THERMAL AND NONTHERMAL NATURE OF THE SOFT EXCESS EMISSION FROM SÉRSIC 159-03 OBSERVED WITH XMM-NEWTON

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ABSTRACT

Several nearby clusters exhibit an excess of soft X-ray radiation that cannot be attributed to the hot virialized intracluster medium. There is no consensus to date on the origin of the excess emission: it could be either of thermal origin or due to an inverse Compton scattering of the cosmic microwave background. Using high-resolution XMM-Newton data of Sérésic 159-03 we first show that strong soft excess emission is detected out to a radial distance of 0.9 Mpc. The data are interpreted using the two viable models available, i.e., by invoking either a warm reservoir of thermal gas or relativistic electrons that are part of a cosmic-ray population. The thermal interpretation of the excess emission, slightly favored by the goodness-of-fit analysis, indicates that the warm gas responsible for the emission is high in mass and low in metallicity.

Subject headings: large-scale structure of universe — X-rays: galaxies: clusters — X-rays: individual (Sérsic 159-03)

Online material: color figures

1. INTRODUCTION

Galaxy clusters often feature an excess of soft X-ray radiation above the contribution from the hot intracluster medium (ICM), known as the “cluster soft excess” phenomenon. Among the clusters that display this phenomenon is Sérsic 159-03, whose soft excess was initially discovered from ROSAT PSPC data by Bonamente et al. (2001) and later confirmed by an earlier XMM-Newton observation by Kaastra et al. (2003); the Sérsic 159-03 excess is one of the strongest observed to date. In this paper we analyze a deep (122 ks) XMM-Newton observation of this cluster. This is the highest signal-to-noise ratio (S/N) observation of a soft excess cluster to date, and we use these data for the first time to confirm the earlier detections and to determine the presence and characteristics of the soft excess. In a companion paper (Mittaz et al. 2005) we use the XMM-Newton data of this and other clusters to investigate the presence of O vii lines associated with the soft excess.

The origin of the soft excess emission in galaxy clusters is still uncertain. There is increasing evidence in favor of a thermal origin of the soft excess, especially since the report of O vii emission lines associated with the soft excess of a few clusters observed by XMM-Newton (Kaastra et al. 2003). Also possible is a nonthermal origin of the phenomenon, which requires the widespread presence of relativistic electrons that scatter the cosmic microwave background (Hwang 1997; Sarazin & Lieu 1998; Lieu et al. 1999; Bonamente et al. 2001).

This paper is structured in the following way. In § 2 we describe the XMM-Newton data of Sérsic 159-03, with emphasis on the performance of the low-energy \( E < 2 \text{ keV} \) response of the EPIC instruments. For this purpose we also analyze an XMM-Newton observation of PKS 2155–304, which we use as a calibration target. In § 3 we establish the presence of the soft excess emission in our XMM-Newton data and provide the thermal and nonthermal modeling. In §§ 4 and 5 we discuss the physical interpretation of the thermal and nonthermal models, comparing our results with the large-scale simulations of Cen & Ostriker (1999) and Cheng et al. (2005). In § 6 we summarize our results and indicate that the thermal scenario is the favored interpretation of these data. Finally, in § 7 we compare our results with earlier works on Sérésic 159-03.

Throughout the paper we assume a Hubble constant of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and an \( \Omega = 1, \Omega_m = 0.27, \) and \( \Omega_b = 0.05 \) cosmology. At the source’s redshift of \( z = 0.058 \), 1′′ corresponds to 72 kpc. All quoted uncertainties are at 90% confidence unless otherwise specified.

2. XMM-NEWTON DATA FROM SÉRSIC 159-03

2.1. Data and Data Reduction

Sérsic 159-03 was observed by XMM-Newton on 2002 November 20–21 for 122 ks (the observation ID was 0147800101). The observation collected data with the EPIC imaging spectrometers (MOS1, MOS2, and pn) using the thin filter.

The data were reduced using the SAS software provided by the XMM-Newton team following the standard procedure: the EPIC pipelines were run on the raw data to apply the most current calibration information, which is available through the CCF files also provided by the XMM-Newton calibration team. For the MOS detectors (MOS1 and MOS2), events were selected having pattern \( \leq 12 \) and flag \( = 0 \). For pn, we selected events with pattern \( = 0 \) and flag \( = 0 \). This is the same selection as that in Kaastra et al. (2003).

2.2. Time-variable Particle Background

The EPIC background comprises a variable component due to soft protons, which is sometimes enhanced by orders of magnitude over the quiescent rate. The energy band above \( \sim 10 \text{ keV} \) is dominated by this radiation and can therefore be used to monitor the presence of such particle background “flares” (e.g., Arnaud et al. 2001; Lumb et al. 2002; Nevalainen et al. 2003).
We extract light curves from our Sérsic 159-03 observation at energies ≥9.5 keV (MOS) and ≥10 keV (pn) and discard those time intervals for which the count rate exceeds the quiescent count rate.

The threshold levels for rejection were set, respectively, to 108 and 112 counts (500 s)\(^{-1}\) for MOS1 and MOS2 and 168 counts (500 s)\(^{-1}\) for pn, similar to the levels of Kaaret et al. (2003). This reduction process leaves, respectively, 69, 67, and 64 ks of clean data for MOS1, MOS2, and pn.

