashed lines show the larger value for O vii or O viii. Since the theoretical O vii or O viii to Ne ix EW ratios depend on the number density ratio of Ne/O, we indicate three cases: 0.14 as the canonical value, 0.41 as the highest one found in the literature, and 0.82 as the extremely high Ne/O case. The allowed temperature is the range in which both the Ne ix and O curves are below 1. There is no allowed temperature range for Ne/O = 0.14, while it is $2 \times 10^6$ K < $T < 5.8 \times 10^6$ K for the extremely high Ne/O case. The ionization fraction given in Tables 2 and 3 of Chen et al. (2003) for collisional ionization case was assumed.

The theoretical O vii or O viii to Ne ix EW ratios depend on the number density ratio of Ne/O, while the Ne/O ratio is not well known even for solar or interstellar values. The widely used solar Ne/O number density ratio is 0.14 (Anders & Grevesse 1989). However, it is difficult to measure the abundance of Ne due to its absence in the solar photospheric spectrum or in meteorites. Furthermore, the O abundance also contains uncertainties; improved modeling of solar photosphere lines has yielded lower abundances for some elements including O and Ne (Asplund et al. 2005). Recent measurements using coronal X-ray or quiet-Sun EUV lines find Ne/O < 0.30 (95% confidence) or 0.17 ± 0.05 (estimated systematic errors), respectively (Schmelz et al. 2005; Young 2005). A higher Ne/O ratio, 0.41, was suggested by X-ray spectroscopy of mostly giant stars and multiple systems (Drake & Testa 2005). Recent measurements of sight lines to 4U 1820−303 and LMC X-3 through the interstellar medium yield 0.20$^{+0.10}_{-0.07}$ (90% confidence) and >0.14 (95% confidence), respectively (Yao & Wang 2006; Wang et al. 2005). Thus, the situation is not yet clear, with reported values ranging from 0.14 to 0.41.

Since our boxcar fitting cannot determine the Ne/O ratio, we indicate three cases in Figure 10: 0.14 as the canonical value, 0.41 as the highest one found in the literature, and 0.82 as an extremely high Ne/O case. We found that Ne/O > 0.25 (2σ) is necessary in order to reproduce the boxcar-fit results with an assumption of single-temperature plasma; for example, there is no intersection of the O curve and 1 for Ne/O = 0.14. Thus, the canonical Ne/O ratio (Ne/O = 0.14) is rejected in this analysis. On the other hand, if Ne/O is larger than 0.25, then there is an allowed temperature range. Even when adopting an extremely high Ne/O ratio, Ne/O = 0.82, the temperature range can be constrained to be $T > 2 \times 10^6$ K. Combining this constraint with that from the Ne x/Ne ix ratio, we obtained a conservative temperature range, $2 \times 10^6$ K < $T < 5.8 \times 10^6$ K.

We next used the EWs determined with the ratio method (§ 3.1). This method is independent of the intrinsic shape of the absorption. The left panel of Figure 11 shows the theoretical equivalent width ratios of O vii/O viii and Ne x/Ne ix as a function of temperature $T$ again based on Figures 2 and 3 of Chen et al. (2003) in the case of collisional ionization equilibrium. Note that here we use the O vii/O viii ratio because O viii was also detected at more than 90% confidence with the ratio method. We show the observed 2 σ upper limits obtained in § 3.1 with horizontal lines in the left panel of Figure 11. The allowed temperature range is that for which the curves lie below the horizontal upper limits of that ratio, i.e., $T > 2.2 \times 10^6$ K for O vii/O viii and $T < 5.7 \times 10^6$ K for Ne ix/Ne x. By combining these two constraints, we restricted the temperature of the plasma to $2.2 \times 10^6$ K < $T < 5.7 \times 10^6$ K at the 2 σ confidence level.

From the Ne ix/O viii ratio, we can investigate the allowed Ne/O number density ratio as a function of temperature $T$. This is shown in the right panel of Figure 11. The ±1 σ error range is also shown. The allowed Ne/O ratio is not very sensitive to temperature; it is roughly 0.3 ± 0.15 to 0.5 ± 0.3 within the allowed temperature range found above. Although our best-fit Ne/O ratio suggests a Ne overabundance, all of the ratios discussed previously including the canonical value of 0.14 is within our ~1 σ confidence limit. Note that both the temperature range and the Ne/O ratio are consistent in the two estimates (boxcar-fitting and ratio values).

