A MASSIVE WARM BARYONIC HALO IN THE COMA CLUSTER

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ABSTRACT

Several deep PSPC observations of the Coma Cluster reveal a very large scale halo of soft X-ray emission, substantially in excess of the well-known radiation from the hot intracluster medium. The excess emission, previously reported in the central region of the cluster using lower sensitivity Extreme Ultraviolet Explorer (EUV) and ROSAT data, is now evident out to a radius of 2.6 Mpc, demonstrating that the soft excess radiation from clusters is a phenomenon of cosmological significance. The X-ray spectrum at these large radii cannot be modeled nonthermally but is consistent with the original scenario of thermal emission from warm gas at $\sim 10^6$ K. The mass of the warm gas is on par with that of the hot X-ray-emitting plasma and significantly more massive if the warm gas resides in low-density filamentary structures. Thus, the data lend vital support to current theories of cosmic evolution, which predict that at low redshift $\sim 30\%$–$40\%$ of the baryons reside in warm filaments converging at clusters of galaxies.

Subject headings: large-scale structure of universe — X-rays: galaxies: clusters — X-rays: individual (Coma cluster)

1. INTRODUCTION

Clusters of galaxies are strong emitters of X-rays, which originate from a hot and diffuse intracluster medium (ICM). At the typical temperatures of a few times $10^7$ K, the bulk of the hot ICM emission is detected at energies $\geq 1$ keV, intervening Galactic absorption being responsible for a substantial reduction of flux below $\sim 1$ keV. However, hot gas is not the only high-energy component seen in clusters, and the extreme-ultraviolet (EUV) and soft X-ray band below $\sim 1$ keV offer a unique window to investigate the presence of other phases in the ICM.

In 1996, Lieu et al. (1996) reported the discovery of excess EUV and soft X-ray emission above the contribution from the hot ICM in the Coma Cluster; their conclusions were based on Extreme Ultraviolet Explorer (EUV) Deep Survey data (65–200 eV) and ROSAT PSPC data (0.15–0.3 keV). Subsequently, Bowyer, Berghofer, & Korpela (1999) reanalyzed the EUVE data and confirmed the existence of strong excess emission in the central 15′ of Coma. Arabadjis & Bregman (1999) reanalyzed the PSPC data and reported that the fitted H i column density in the center of the cluster was significantly smaller than the measured Galactic value, consistent with the earlier reports of soft X-ray excess emission. Recently, the spatial distribution of the soft X-ray emission in the center of the Coma Cluster was investigated by Bonamente et al. (2002) and Nevalainen et al. (2003). In this paper we present the analysis of a mosaic of ROSAT PSPC observations around the Coma Cluster, revealing a very diffuse soft X-ray halo extending to considerably larger distances than reported in the previous studies.

The nature of the excess emission has been under active scrutiny. The emission could originate from inverse Compton scattering of cosmic microwave background (CMB) photons against a population of relativistic electrons in the ICM, as advocated by Hwang (1997), Sarazin & Lieu (1998), Ensslin & Biermann (1998), and Lieu et al. (1999). Alternatively, warm gas at $T \sim 10^6$ K could be responsible for the soft emission (Lieu et al. 1996; Nevalainen et al. 2003). Warm gas may reside inside the cluster or in very diffuse filamentary structures outside the cluster projecting onto it, as seen in large-scale hydrodynamic simulations (e.g., Cen & Ostriker 1999; Davé et al. 2001; Cen et al. 2001). The warm gas scenario appears to be favored by the current X-ray spectral analyses (e.g., Bonamente, Lieu, & Mittaz 2001; Buote 2001), although a search for the UV O vi emission lines (1032–1039 Å in rest frame) has not yielded positive results (Dixon, Hurwitz, & Ferguson 1996; Dixon et al. 2001). The nondetection of emission lines can be reconciled with the soft excess detection if the gas has very low metal abundances or alternatively if the gas exists in a temperature range where O vi is not the predominant oxygen ion. The spectral analysis of PSPC data reported in this paper indicates that the emission is very likely thermal in nature.

The PSPC observations are described in § 2, and the distribution of the Galactic H i over the field of view is presented in § 3. Analysis of the PSPC spectra is given in § 4, followed by the interpretation in § 5 and conclusions in § 6.