2.3. Background Subtraction

We use the background event files provided by the XMM-Newton Science Operation Center for the purpose of background subtraction (Lumb et al. 2002). This is a collection of eight blank-sky fields at high Galactic latitude, which we filtered using the same criteria as for the cluster field. In so doing, we ensured that the soft proton background (see § 2.2) was correctly subtracted. The cosmic X-ray background, however, is the dominant background component at the low energies (\(E < 1\) keV) at which the cluster soft excess radiation is present. This photon component of the background features sky variations (~35% at ~0.25 keV, Snowden et al. 1998; Kaaret et al. 2003), which need to be accounted for when establishing the presence of the soft excess emission.

The XMM-Newton detectors cover an area of ~14' radius (~1 Mpc) and therefore cannot be used to investigate the cosmic X-ray background in the neighborhood of Sérsic 159-03. For this purpose, we analyze a ROSAT pointed observation of the cluster, covering an area of ~1° radius (~4.3 Mpc). This is the same observation in which we initially discovered the soft excess emission of Sérsic 159-03 (Bonamente et al. 2001). The radial profiles of the X-ray emission in the R2, R4, and R7 bands (respectively, ~0.25, ~0.75, and ~1.5 keV) are shown in Figure 1. The figure clearly indicates that the R2-, R4-, and R7-band surface brightness profiles reach a constant value at ~12' radius from the cluster’s center. The emission in all PSPC bands remains at a constant level out to the limiting radius of the PSPC detector.

On larger scales, a low-resolution measurement of the local soft X-ray background is available through the ROSAT All Sky Survey (RASS) maps (Snowden et al. 1998). We obtain RASS images around Sérsic 159-03 and around the eight pointings that constitute the XMM-Newton background through the NASA/Chandra X-ray Center Skyview facility. We use the R12- and R45-band images\(^5\) that cover the \(E \leq 1\) keV band, where the soft excess is strongest, and observe that the 1° region around Sérsic 159-03 features a soft X-ray background, ~20% higher than that of the Lumb et al. (2002) background fields in both R12 and R45 bands (Table 1), and we find no indication of a spatial gradient in the R12- and R45-band emission. The 0–1° region is clearly affected by the diffuse cluster emission, which is included in the RASS maps.

The analysis of the ROSAT data around Sérsic 159-03 indicates that the cluster’s soft emission reaches the background level at a distance of ~12' from the cluster’s center. The available data cannot be used to determine the nature of the ~20% enhancement of the background near Sérsic 159-03 with respect to the background fields of Lumb et al. (2002). For that purpose, spectroscopic observations that measure the redshift of the background emission with a resolution of a few electron volts are needed. Observations with this resolution will become available with ASTRO-E2. The enhancement is likely of local (Galactic) origin, although large-scale emission at the cluster’s redshift cannot be ruled out.

In this paper we follow a conservative approach and assume that the enhancement in the background is entirely of local origin. We therefore use the 12°–14° XMM-Newton data to model this background enhancement and then subtract this additional background component from the Sérsic 159-03 spectra. This method is equivalent to that of Mittaz et al. (2005), in which we use XMM-Newton data to investigate in more detail the presence of O vii and O viii emission lines in the soft excess spectra of a few galaxy clusters, including Sérsic 159-03. Kaaret et al. (2003) followed a different approach and opted to use the background fields of Lumb et al. (2002), with the addition of a systematic error in an effort to account for possible variations of the soft X-ray background. Our choice to use the 12°–14° region to estimate the local soft X-ray background results in no detection of O vii emission lines from Sérsic 159-03. This conclusion is evident in the 4°–6° spectrum of Sérsic 159-03 (Fig. 2), which shows no evidence of an emission feature at \(E \sim 0.5\) keV. Similar results apply to the 6°–9° and 9°–12° annuli. Further details on the presence of emission lines associated with the soft excess can be found in Mittaz et al. (2005).

2.4. Assessment of EPIC’s Soft X-Ray Calibration

We limit our analysis to the 0.3–7 keV energy range, where the accuracy of the EPIC effective area calibration is \(\leq 10\%\).

### Table 1

| Field | 0°–1° | 1°–2° | 2°–5° | 5°–10 |
|-------|-------|-------|-------|------|
| R12   | 0.19  | 0.14  | 0.15  | 0.19 |
| Average background | 0.11  | 0.11  | 0.11  | 0.11 |

Notes.—Fluxes are in units of \(10^{-13}\) counts s\(^{-1}\) arcmin\(^{-2}\). The resolution of the RASS maps are ~40', so that the central 1° region of the Sérsic 159-03 observation is affected by the hot ICM emission.

\(^{5}\) RASS bands R12 and R45 are similar to bands R2 and R4, respectively, of the pointed ROSAT data.

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**Fig. 1.** —Radial profiles of the ROSAT PSPC surface brightness. In black the R2-band emission, in medium gray the R4 band, and in light gray the R7 band. Dotted lines are the best-fit constant model to the 20'–55' data. [See the electronic edition of the Journal for a color version of this figure.]
We assess directly the soft calibration of the EPIC detectors by analyzing the XMM-Newton observation of PKS 2155−304, a bright BL Lac source observed with the thin filter for 58.5 ks (observation ID 0080940301). The observation, reduced following the same steps as the cluster observation, features, respectively, 24 and 33 ks of useful MOS2 and pn data (MOS1 was used in timing mode). This observation was affected by event pile-up near the detector aim-point position. In order to eliminate this unwanted effect, our spectra were extracted from an annular region that excludes the aim point. This choice renders our data free of pile-up events.