5.1.2. Density, Line-of-Sight Length, and Metallicity

We can constrain the average hydrogen density $n_H$ of the warm-hot gas and its path length $L$ along the line of sight by combining absorption and emission observations of the same ion, Ne ix in our case. The column density of an ion is

$$N_{\text{ion}} = f_{\text{ion}} Z n_H L,$$  \hspace{1cm} (5)

where $Z$ is the abundance of the element relative to hydrogen. Equation (2) gives $N_{\text{ion}}$ as a function of the observed EW. The surface brightness of an emission line $I$ is

$$I = \frac{C}{(1+z)^2} Z n_H^2 L,$$  \hspace{1cm} (6)

where the exponent of $1+z$ is 3 instead of 4 because we measure surface brightness in photons, not ergs, and $C$ is a coefficient
respectively, obtained from the observed Ne emission and absorption. The horizontal lines represent the upper limits determined by this work. The allowed range is that for which the curves are below the horizontal upper limit lines of the same style, i.e., \( T > 2.2 \times 10^6 \) K for O vii/O viii (solid line) and \( T < 5.7 \times 10^6 \) K for Ne ix/O viii (dashed line). Right: Ne/O number density ratio as a function of temperature \( T \). The three curves correspond to the best-fit values and \( \pm 1 \) \( \sigma \) errors, respectively, obtained from the observed Ne ix/O viii ratio.

depending on temperature but not on the elemental abundance. Solving these two equations simultaneously gives

\[
\begin{align*}
n_{\text{H}} &= \frac{f_{\text{H}}(1+z)^3}{C} \frac{I}{N_{\text{H}},} \\
ZL &= \frac{C}{f_{\text{H}}(1+z)^3} \frac{N^2}{I}.
\end{align*}
\]

The coefficient \( C \) is

\[
C = \frac{1}{4\pi} \left( \frac{n_e}{n_{\text{H}}} \right)^2 \frac{1}{Z(M)} \sum_j \frac{P_j}{E_j}.
\]

Here \( n_e/n_{\text{H}} = 1.17 \), \( Z(M) \) is the abundance of the element assumed by Mewe et al. (1985; 8.32 \( \times 10^{-5} \) for neon), \( P_j \) is tabulated in Table IV of Mewe et al. (1985), \( E \) is the energy of the line, and the sum is over all lines not resolved with CCD energy resolution.

For the Ne ix emission \( C \) comes from six lines: the Ne ix resonance line (13.44 Å), three satellite lines of Ne viii (13.44, 13.46, and 13.55 Å), the Ne ix intercombination line (13.55 Å), and the Ne ix forbidden line (13.70 Å).

We derive the parameters of the material producing the Ne ix absorption and emission as a function of temperature from its column density and intensity at the position of X Com found at the ends of \( \S 3 \) 3.2 and 4, respectively. For example, a temperature of \( 4.0 \times 10^6 \) K gives \( C = 5.37 \times 10^{-13} \) photons cm\(^3\) s\(^{-1}\) sr\(^{-1}\) and \( f_{\text{H}} = 0.50 \). Then

\[
n_{\text{H}} = (6.1 \times 10^{-6} \text{ cm}^{-3}) \left( \frac{I}{2.5 \times 10^{-8}} \right) \left( \frac{N_{\text{Neix}}}{4.4 \times 10^{16} \text{ cm}^{-2}} \right)^{-1},
\]

\[
\left( \frac{Z}{Z_\odot} \right) L = (41 \text{ Mpc}) \left( \frac{I}{2.5 \times 10^{-8}} \right)^{-1} \left( \frac{N_{\text{Neix}}}{4.4 \times 10^{16} \text{ cm}^{-2}} \right)^2.
\]