The redshift to the Coma Cluster is $z = 0.023$ (Struble & Rood 1999). Throughout this paper we assume a Hubble constant of $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ (Freedman et al. 2001), and all quoted uncertainties are at the 68% confidence level.

2. THE ROSAT PSPC DATA

The ROSAT PSPC instrument has unique capabilities for the study of the low-energy excess emission in clusters of galaxies. Along with an effective area of $\sim 200$ cm$^2$ at 0.25 keV, the spectral response between 0.2 and 2 keV is well calibrated (Snowden et al. 1994). Moreover, the large field of view ($\sim 15′$ radius), low detector background, and availability of a large number of deep cluster observations and of the ROSAT All-Sky Survey (RASS) data render the PSPC a unique instrument to detect and investigate the large-scale diffuse emission from galaxy clusters.

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Coma is the nearest rich galaxy cluster, and the X-ray emission from its hot ICM reaches an angular radius of at least 1° (e.g., White, Briel, & Henry 1993; Briel et al. 2001). If the soft X-ray background level is estimated from the edge of the PSPC field of view as is customarily done for more distant clusters, the background can be significantly overestimated as a result of the extended cluster emission (Bonamente et al. 2002). Here we show how several off-center PSPC observations provide a reliable measurement of the background and reveal a very extended halo of soft X-ray excess radiation, covering a region several megaparsecs in extent in the Coma Cluster.

The RASS maps of the diffuse X-ray background (Snowden et al. 1997) are suitable to measure the extent of the soft X-ray emission (R2 band, 0.15–0.3 keV) around the Coma Cluster and to compare it with that of the higher energy X-ray emission (R7 band, 1–2 keV). In Figure 1 we show a radial profile of the surface brightness of PSPC bands R2 and R7 centered on Coma: the higher energy emission has reached a constant background value at a radius of 5°, while the soft X-ray emission persists out to a radius of 3°. Thus, the RASS data indicate that the soft emission is more extended than the 1–2 keV emission, which originates primarily from the hot phase of the ICM.

The all-sky survey data are based on very short exposures (~700 s); therefore, for detailed studies of the soft X-ray emission in the Coma Cluster, we use the four PSPC observations shown in Figure 2. Four additional deep PSPC observations (also shown in Fig. 2) are used to determine the local background. We show in § 3 that the distribution of \( N_H \) is essentially constant within 5° of the cluster center.

Therefore, the off-source PSPC fields located 2°5–4° away from the cluster center provide an accurate measurement of the soft X-ray background and are also far enough away from the cluster center to avoid being contaminated by cluster X-ray emission (Fig. 1).

3. GALACTIC H I ABSORPTION IN THE DIRECTION OF THE COMA CLUSTER

Knowledge of the Galactic absorption is essential to determine the intrinsic X-ray emission from extragalactic objects, particularly at energies \( \leq 1 \) keV. Throughout this paper, we use the absorption cross sections of Morrison & McCammon (1983) in our models. These cross sections are in good agreement with the recent compilation of Yan, Sadeghpour, & Dalgarno (1998), as discussed by Arabadjis & Bregman (1999). At the resolution of the PSPC, the He cross section in the most recent compilation by Wilms, Allen, & McCray (2000) is also indistinguishable from the values of Morrison & McCammon (1983), as discussed by Bonamente et al. (2002).

We use two methods to determine the distribution of neutral hydrogen in the Coma Cluster. First, we use the radio measurements of Dickey & Lockman (1990) and of Hartmann & Burton (1997), which are plotted in Figure 3. The radio measurements are in excellent agreement and show the measured H I column density varying smoothly from \( 9 \times 10^{19} \) to \( 11 \times 10^{19} \) cm\(^{-2}\) within a radius of 5° from the center of the Coma Cluster. Second, we employ the far-infrared \( IRAS \) flux and H I column density (Boulanger & Perault 1988). The slope of the correlation is \( 1.2 \times 10^{20} \) cm\(^{-2}\) (MJy sr\(^{-1}\))^\(-1\), and the offset is determined by fixing the central \( N_H \) value to \( 9 \times 10^{19} \) cm\(^{-2}\), which is well established from independent radio measurements of the center of the Coma Cluster (Dickey & Lockman 1990; Lieu et al. 1996;
Hartmann & Burton 1997). Figure 3 shows that the radial variation of $N_{\text{H}}$ inferred from the IRAS data is in extremely good agreement with the radio measurements. The data indicate that (1) the H i column density within the central 1.5 of the cluster is constant $\left[\left(9 \pm 1\right) \times 10^{19}\ \text{cm}^{-2}\right]$ and (2) in the region where the off-source background fields are located (2.5–4° from the cluster center), the H i column density is between $9 \times 10^{19}$ and $11 \times 10^{19}\ \text{cm}^{-2}$. An $N_{\text{H}}$ variation of this magnitude has a negligible effect on the soft X-ray flux in the PSPC R2 band (e.g., Fig. 5 in Snowden et al. 1998).