BL Lac objects are variable, and their X-ray spectra are generally well fit by power-law models (e.g., Ravasio et al. 2002; Wolter et al. 1998). A spectral break is sometimes needed to account for spectral curvature (e.g., Perri et al. 2003; Chiappetti et al. 1999).

We fit the PKS 2155−304 data in the same way in which we will subsequently fit the cluster data. We fit jointly the MOS and pn spectra after ascertaining that the individual spectra are consistent with one another. Spectra were binned with a minimum of 25 counts channel$^{-1}$. First, we fit the full 0.3−7 keV range with an absorbed power-law model, fixing the $N_{\text{H}}$ column density at the Galactic value of $1.36 \pm 0.10 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The model fits the data well, and the low-energy residuals are ≤5% (Fig. 3, top). We then fit the same model to the 2−7 keV data. In Table 2 we show the results of the fits: the two fitting methods yield consistent results, indicating that the source follows a simple power law in the selected energy range, as is already known from a previous study (Kaastra et al. 2003). We now extrapolate the best-fit 2−7 keV model down to 0.3 keV in order to investigate the low-energy residuals. The average residuals in the 0.3−1 keV band are, respectively, +5% and +6% for MOS2 and pn, as shown in Figure 3 (bottom), with deviations of less than ∼10%. We therefore conclude that the level of systematic uncertainties of the EPIC detectors at $E < 1$ keV is less than 10% and that cluster soft excess fluxes in this band are real when they exceed that value. A steep power-law model like that of PKS 2155−304 exaggerates any positive low-energy residuals relative to a thermal cluster spectrum, thereby providing a conservative test of the low-energy calibration. A difference by a few percent in the 0.3−1 keV soft excess fluxes of MOS and pn is also within the calibration uncertainties.

\begin{table}[h]
\centering
\caption{XMM-Newton Observation of the Calibration Source PKS 2155−304}
\begin{tabular}{|c|c|c|c|}
\hline
$\alpha$ & Normalization & Normalization & $\chi^2$ \\
MOS2 Data & pn Data & (dof) & \\
\hline
\hline
0.3−7 keV Fit & 2.793 ± 0.004 & 0.0341 ± 0.0001 & 0.0248 ± 0.0001 & 1.23 (1085) \\
\hline
2−7 keV Fit & 2.760 ± 0.030 & 0.033 ± 0.001 & 0.024 ± 0.001 & 1.03 (626) \\
\hline
\end{tabular}
\end{table}

\textit{Note.—} The normalization constant of the power-law model is in the XSPEC customary units.
Alternatively, we fit the 0.3–7 keV spectra with a power-law model of a variable absorbing column. The resulting power-law index is consistent with the numbers in Table 2, and the best-fit column density is consistent with the Galactic value. This finding indicates that the apparent deficit in the absorbing column seen in this cluster (§3.2) and in others (Kaasstra et al. 2003) is not an artifact due to calibration uncertainties but the result of a genuine excess of soft photons.

3. PRESENCE OF SOFT X-RAY EXCESS EMISSION IN THE EPIC DATA OF SÉRISIC 159-03

3.1. Spectral Extraction and Fitting

We extracted spectra in eight annuli of outer radii 1', 2', 3', 4', 6', 9', 12', and 14'. We used the outermost annulus (12'-14') only for the purpose of obtaining a model of the local soft X-ray background, as described in §2.3. Spectra were extracted in 15 eV bins and then rebinned to ensure that at least 25 counts were present in each bin. We used the XSPEC software for the spectral analysis, while the optically thin thermal model used MEKAL, and the Galactic absorption cross sections were those of Morrison & McCammon (1983). The absorption column was fixed at the Galactic value (1.8 x 10²⁰ cm⁻²; Dickey & Lockman 1990), except in one case explicitly discussed in §3.2. We fit jointly the MOS1, MOS2, and pn spectra, enforcing the same normalization constants between the MOS1 and MOS2 spectra and allowing the pn spectrum to have a separate normalization. We use the 0.3–7 keV energy range in the spectral fitting.

3.2. Simple Models of the Sérsic 159-03 Spectra

3.2.1. One-Temperature Model with Central “Cooling” Gas

First, we attempt to fit the 0.3–7 keV spectra with a simple thermal model. The innermost regions of Sérsic 159-03 host cooler gas, due to the cooling of the hot ICM. Earlier XMM-Newton observations (Kaasstra et al. 2001, 2004b; Peterson et al. 2003) revealed that the cooler gas in Sérsic 159-03 is confined to the central 2'. We account for this cooler gas as in Kaasstra et al. (2003), i.e., by adding a second phase at 2/3 the temperature of the hot ICM in the innermost two annuli (0'-1' and 1'-2' radius). This simple model fails to describe the data accurately and results in very steep temperature and abundance gradients (see Fig. 4). A steep temperature profile was also found in an earlier XMM-Newton observation of Sérsic 159-03 by Kaasstra et al. (2001), where the spectra were fitted to a similar one-temperature model. In the top panels of Figures 5 and 6 we show the residuals from the best-fit one-temperature model for two representative annuli. The residuals exceed the ±5% level seen in the case of the calibration target PKS 2155–304 (Fig. 3) and follow large-scale trends such as a negative deviations between 1.2 and 3 keV and positive deviations at low and high energies, which are especially evident in the higher quality pn data (Figs. 5 and 6, light gray). This behavior indicates the need for an additional spectral component, as will be discussed in §3.3.