where \( Z_\odot = 1.23 \times 10^{-4} \) is the solar abundance of Ne relative to H (Anders & Grevesse 1989). The derived values of \( n_{\text{H}} \) and \( ZL \) depend strongly on the temperature. We show in Figure 12 the values as a function of temperature, where solid and dashed curves represent best-fit values and \( 1 \) \( \sigma \) confidence regions, respectively. Vertical dotted lines indicate the allowed temperature range, \( 2.0 \times 10^6 \) K < \( T < 5.8 \times 10^6 \) K (see Fig. 10). We constrained \( n_{\text{H}} \) to be \( 2 \times 10^{-6} \) cm\(^{-3}\) < \( n_{\text{H}} < 8 \times 10^{-5} \) cm\(^{-3}\) and \( ZL \)
to be $1 \, Z_\odot < Z_L < 300 \, Z_\odot$ Mpc. These limits are at approximately the 3 $\sigma$ confidence level, since they sum the 2 $\sigma$ limit on temperature and the 1 $\sigma$ limit on $n_{\text{HI}}$ and $Z_L$ (i.e., do not sum the errors in quadrature). The derived hydrogen density corresponds to $10 < \delta < 400$. Here $\delta$ is the overdensity with respect to the mean density of the universe: $\delta \equiv n_{\text{HI}}/n_{\text{th}}$ with $n_{\text{th}} = X\Omega_b\rho_c(1+z)^3/h_0^2$, where $X = 0.71$ is the hydrogen-to-baryon mass ratio and $\Omega_b = 0.0224 \, h^{-2}$ is the baryon density relative to the critical density $\rho_c$.

Although the constraint we obtained on $Z_L$ is not tight, we note that the lower limit on $L$ is $1 \, (1 \, \text{Mpc})(Z/Z_\odot)^{-1}$. The measured value of $Z/Z_\odot$ at the position of $X$ Com is $0.16 \pm 0.05$ (68% confidence error) for iron (De Grandi & Molendi 2001), where $Z_\odot = 4.68 \times 10^{-5}$ is the solar abundance of iron (Anders & Grevesse 1989). Thus, the scale of the plasma that contains Ne $\alpha$ is at least 2.6 times the size of the Coma Cluster ($r_{200} = 2.4 \, h_7^{-1}$ Mpc) if the Ne and Fe abundances are approximately the same. For at least two clusters (2A 0335+096 and Sérsic159-03) RGS observations show that the Ne/Fe is approximately unity or slightly less (Werner et al. 2006; de Plaa et al. 2006). We conclude that the material containing Ne $\alpha$ is likely not in the Coma Cluster.

5.2. Could the Ne $\alpha$ Emission Come from Material within the Cluster Virial Radius?

We investigate the suggestion by Cheng et al. (2005) that gas associated with merging subgroups inside the cluster virial region, which preserves its identity for a while before being destroyed by the hot intracluster medium, is responsible for the cluster soft excess. In particular, we determine whether this material could produce the Ne $\alpha$ emission we observe. We disregard the constraints from the absorption measurements here. Instead, we assume that the temperature of this material is $2 \times 10^6$ K, the peak of the Ne $\alpha$ ion fraction, and that the material is in pressure equilibrium with the ICM. Neither of these assumptions is very constraining. Changing the temperature to $4 \times 10^6$ K, the midpoint of the allowed range found above, changes the results calculated below by less than a factor of 2. The second assumption yields a density of warm-hot material similar to the densest regions of groups, which we could have assumed at the outset, since that is the suggestion we are investigating.

First we need the properties of the hot ICM. The emission-weighted temperature at the position of $X$ Com is 7.4 keV from the temperature map of Honda et al. (1996). The emission measure-weighted hydrogen density at the position of $X$ Com is $2 \times 10^{-4} \, h_{70}^{1/2} \, \text{cm}^{-3}$ (Briel et al. 1992). Next we need the properties of the warm-hot material. A temperature of 0.172 keV and pressure equilibrium with the ICM yields a hydrogen density of $8.6 \times 10^{-3} \, h_{70}^{1/2} \, \text{cm}^{-3}$, or $\delta \sim 3.4 \times 10^4$, and entropy $\sim 4 \, k \, h_{70}^{-1/2}$ cm$^2$. The latter two values place the warm-hot material on the extremely high density tail of the phase plot in Figure 4 of Cheng et al. (2005). Equation (8) with $C(2 \times 10^6 \, K) = 1.19 \times 10^{-12}$ photons cm$^{-3}$ s$^{-1}$ sr$^{-1}$, the above hydrogen density, and the observed Ne $\alpha$ surface brightness imply that the path length through the material $L$ is $\sim 100$ pc. The sound crossing time across $L$ is $\sim 5 \times 10^4$ yr, during which the material travels $600$ pc moving at $\sigma_{\text{gas}}$. Thus, pressure equilibrium is a good assumption because the ICM pressure hardly changes over such a small distance.