With the present IR and radio data we cannot address the possibility of variations in the H i distribution on scales smaller than $\sim 10^\circ$. On occasions for which a comparison with stellar Lyα and QSO X-ray spectra could be made, the $N_{\text{H}}$ was found consistent with the wide-beam measurements to within $\sim 1 \times 10^{19}\ \text{cm}^{-2}$ (Laor et al. 1994; Elvis, Wilkes, & Lockman 1989; Dickey & Lockman 1990).

4. SPECTRAL ANALYSIS

The four PSPC Coma observations were divided into concentric annuli centered at R.A. = $12^h59^m48^s$, decl.
25°57′0″ (J2000.0), and the spectra were co-added to reduce the statistical errors. The pointed PSPC data were reduced according to the prescriptions of Snowden et al. (1994). The data sets were corrected for detector gain fluctuations, and only events with average master veto rate ≤170 counts s\(^{-1}\) were considered, in order to discard periods of high particle background. The PSPC rejection efficiency for particle background is 99.9% in the 0.2–2 keV energy range (Plucinsky et al. 1993), and the background is therefore solely represented by the photonic component. For each of the four off-source fields in Figure 1, a spectrum was extracted after removal of point sources. The spectra were statistically consistent with one another within at most 10% point-to-point fluctuations. The off-source spectra were therefore co-added, and a 10% systematic uncertainty in the background was included in the error analysis. Further details of the PSPC data analysis can be found in Bonamente et al. (2002).

### Table 1

| Region (arcmin) | 0.2–2 keV Fit, Galactic \(N_H\) | 0.2–2 keV Fit, Free \(N_H\) |
|-----------------|----------------|----------------|
|                 | \(kT\) (keV) | \(A\) | \(\chi^2_{red}/dof\) | \(kT\) (keV) | \(A\) | \(\chi^2_{red}/dof\) |
| 0–20            | 3.9 ± 0.15   | 0.25  | 9.74/181 | 6.15 ± 0.1 | 6.5±0.4 | 0.25  | 2.8/180 |
| 20–40           | 2.4 ± 0.1    | 0.2   | 7.4/181  | 2 ± 0.3    | 2 ±0.3  | 0.2   | 3.7/180 |
| 40–55           | 2.3±0.1      | 0.2   | 6.2/175  | <0.01      | 2.3 ± 0.1 | 0.2   | 4.2/174 |
| 55–70           | 1.8±0.3      | 0.2   | 3.5/151  | ≤0.02      | 1.85±0.4 | 0.2   | 2.9/150 |
| 70–90           | 1.9±0.1      | 0.2   | 3.1/139  | ≤0.02      | 2 ±0.3  | 0.2   | 2.5/138 |

4.1. Single-Temperature Fits

Initially, we fit the spectrum of each annulus in XSPEC, using a single-temperature MEKAL plasma model (Mewe, Gronenschild, & van den Oord 1985; Mewe, Lemen, & van den Oord 1986; Kaastra 1992) and the WABS Galactic absorption model (Morrison & McCammon 1983). The results of the single-temperature fit are given in Table 1 and are shown for one of the annuli in Figure 4. If the neutral hydrogen column density is fixed at the Galactic value (9×10\(^{19}\) cm\(^{-2}\); see §3), the fits are statistically unacceptable (reduced \(\chi^2\) ranging from 3.1 to 9.7). Allowing the neutral hydrogen column density to vary results in an unrealistically low \(N_H\) for all of the annuli and also produces statistically unacceptable fits (reduced \(\chi^2\) ranging from 2.5 to 4.2). We conclude that a single-temperature plasma model does not adequately describe the spectral data, particularly at energies below 1 keV (Fig. 4). Therefore, in the analysis that

**Fig. 4.—** ROSAT PSPC spectrum of the 20′–40′ region around the center of the Coma Cluster, fitted to a single-temperature model with variable \(N_H\) (red) and with Galactic \(N_H\) (green).
follows, we fit only the high-energy portion of the spectrum (1–2 keV) with a single-temperature plasma model and introduce an additional model component to account for the low-energy emission.