Alternatively, we tried to account for cooler gas in the central regions using a classical cooling flow model by fitting the 0.3–7 keV spectra of the inner annuli with a one-temperature thermal model plus a cooling flow model. The fits are not acceptable and have the same goodness-of-fit as those obtained using the one-temperature thermal model plus the additional phase at 2/3 the temperature described above in this section.

3.2.2. One-Temperature Model with Central “Cooling” Gas and with Variable N_H

We investigate the possibility of modeling the Sérsic 159-03 spectra with the same one-temperature thermal model discussed in §3.2.1, but with the absorption column density as a free parameter. Although the best-fit χ² statistic improves, the fit is physically unacceptable, as the best-fit absorption column is

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7 See Bonamente et al. (2001) for discussion on the available cross section compilations.
Fig. 5.—Residuals of the (top) one-temperature model of $\S$ 3.2.1, (middle) two-temperature model of $\S$ 3.3.1, and (bottom) nonthermal model of $\S$ 3.3.2 for the 1$''$–2$''$ annulus. In black and medium gray are the MOS1 and MOS2 data, and in light gray the pn data. For clarity, after the fit the residuals were rebinned to achieve an $S/N = 30$. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 6.—Same as Fig. 5, but for the 2$''$–4$''$ annulus. [See the electronic edition of the Journal for a color version of this figure.]
significantly sub-Galactic (Fig. 7). The best-fit $N_H$ is consistent with null Galactic absorption in certain annuli. A similar result was found in the data of the Coma Cluster (Bonamente et al. 2003), as well as of several other clusters observed by Kaastra et al. (2003), and is indicative of an excess of soft X-ray radiation with respect to this simple one-temperature, hot ICM model.

3.2.3. One-Temperature Model Fit to the 2–7 keV Band

Next, we discard the low-energy portion of the spectra ($E < 2$ keV) from the fit and fit the 2–7 keV data to the simple one-temperature thermal model. In this case, we are no longer sensitive to the presence of the central cooling gas, and we drop the additional thermal model (at 2° of the temperature of the hot plasma) from the 0′−1′ and 1′−2′ annuli. The results are now statistically acceptable, and the radial profiles of temperature and abundance are less steep than in the case of the 0.3–7 keV fit discussed above (Fig. 4). In order to assess the presence of the soft excess emission, we extrapolate this best-fit hot ICM model at lower energies in the same way as we did for the calibration source PKS 2155–304. Strong soft excess emission is found in all annuli, as shown in Figure 2 for the 4′−6′ region. In Figures 8 and 9 we show the fractional excess in the 0.3–1 keV band, defined as $\eta = (O - P)/P$, where $O$ is the observed soft flux and $P$ is the prediction from the hot ICM model. The soft excess exceeds...
the level of the calibration uncertainties (see § 2.4), and it is therefore due to a genuine excess of soft X-ray radiation with respect to the 2–7 keV thermal model. It is important to stress that this model is not used to measure the soft excess flux but only to establish the presence of an excess emission at low energy that cannot be attributed to calibration uncertainties. Soft excess fluxes will be measured by the models of § 3.3. In fitting the 2–7 keV band alone we have ignored the Fe-L complex, which is an important temperature diagnostic of the X-ray spectra. This model is also presented for the sake of comparison with earlier results, e.g., those of Nevalainen et al. (2003), in which the authors fit the 2–7 keV XMM-Newton spectra of A3112, A1795, and the Coma Cluster and found a fractional excess \( \eta \approx 10\%–40\% \) (see Figs. 4 and 5 of Nevalainen et al. 2003).

### 3.3. More Complex Models of the Sérsic 159-03 Spectra

Having established the presence of an extra soft component in the XMM-Newton spectra of Sérsic 159-03, we employ an additional component in the spectral fitting in order to account for the excess emission.

#### 3.3.1. Two-Temperature Model with Central “Cooling” Gas

First, we consider a two-temperature model in which both the hot ICM temperature and the warm gas temperature are free parameters. In the innermost two annuli the hot thermal component features a \( kT_{\text{hot}}/2 \) subcomponent, as described in § 3.2.1. This model constitutes a significant statistical improvement over the simple one-temperature model (see Fig. 4). The residuals of the two-temperature model are now consistent with the level of the calibration uncertainties and are shown in the middle panels of Figures 5 and 6 for two representative annuli. The additional thermal component features a temperature of \( kT_{\text{warm}} \approx 0.2–0.8 \) keV and abundances of \( \leq 0.1 \) solar (Fig. 10). The abundance and temperature of the warm phase are correlated parameters. In Figure 11 we plot the confidence contours of the two parameters for the 4–6' region, showing how the XMM-Newton data can constrain the physical properties of the warm plasma model. Similar results apply to the other regions. It is also clear from the radial distribution of the emission integral (integrated power-law component). In Figure 12 we show the radial profiles of the power-law index of the power-law component.

#### 3.3.2. One-Temperature Model with Central “Cooling” Gas Plus Power-Law Model

We then consider a one-temperature model plus a power-law component. This model is again an improvement over the simple one-temperature model, and the \( \chi^2 \) fit statistic indicates that the two-temperature model is only marginally preferred to this non-thermal model (Fig. 4). The residuals of this nonthermal model are shown in the bottom panels of Figures 5 and 6 for two representative annuli. In Figure 13 we show the radial profiles of the power-law index of the power-law component.