How long could this warm-hot material survive? We assume that its size across the line of sight is also $L$, i.e., that the warm-hot material comprises tiny blobs of diameter $\sim 100$ pc. Following Cowie & McKee (1977) the classical heat conduction across the blob-cluster interface is saturated. The saturated evaporation time is $\sim 1 \times 10^4$ yr, from their equation (64). Any blobs that might exist are very quickly destroyed. Furthermore, they are not replenished, since the time for group gas at a temperature of 2 keV and the above density to cool to a temperature at which there is a significant population of Ne $\alpha$ is $\sim 5 \times 10^4$ yr.

Even after the blobs evaporate it takes some additional time for the Ne ion distribution to equilibrate to that appropriate to the new temperature in which the Ne finds itself. The longest lived ion capable of emitting the Ne $\alpha$ resonance line we detect is Ne $\alpha$, which it does by electron capture to an excited level followed by radiative de-excitation. The ionization time $\tau_{\text{ion}}$ to convert Ne $\alpha$ to Ne $\alpha$ is mostly determined by the collisional ionization efficiency $S_{\text{Ne},X}$, i.e., $\tau_{\text{ion}} \sim 1/n_e S_{\text{Ne},X}$. The recombination rate is negligibly small, and the ionization time to convert Ne $\alpha$ to Ne $\alpha$ is smaller than that for Ne $\alpha$ to Ne $\alpha$ in our case. The empirical formula for $S_{\text{Ne},X}$ for coronal plasma is given in McWhirter (1965, eq. [40]) as

$$S_{\text{Ne},X} = 1.10 \times 10^{-5} \frac{(kT_e/\chi)^{1/2}}{\chi^{3/2}(6 + kT_e/\chi)} \exp \left( -\frac{\chi}{kT_e} \right) \, \text{cm}^{-3} \, \text{s}^{-1},$$

where $T_e$ and $\chi$ are the electron temperature and the ionization energy in eV, respectively. Substituting the properties of the hot gas, $T_e = 7400$ eV, $\chi = 1360$ eV, and $n_e = 2.3 \times 10^{-4} \, h_{70}^{-1/2}$ cm$^{-3}$, we find $\tau_{\text{ion}} = 3.7 \times 10^4$ yr. The evaporation and the equilibration times are much smaller than the cluster crossing time, the characteristic scale of the situation. Thus, we conclude that, under reasonable assumptions, material within the cluster virial radius is not capable of producing the observed Ne $\alpha$ emission unless we are viewing the Coma Cluster at a very special epoch.

6. SUMMARY

Our main result is the detection of absorption and emission lines from Ne $\alpha$ associated with the Coma Cluster of galaxies. The absorption is centered on the previously known Coma redshift, although it is of marginal statistical significance (98.0%–99.2% confidence depending on the analysis method). The emission is statistically significant (3.4 $\sigma$) and is positionally coincident with Coma. While the absorption line is resolved, its width is much smaller than the spectral resolution of the emission-line data. We do not know whether the emission and absorption lines have the same profile. The properties of the material causing these lines, assuming it is in a single phase in collisional ionization equilibrium, are constrained as follows: temperature $T$ is $2.0 \times 10^6$ K $< T < 5.8 \times 10^6$ K, density $n_H = 2 \times 10^{-6} \, h_{70}^{-1/2}$ cm$^{-3}$, overdensity $\delta < 400$, and the line-of-sight path length through it is $L > (6 \, \text{Mpc})(Z/0.16 \, Z_\odot)^{-1}$.

These properties are similar to those expected of the warm-hot intergalactic medium, and we conclude that we have detected it. The warm-hot intergalactic medium is also expected to be distributed in filaments connecting clusters of galaxies. Since X Com lies behind the apparent continuation of the Coma-A1367 chain of galaxies to the northeast of the Coma Cluster (Gavazzi et al. 1999), the material we detect may reside in this previously identified filament.

We thank the referee for a number of probing questions that improved the paper. This work is supported by a Grant-in-Aid
for Scientific Research from JSPS (14204017) and grants from
NASA (NNG04GK84G and NNG05GN01G). The XMM-Newton
project is supported by the Bundesministerium fuer Wirtschaft
und Technologie/Deutsches Zentrum fuer Luft- und Raumfahrt
(BMWI/DLR, FKZ 50 OX 0001), the Max-Planck Society, and
the Heidenhain-Stiftung, as well as by PPARC, CEA, CNES,
and ASI. Y. T. is supported by grants from the JSPS Research
Fellowships for Young Scientists (DC 16-10681 and PD 18-
7728), and A. F. acknowledges support from BMBF/DLR (grant
50 OR 0207).

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