4.2. Modeling the Hot ICM

To fit the high-energy portion of the spectrum, we apply a MEKAL model to the data between 1 and 2 keV and a photoelectric absorption model with $N_H = 9 \times 10^{19}$ cm$^{-2}$. The metal abundance is fixed at 0.25 solar for the central 20$'$ region (Arnaud et al. 2001) and at 0.2 solar in the outer regions. The spectra are also subdivided into quadrants, in order to obtain a more accurate temperature for each region of the cluster. The results of the ‘‘hot ICM’’ fit are given in Table 2 and are consistent with the results previously derived from the PSPC data by Briel & Henry (1997) and with recent XMM measurements (Arnaud et al. 2001). In addition, the temperature found at large radii is in agreement with the composite cluster temperature profile of De Grandi & Molendi (2002).

4.3. Soft Excess Emission

The measured fluxes in the soft X-ray band can now be compared with the hot ICM model predictions in the 0.2–1 keV band. The results are shown in Table 2 and Figure 5. The error bars reflect the uncertainty in the hot ICM temperature (Table 2) and the uncertainty in the Galactic H I column density [$N_H = (9 \pm 1) \times 10^{19}$ cm$^{-2}$]. The soft excess component is detected with high statistical significance throughout the 90$'$ radius of the pointed PSPC data, which corresponds to a radial distance of 2.6 Mpc. The soft excess emission (Fig. 5, left-hand panel) is much more extended than that of the hot ICM (Fig. 5, right-hand panel), in agreement with the conclusions drawn from the all-sky survey data (Fig. 1).

4.4. Low-Energy Nonthermal Component

Having established the hot ICM temperature for each quadrant (Table 2), we now consider additional components in the spectral analysis. First, we add a power-law nonthermal component, which predominantly contributes to the low-energy region of the spectrum (Sarazin & Liu 1998). The neutral hydrogen column density was fixed at the Galactic value ($N_H = 9 \times 10^{19}$ cm$^{-2}$). The results of fitting the hot ICM plus power-law models to the annular regions are shown in Table 3 and Figure 6. The reduced $\chi^2$ values are poor: the average $\chi^2_{\text{red}}$ is 1.48, and the worst-case value is 1.89; we conclude that the combination of a low-energy power-law component and the hot ICM thermal model does not adequately describe the PSPC spectral data.

4.5. Low-Energy Thermal Component

Finally, we consider a model consisting of a hot ICM thermal component ($\S$ 4.2) and an additional low-temperature