### 4. THERMAL INTERPRETATION OF THE SOFT EXCESS EMISSION

The two-temperature model discussed in § 3.3.1 provides the most satisfactory fit to the 0.3–7 keV spectra. In the following we provide the physical interpretation of the thermal modeling of the soft excess emission, discussing two possible scenarios.

#### 4.1. Clumpy Warm Intracluster Gas à la Cheng et al. (2005)

The warm gas responsible for the soft excess may be in a high-density \( (\sim 10^{-2} \) to \( 10^{-3} \) cm\(^{-3}\)) and clumpy intracluster...
phase with volume filling factor \( f \ll 1 \). This is the scenario that results from the simulations of Cheng et al. (2005), in which a small fraction of the intracluster gas remains at low temperature and high density during the accretion process. This phase of the ICM is able to reproduce quantitatively the typical soft excess emission detected in several clusters (e.g., Bonamente et al. 2002).

We provide an estimate of the warm gas mass, assuming that the warm gas is in pressure equilibrium with the hot gas. First, we deproject the emission integral \( I_{\text{hot}} = \int n_{\text{hot}}^2 dV \) of the hot phase (Fig. 12) to obtain the hot gas density (Fig. 14). Our results for the hot gas density are in very good agreement with those from an earlier XMM-Newton observation by Kaastra et al. (2001). The warm gas density is then calculated assuming pressure equilibrium, \( n_{\text{warm}} = (kT_{\text{hot}}/kT_{\text{warm}})n_{\text{hot}} \), and it is in the \( 10^{-2} \) to \( 10^{-3} \) cm\(^{-3} \) range. Using the measured emission integral of the warm phase, defined as \( I_{\text{warm}} = \int n_{\text{warm}}^2 dV \), we estimate the volume filling factor \( f \) and hence the warm gas mass. The volume filling factor is of a few percent (\( f \approx 0.01-0.1 \)) and the total warm gas mass is \( M_{\text{warm}} \approx 3 \times 10^{12} M_\odot \) from MOS and \( (2.7^{+0.4}_{-0.5}) \times 10^{12} M_\odot \) from pn data. For comparison, the hot gas mass is \( M_{\text{hot}} \approx 1.2 \times 10^{13} M_\odot \) from MOS and \( (1.3 \pm 0.2) \times 10^{13} M_\odot \) from pn data. Reiprich & Boehringer (2002) measure a total gravitational mass of \( M = 1.8 \times 10^{14} M_\odot \) out to the same radius of our analysis (0.9 Mpc), resulting in a gas mass fraction of \( f_{\text{gas}} \approx 0.07 \). If the excess emission follows the simple model presented in this section, the warm gas will contribute an additional \( \sim 25\% \) of the total baryonic mass. The cooling time of the warm gas is shorter than the Hubble time at all radii, and the replenishment of the warm gas becomes a dynamical phenomenon.
For comparison with the soft excess of the Coma Cluster (Bonamente et al. 2003) we also estimate the warm gas mass in the case of an intracluster phase with volume filling factor \( f = 1.0 \). In this case, the warm gas would not be in pressure equilibrium with the hot gas, and it would have a total mass of \( M_{\text{warm}} \sim 9 \times 10^{13} \, M_{\odot} \), \((9 \pm 2) \times 10^{13} \, M_{\odot}\) from MOS and \((9 \pm 2) \times 10^{13} \, M_{\odot}\) from pn data. This result is similar to that of Coma, for which a value of \( f = 1.0 \) warm gas yielded \( M_{\text{warm}}/M_{\text{hot}} \sim 0.7 \) (Bonamente et al. 2003).

If the soft excess emission is indeed clumpy, as described by the Cheng et al. (2005) model, significant azimuthal variations of the excess could be present. In order to test the presence of azimuthal variations of the soft emitter, we divided the two annuli with the highest quality data (4–6′ and 6–9′) into quadrants and applied to them the analysis described in § 3.2.3 to measure the fractional excess in the 0.3–1 keV band. In Figure 15 we plot the fractional excess detected in each quadrant, normalized by the average fractional excess in that annulus. A value of \( \psi(\eta) = 1 \) indicates that in that sector, the soft excess is consistent with the azimuthal average, and a value of \( \psi(\eta) = 0 \) indicates no excess. In black and medium gray are the MOS1 and MOS2 data, and in light gray the pn data. [See the electronic edition of the Journal for a color version of this figure.]

4.2. Warm Intergalactic Gas a` la Cen & Ostriker (1999)

Alternatively, the warm gas may be located in a diffuse halo or filaments around the cluster, not in direct contact with the hot ICM and extending beyond the cluster’s virial radius.

We assume that the detected warm emission resides in filaments of constant density \( n_{\text{fl}} \). In this case, the emission integral of each annulus becomes

\[
I_{\text{warm}} = \int n_{\text{fl}}^2 A \, dL,
\]

where \( dV = A \, dL \) is the volume of the filament, \( A \) is the area of each annulus, and \( L \) is the length of the filament along the line of sight. From the measured emission integral we cannot, at the same time, determine the density and the length of the filament. If we assume that \( n_{\text{fl}} = 10^{-4} \, \text{cm}^{-3} \), corresponding to a baryon overdensity of \( \delta \sim 300 \), we can measure the filament length and mass implied by this model. The filaments would be as long as an improbable few hundred megaparsecs (Fig. 16), and the total filament mass would be \( M_{\text{fil}} \sim 7.5 \times 10^{13} \, M_{\odot} \), \((6.6 \pm 1.4) \times 10^{13} \, M_{\odot}\) from MOS and \((8.4 \pm 1.3) \times 10^{13} \, M_{\odot}\) from pn data], resulting in a filament-to-hot gas mass ratio of \( M_{\text{fil}}/M_{\text{hot}} \sim 6 \) \((5.5 \pm 1.3) \) from MOS data and \(6.4 \pm 1.4\) from pn data]. If the filaments were less dense, then the length and mass estimates would increase; in fact, \( L \propto n_{\text{fl}}^{-2} \) and \( M_{\text{fil}}/M_{\text{hot}} \propto n_{\text{fl}}^{-1} \) for a given emission integral \( I_{\text{warm}} \). These results are again similar to those of the Coma Cluster, for which \( M_{\text{fil}}/M_{\text{hot}} \sim 3 \) (Bonamente et al. 2003). Similar models for the excess emission, based on a diffuse halo of warm gas, were described in Kaastra et al. (2004a) and Lieu & Mittaz (2004). One can derive similar results for the filament mass of this scenario by assuming that the filaments have a given size, instead of a given density, as assumed above. In this case, the large emission integral of the warm gas measured at small radii (Fig. 12) implies denser filaments toward the central cluster regions.

Mittaz et al. (2004) investigated whether the soft excess emission could be quantitatively explained by the large-scale filaments seen in the simulations of Cen & Ostriker (1999), Cen et al. (2001), and Davé et al. (2001). The emission from filaments around the simulated clusters was a few orders of magnitude below the level needed to explain the typical soft excess emission, such as that of Sérsic 159-03, for example. We therefore warn the reader that those simulations are not in quantitative agreement with the soft excess measured in Sérsic 159-03 and in other clusters.

Other simulations by Fang et al. (2002) also find that a large fraction of baryons is in a warm filamentary phase of the intergalactic medium. If the excess emission of Sérsic 159-03 is due to the filaments model described in this section, the excess implies \( H \perp \) column densities \( N_{\text{HI}} > 10^{21} \, \text{cm}^{-2} \), as shown in Figure 17. The associated O \( \perp \) and O \( \parallel \) column density depends on the exact ionization structure of the gas: assuming a ionization fraction of \( \sim 10\% \), which is valid for a gas in collisional equilibrium at \( kT \sim 0.3 \, \text{keV} \) (e.g., Fang et al. 2002), and an average metal abundance of 5% solar (see § 3.3), the O \( \perp \) and O \( \parallel \) column densities implied by the excess emission of Sérsic 159-03 are...
4.3. Discussion of Thermal Interpretation

The first thermal scenario (§ 4.1) is preferred to the second (§ 4.2), given that the calculations of Mittaz et al. (2004) show no quantitative agreement between the measured soft excess and the simulation predictions. In the case of a clumpy intracluster gas à la Cheng et al. (2005), a shorter-than-Hubble cooling time is an inherent feature of the model, and the soft excess emission is a dynamical phenomenon. The filaments à la Cen & Ostriker (1999) discussed in § 4.2 would be as long as several hundred megaparsecs, or even in excess of 1 Gpc if the filaments are less dense than \( n = 10^{-4} \) cm\(^{-3}\), in disagreement with the current observational and theoretical understanding of large-scale structures.

The total baryon content of clusters is a useful probe of cosmology. The thermal interpretation of the soft excess implies a warm gas mass that may be comparable to that of the hot ICM and therefore significant when evaluating the baryon mass in clusters. Allen et al. (2004) analyze a sample of clusters at \( z < 0.9 \) and find that the baryonic fraction in that sample is \( f \sim 0.12 \). In calculating the total baryonic mass, they account for the X-ray–emitting hot ICM and the luminous matter and use a bias factor \( b \) that accounts for the fact that the baryon fraction in clusters, as seen in simulations (Eke et al. 1998), is lower than for the universe as a whole by about 15%. They give constraints on \( \Omega_\Lambda \) and \( \Omega_m \) that are in agreement with other measurements (supernova Type Ia [SNIa] and cosmic microwave background [CMB] measurements). The soft excess emission in Sérsic 159-03 and in other clusters (e.g., Bonamente et al. 2002) may be indicative of a massive warm baryonic component in clusters. Given our mass estimates for the warm baryons provided in § 4, we envisage two possibilities that conciliate the thermal origin of the soft excess with the results of Allen et al. (2004): either the warm baryons have a mass of \( \leq 15\% \) of the hot gas mass or the warm gas, located in structures that are not virialized (e.g., the model in § 4.2), should not be counted as "cluster" baryons.

5. NONTHERMAL INTERPRETATION OF THE SOFT EXCESS EMISSION

Alternatively, the excess emission may be nonthermal in nature. In this section we investigate the physical interpretation of the nonthermal modeling of § 3.3.

5.1. IC Scattering of Relativistic \( e^- \) off the CMB

A population of relativistic electrons in the cluster would scatter the CMB and give rise to soft X-ray radiation via an inverse Compton scattering (e.g., Hwang 1997; Sarazin & Lieu 1998; Lieu et al. 1999). A relativistic electron with a Lorentz factor \( \gamma \) will upscatter a CMB photon to an energy of

\[
E = 75 \left( \frac{\gamma}{300} \right)^2 \text{ eV.}
\]

Electrons with \( \gamma = 600–1500 \) are needed to generate soft excess photons in the 0.3–2 keV band.