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**TABLE 2**

**BEST-FIT HOT ICM MODEL AND SOFT X-RAY FLUXES**

| Region (arcmin) | Hot ICM $kT$ (keV) | $\rho$ | $\chi^2_{\text{red}}$/dof | Measured Flux (counts s$^{-1}$) | Hot ICM Prediction$^c$ (counts s$^{-1}$) |
|----------------|-------------------|-------|--------------------------|-------------------------------|---------------------------------|
| 0–20:          |                   |       |                          |                               |                                 |
| All           | 7 ± 0.25          | 23.6 ± 0.1 | 1.42/100 | 8.85 ± 0.016 | 8.0 ± 0.05/0.022 |
| NE            | 5.8 ± 0.4         | 4.9 ± 0.1  | 0.82/100 | 2.03 ± 0.007 | 1.81 ± 0.05/0.026 |
| NW            | 6.6 ± 0.6         | 5.0 ± 0.05 | 0.89/98  | 1.86 ± 0.007 | 1.72 ± 0.05/0.025 |
| SE            | 6.8 ± 0.5         | 6.6 ± 0.05 | 0.82/98  | 2.42 ± 0.008 | 2.18 ± 0.05/0.033 |
| SW            | 13.6$^{+2.9}_{-1.9}$ | 7.7 ± 0.05 | 1.01/98  | 2.27 ± 0.007 | 2.09 ± 0.05/0.036 |
| 20–40:         |                   |       |                          |                               |                                 |
| All           | 4.2 ± 0.3         | 6.1 ± 0.05 | 0.98/100 | 2.65 ± 0.002 | 1.88 ± 0.05/0.026 |
| NE            | 2.6 ± 0.3         | 0.85 ± 0.015 | 0.69/98  | 0.53 ± 0.006 | 0.345 ± 0.005/0.019 |
| NW            | 4.3 ± 0.7         | 1.65 ± 0.05 | 0.76/98  | 0.685 ± 0.007 | 0.50 ± 0.011/0.015 |
| SE            | 8$^{+3.2}_{-1.2}$ | 1.55 ± 0.03 | 0.57/98  | 0.632 ± 0.007 | 0.42 ± 0.012/0.013 |
| SW            | 7.8$^{+2.1}_{-1.4}$ | 3.3 ± 0.1  | 0.89/98  | 0.935 ± 0.007 | 0.714 ± 0.03/0.02 |
| 40–55:         |                   |       |                          |                               |                                 |
| All           | 5.3$^{+1.3}_{-1.3}$ | 2.9 ± 0.1  | 0.89/95  | 1.8 ± 0.038 | 0.65 ± 0.03/0.015 |
| NE            | 3.1$^{+1.3}_{-1.3}$ | 0.33 ± 0.03 | 0.69/50  | 0.36 ± 0.001 | 0.095 ± 0.005/0.003 |
| NW            | 8.0$^{+2.3}_{-1.3}$ | 0.42 ± 0.03 | 0.93/54  | 0.68 ± 0.015 | 0.18 ± 0.012/0.008 |
| SE            | 3.6$^{+1.3}_{-1.3}$ | 0.34 ± 0.03 | 0.96/48  | 0.38 ± 0.001 | 0.091 ± 0.013/0.004 |
| SW            | 3.5 ± 0.7         | 1.6 ± 0.05 | 1.0/78   | 0.67 ± 0.01  | 0.38 ± 0.013/0.01 |
| 55–70:         |                   |       |                          |                               |                                 |
| All           | 2.6$^{+0.9}_{-0.5}$ | 0.98 ± 0.05 | 0.97/136 | 0.85 ± 0.024 | 0.3 ± 0.006/0.009 |
| NE            | 3.5$^{+1.3}_{-1.3}$ | 0.5 ± 0.04  | 1.02/70  | 0.5 ± 0.02  | 0.137 ± 0.019/0.004 |
| SW            | 2.3$^{+0.8}_{-0.5}$ | 0.48 ± 0.04 | 0.93/65  | 0.35 ± 0.014 | 0.16 ± 0.005/0.006 |
| 70–90:        |                   |       |                          |                               |                                 |
| SW            | 2.9$^{+0.5}_{-0.8}$ | 0.42 ± 0.03 | 1.21/59  | 0.335 ± 0.014 | 0.121 ± 0.005/0.005 |

$^a$ Soft X-ray fluxes are in the 0.2–1 keV band.

$^b$ $I$ is the best-fit emission integral in units of $10^{12}[4\pi(1+z)D^2]$, where $D$ is the distance to the source (in cm) and $z$ is the redshift.

$^c$ The two error brackets account, respectively, for the uncertainty in the hot ICM temperature and the uncertainty in the Galactic H I column density ($\Delta N_H = 1 \times 10^{19}$ cm$^{-2}$).
thermal component. As before, the neutral hydrogen column density was fixed at the Galactic value (see § 3). The results of fitting the hot ICM plus warm thermal models are shown in Table 3 and Figure 6. The reduced $\chi^2$ values are significantly improved relative to the previous case: the average reduced $\chi^2$ is 1.24, and the worst-case value is 1.45. In every region the fit obtained with a warm thermal component was superior to the fit using a nonthermal component, as indicated by inspection of the $\chi^2_{\text{red}}$ values and by an $F$-test (Bevington 1969) on the two $\chi^2$ distributions (Table 3).