Relativistic electrons in clusters may be generated by diffusive shock acceleration. The acceleration produces a power-law distributed population of electrons, which, upon scattering with the CMB photons, creates a power-law radiation spectrum (Rybicki & Lightman 1979). The relationship between the two power-law indices is

\[
\mu = -1 + 2\alpha,
\]

where \( \mu \) is index of the differential number electron distribution and \( \alpha \) is the differential photon number index. Typically observed for Galactic cosmic-ray electrons is an index \( \mu \sim 2.7 \), corresponding to \( \alpha \sim 1.85 \). Relativistic electrons undergo Coulomb losses at low energies and radiative losses at higher energies. In the \( \gamma = 600–1500 \) regime (where \( \gamma \) is the electron Lorentz factor) and for typical cluster conditions, radiative losses will steepen the electron spectrum in a few times \( 10^9 \) yr since acceleration (Lieu et al. 1999; Ip & Axford 1985). The results of Figure 13 show a power-law index \( \alpha \geq 2 \). This indicates that if the soft excess is of cosmic-ray origin, the electron population would have been injected in the cluster environment a few times \( 10^9 \) yr ago.

The modelling of § 3.3 yields the luminosity of the power-law component, which can then be used to determine the energy of the underlying electron population (Lieu et al. 1999) via

\[
E_e = 8 \times 10^{42} L_{42} \left( \frac{3 - \mu}{2 - \mu} \right) \frac{\gamma_{\text{min}}^{2-\mu}}{\gamma_{\text{max}}^{2-\mu} - \gamma_{\text{min}}^{2-\mu}} \text{ ergs,}
\]

where \( L_{42} \) is the luminosity of the nonthermal radiation in units of \( 10^{42} \) erg s\(^{-1}\) and \( \gamma_{\text{min}} \) and \( \gamma_{\text{max}} \) are the Lorentz factors corresponding to the boundaries of the XMM-Newton data (0.3–7 keV). From this one can calculate the electron pressure \( P = E_e / 3V \) and compare it with the hot ICM pressure. The results are shown in Figure 18, and they indicate that the nonthermal electron pressure is a few percent of the thermal pressure at all radii.

5.2. Discussion of the Nonthermal Interpretation

If the soft excess is of nonthermal nature, relativistic electrons must be present throughout the central 1 Mpc radius of Sérsic 159-03. The cluster has no known signature of nonthermal activity (e.g., no detected radio halo or strong radio sources). It is possible, however, that nonthermal activity may have occurred in the past. The steeper-than-Galactic power-law indices indicate an aging of the nonthermal population.

---

\(^8\) This calculation assumes an oxygen abundance of \( 8.5 \times 10^{-4} \) relative to the hydrogen number density and oscillator frequencies of 0.696 and 0.416 for the O\( \text{\textsc{vi}} \) and O\( \text{\textsc{vii}} \) absorption lines (e.g., Fang et al. 2002).
The presence of relativistic particles at a distance of ~1 Mpc from the cluster center is challenging. In fact, the Bohm diffusion time for relativistic electrons exceeds a Hubble time in the typical cluster environment (Volk et al. 1996). The widespread presence of relativistic particles would require several sites of local acceleration or alternative means of transport from the acceleration site to roughly megaparsec distances. The acceleration could be provided by several shocks (e.g., accretion shocks) or, alternatively, by AGN jets, of which we have no evidence at present. Diffuse shocks accelerate ions as well as electrons (Bell 1978a, 1978b; Axford et al. 1977; Blandford & Ostriker 1978). The ions, due to their higher mass, do not emit effectively but will carry the bulk of the energy, exceeding the electron energy by a factor of ~20–50. This in turn implies that the estimates of Figure 18 will have to be increased by the same factor, with the relativistic particles now in approximate energy equipartition with the hot ICM pressure. This result was already noted in the Coma Cluster (Lieu et al. 1999) and in our previous study of Sérsic 159-03 with ROSAT data (Bonamente et al. 2001). With the current XMM-Newton data we have provided more precise estimates of the nonthermal pressure in Sérsic 159-03. The presence of relativistic ions can only be avoided if the electrons are accelerated by an alternative means that does not accelerate the ions, such as AGN electron/positron jets.

6. ORIGIN OF THE SOFT EXCESS EMISSION OF SÉRIS 159-03

The soft excess emission of Sérsic 159-03 is of genuine celestial origin. Knowledge of the XMM-Newton detectors and direct use of the calibration source PKS 2155–304 (§ 2.4) showed that the emission is not a detector artifact. Moreover, the emission cannot be the result of wrong assumptions concerning the H I Galactic absorbing column. In order to explain the excess emission, the Galactic column density is required to be more than 2 times lower than the measured Galactic value [(1.8 ± 0.1) × 10^20 cm^-2] and even lower than the Lockman Hole value (≈7 × 10^19 cm^-2) for certain annuli. Bregman et al. (2003) showed that anisotropies in the distribution of the H I column density toward galaxy clusters may affect the transmission of extragalactic soft X-ray radiation. Such an effect, however, is only relevant at energies $E < 0.3$ keV (e.g., Figs. 1 and 9 of Bregman et al. 2003), and it has no influence on the soft excess at $E = 0.3–2$ keV detected in this paper with XMM-Newton.