5. INTERPRETATION

The spectral analysis of § 4 indicates that the excess emission can be explained as thermal radiation from diffuse warm gas. The nonthermal model appears viable only in a

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**TABLE 3**

| Region (arcmin) | Nonthermal Component | Low-Energy Thermal Component | $F$-Test Probability$^a$ (%) |
|-----------------|----------------------|------------------------------|----------------------------|
|                 | $\alpha$ | $\chi^2_{\text{red}}$/dof | $kT$ (keV) | $A$ | $I$ | $\chi^2_{\text{red}}$/dof |           |
| 0–20:           |          |                        |            |    |    |                          |           |
| NE .............. | 2.65 ± 0.05 | 1.42/180 | 0.29 ± 0.05 | 0.02 ± 0.015 | 1.3 ± 0.25 | 1.36/179 | 61.3 |
| NW .............. | 1.42 ± 0.01 | 1.54/180 | 0.25 ± 0.05 | 0.05 ± 0.03 | 2.0 ± 1.0 | 1.18/179 | 96.2 |
| SE .............. | 1.51 ± 0.02 | 1.52/180 | 0.12 ± 0.015 | 0.07 ± 0.03 | 1.5 ± 0.5 | 1.36/179 | 77.1 |
| SW .............. | 1.40 ± 0.005 | 1.45/180 | 0.093 ± 0.01 | 0.1 | 0.93 ± 0.06 | 1.41/180 | 57.4 |
| 20–40:          |          |                        |            |    |    |                          |           |
| NE .............. | 1.93 ± 0.07 | 1.45/180 | 0.22 ± 0.015 | 0.06 ± 0.05 | 0.7 ± 0.08 | 1.25/179 | 83.9 |
| NW .............. | 1.73 ± 0.07 | 1.59/180 | 0.21 ± 0.015 | 0.07 ± 0.04 | 0.8 ± 0.09 | 1.45/179 | 73.1 |
| SE .............. | 1.70 ± 0.07 | 1.3/180 | 0.22 ± 0.015 | 0.06 ± 0.04 | 0.95 ± 0.06 | 1.1/179 | 86.8 |
| SW .............. | 2.30 ± 0.15 | 1.43/180 | 0.23 ± 0.08 | 0.04 ± 0.025 | 1.45 ± 0.1 | 1.33/179 | 68.6 |
| 40–55:          |          |                        |            |    |    |                          |           |
| NE .............. | 2.37 ± 0.05 | 1.64/131 | 0.21 ± 0.015 | 0.1 ± 0.04 | 1.15 ± 0.2 | 1.1/130 | 98.8 |
| NW .............. | 2.37 ± 0.07 | 1.15/134 | 0.21 ± 0.025 | 0.03 ± 0.03 | 1.7 ± 0.15 | 1.06/133 | 68.1 |
| SE .............. | 2.44 ± 0.06 | 1.59/130 | 0.215 ± 0.015 | 0.05 ± 0.03 | 1.7 ± 0.2 | 1.24/129 | 92.1 |
| SW .............. | 1.91 ± 0.05 | 1.15/160 | 0.215 ± 0.025 | 0.03 ± 0.015 | 2.0 ± 0.2 | 1.15/159 | 50.0 |
| 55–70:          |          |                        |            |    |    |                          |           |
| NE .............. | 2.35 ± 0.06 | 1.69/150 | 0.20 ± 0.02 | 0.18 ± 0.017 | 1.2 ± 0.45 | 1.08/149 | 99.7 |
| SW .............. | 2.21 ± 0.15 | 1.40/144 | 0.23 ± 0.025 | 0.12 ± 0.04 | 0.7 ± 0.15 | 1.10/143 | 92.5 |
| 70–90:          |          |                        |            |    |    |                          |           |
| SW .............. | 2.2 ± 0.05 | 1.89/140 | 0.22 ± 0.02 | 0.15 ± 0.014 | 0.7 ± 0.2 | 1.41/139 | 95.8 |

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*$^a$ The $F$-test describes the likelihood that the thermal model constitutes an improvement over the nonthermal model (Bevington 1969).
few quadrants and will not be further considered in this paper.

5.1. A Warm Phase of the ICM

If the soft excess emission originates from a warm phase of the ICM, the ratio of the emission integral of the hot ICM (Table 2) and the emission integral of the warm gas (Table 3) can be used to measure the relative mass of the two phases. The emission integral is defined as

\[ I = \int n^2 \, dV , \tag{1} \]

where \( n \) is the gas density and \( dV \) is the volume of the emitting region (Sarazin 1988). The emission integral is readily measured by fitting the X-ray spectrum.4

The emission integral of each quadrant determines the average density of the gas in that region, once the volume of the emitting region is specified (eq. (1)). Assuming that each quadrant corresponds to a sector of a spherical shell, the density in each sector can be calculated. The density of the warm gas ranges from \( 7 \times 10^{-5} \) to \( 10^{-4} \) cm\(^{-3} \), and the density of the hot gas varies from \( 1.5 \times 10^{-3} \) to \( 6 \times 10^{-5} \) cm\(^{-3} \).