The thermal and nonthermal models examined in this paper constrain the nature of the soft excess emission from Sérsic 159-03. The formal $\chi^2$ goodness-of-fit statistic does not provide a definitive indication of the origin of the soft emission. The thermal scenario is only marginally favored over the nonthermal (Fig. 4), similarly to the case of the Coma Cluster (Bonamente et al. 2003). The large extent of the detected excess emission (~1 Mpc radius) renders unlikely a purely nonthermal interpretation of the excess, due to the long diffusion times of relativistic particles, which cannot easily diffuse throughout the entire cluster volume (see § 5).

The XMM-Newton data from Sérsic 159-03 indicate that warm gas located within the virial radius provides the bulk of the soft excess radiation. The gas may be in a clumpy phase of the ICM (§ 4.1), as advocated by the simulations of Cheng et al. (2005), with a mass of 25% of the hot gas mass. Although we do not confirm the direct detection of O V ii and O V iii emission lines associated with the excess emission, the warm gas emission is consistent with a metal abundance of a few percent solar. The soft emission is unlikely to originate from large-scale filaments à la Cen & Ostriker (1999), which would encompass a total mass in excess of that of the hot ICM.

It is possible that a fraction of the soft excess, especially in the central regions, is of nonthermal nature (§ 5). Although there is no evidence at present of nonthermal activity in Sérsic 159-03, past AGNs or diffusive shock acceleration may have fostered the presence of relativistic electrons in the cluster environment. Our calculations show that the relativistic particles would be near or below pressure equipartition with the hot gas.

7. COMPARISON WITH EARLIER OBSERVATIONS OF SÉRIS 159-03

The initial report of soft excess in Sérsic 159-03 was based on low-resolution ROSAT PSPC data (Bonamente et al. 2001). The ROSAT data were able to detect soft excess emission out to a radius of ~9'. The mass estimates for the warm intrachannel gas model had significantly larger errors but are in agreement with the present XMM-Newton results. The nonthermal fit results based on these earlier data have a power-law index that is significantly higher than that of the present analysis (see Table 2 of Bonamente et al. 2001). The reason is likely attributable to the narrower ROSAT band, and it is the cause of the higher nonthermal pressure estimates we obtained based on that observation.

The first XMM-Newton results on Sérsic 159-03 were based on an earlier ~30 ks observation and are described in Kaasstra et al. (2001). In that paper no attempt was made to detect or measure the soft excess, but the authors focused on the properties of the hot gas. Our estimates of the hot gas temperature, abundance and density are in good agreement with theirs (see Figs. 1–3 of Kaasstra et al. 2001).

Kaasstra et al. (2003) analyzed the same XMM-Newton observation as Kaasstra et al. (2001) in order to investigate the soft excess emission. They report the presence of soft excess emission out to a radius of ~12', in agreement with our present results. Their thermal and nonthermal models for the excess emission also indicate that the two models have similar goodness of fit in the central regions, in agreement with our present findings. The background subtraction technique they employ, however, differs from the one used in this paper in that we now use a local background. The different background subtraction is the reason for a variance with our results at large radii, e.g., their detection of O V ii emission lines associated with the soft excess emitter is not confirmed in our analysis (see § 2.3).
The same authors provide an estimate of the warm gas mass in Kaastra et al. (2004a), based on the same earlier XMM-Newton observation. Their warm gas estimate follows a model reminiscent of our warm intergalactic filaments à la Cen & Ostriker (1999). They assume a fiducial radius for the volume of the emission and estimate a constant density for the warm gas and find a warm gas mass of $\sim 6 \times 10^{14} M_\odot$ higher than our corresponding estimate by a factor of $\sim 10$. The difference can be explained by the simplifying assumptions of their model.

The properties of the central "cooling" gas of Sérsic 159-03 were also studied in detail by Kaastra et al. (2004b). They find that cooling gas is significantly present only at radii $<2''$. Our best-fit hot ICM temperatures are again in agreement with those of Kaastra et al. (2004b).

8. CONCLUSIONS

In this paper we have analyzed a high-S/N XMM-Newton observation of Sérsic 159-03 and provided a wide range of models for the soft excess emission. We employed a different method of background subtraction than the earlier XMM-Newton observations of Kaastra et al. (2003), which accounts for spatial variations of the soft X-ray background.

First, we showed that soft excess emission is strongly detected throughout a $\sim 1$ Mpc radius region, confirming earlier detections based on lower S/N data (Kaastra et al. 2003; Bonamente et al. 2001). We ruled out the possibility that the excess emission is caused by peculiarities in the absorbing column of Galactic gas or that the emission is an artifact of the XMM-Newton detectors.

We then investigated several thermal and nonthermal models in search of the origin of the soft excess emission. The thermal models assume the presence of warm ($\sim 10^6-10^7$ K) gas either intermixed with the hot gas or in diffuse structures extending beyond the cluster virial radius. The nonthermal model requires the widespread presence of relativistic electrons with Lorentz factor $\sim 1000$.

We calculated the density and mass budget for the thermal models and the pressure budget for the nonthermal model and concluded that the most likely interpretation for the soft excess emission of Sérsic 159-03 is warm gas located within the virial radius of the cluster, which contributes an additional 25% of the total cluster baryonic mass.

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