We assume that both the warm gas and the hot gas are distributed in spherical shells of constant density. Since the emission integral is proportional to \( n^2 \, dV \) and the mass is proportional to \( n \, dV \), the ratio of the warm to hot gas mass is

\[ \frac{M_{\text{warm}}}{M_{\text{hot}}} = \frac{\int n_{\text{warm}} \, dV}{\int n_{\text{hot}} \, dV} = \frac{\int dI_{\text{warm}}/n_{\text{warm}}}{\int dI_{\text{hot}}/n_{\text{hot}}} . \tag{2} \]

We evaluate equation (2) by summing the values of \( I_{\text{hot}}/n_{\text{hot}} \) and \( I_{\text{warm}}/n_{\text{warm}} \) for all regions (Tables 2 and 3) and conclude that \( M_{\text{warm}}/M_{\text{hot}} = 0.75 \) within a radius of 2.6 Mpc.

5.2. Warm Filaments around the Coma Cluster

It is also possible that the warm gas is distributed in extended low-density filaments rather than being concentrated near the cluster center like the hot ICM. Recent large-scale hydrodynamic simulations (e.g., Cen et al. 2001; Davé et al. 2001; Cen & Ostriker 1999) indicate that this is the case and that 30%–40% of the present epoch’s baryons reside in these filamentary structures. Typical filaments feature a temperature of \( T \sim 10^4 \)–\( 10^7 \) K, consistent with our results in Table 3, and a density of \( 10^{-5} \) to \( 10^{-4} \) cm\(^{-3} \) ( overdensity of \( \delta \sim 50-500 \); Cen et al. 2001).

The ratio of mass in warm filaments to mass in the hot ICM is

\[ \frac{M_{\text{fil}}}{M_{\text{hot}}} = \frac{\int n_{\text{fil}} \, dV_{\text{fil}}}{\int n_{\text{hot}} \, dV} = \frac{\int dI_{\text{warm}}/n_{\text{fil}}}{\int dI_{\text{hot}}/n_{\text{hot}}} . \tag{3} \]

Assuming a filament density of \( n_{\text{fil}} = 10^{-4} \) cm\(^{-3} \), equation (3) yields the conclusion that \( M_{\text{fil}}/M_{\text{hot}} = 3 \) within a radius of 2.6 Mpc; the ratio will be even larger if the filaments are less dense. The warm gas is therefore more massive than the hot ICM if it is distributed in low-density filaments. More

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4 See description of XSPEC MEKAL model at http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/manual.html.
detailed mass estimates require precise knowledge of the spatial distribution of the filaments.

6. CONCLUSIONS

The analysis of deep PSPC data of the Coma Cluster reveals a large-scale halo of soft excess radiation, considerably more extended than previously thought. The PSPC data indicate that the excess emission is due to warm gas at $T \sim 10^6$ K, which may exist either as a second phase of the ICM or in diffuse filaments outside the cluster. Evidence in favor of the latter scenario is provided by the fact that the spatial extent of the soft excess emission is significantly greater than that of the hot ICM.

The total mass of the Coma Cluster within 14 Mpc is $(1.6 \pm 0.4) \times 10^{15} M_\odot$ (Geller, Diaferio, & Kurtz 1999). The mass of the hot ICM is $\sim 4.3 \times 10^{14} M_\odot$ within 2.6 Mpc (Mohr, Mathiesen, & Evrard 1999). The present detection of soft excess emission out to a distance of 2.6 Mpc from the cluster’s center implies that the warm gas has a mass of at least $3 \times 10^{14} M_\odot$, or considerably larger if the gas is in very low density filaments. The PSPC data presented in this paper therefore lend observational support to the current theories of large-scale formation and evolution (e.g., Cen & Ostriker 1999), which predict that a large fraction of the current epoch’s baryons are in a diffuse warm phase of the intergalactic medium.

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