THE DIFFUSE SOFT EXCESS EMISSION IN THE COMA CLUSTER FROM THE ROSAT ALL-SKY SURVEY

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ABSTRACT

ROSAT All-Sky Survey (RASS) data near the North Galactic Pole was analyzed in order to study the large-scale distribution of soft X-ray emission from the Coma cluster. These ROSAT data constitute the only available X-ray observations of Coma that feature an in situ—temporally and spatially contiguous—background, with unlimited and continuous radial coverage. These unique characteristics of the RASS data are used to deliver a final assessment on whether the soft excess previously detected in the Coma cluster is due to background subtraction errors, or not. This paper confirms the presence of soft X-ray excess associated with Coma, and reports the detection of 1/4 keV band excess out to 5 Mpc from the cluster center, the largest soft excess halo discovered to date. We propose that the emission is related to filaments that converge toward Coma, and generated either by nonthermal radiation caused by accretion shocks, or by thermal emission from the filaments themselves.

Key words: galaxies: clusters: individual (Coma) – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

X-ray emission from galaxy clusters is due primarily to a hot virialized plasma at a temperature $kT \sim 10^7-10^8$ keV that fills the intracluster medium (ICM). Evidence for an additional emission component was initially discovered by Lieu et al. (1996a, 1996b) in the extreme ultraviolet ($h\nu \sim 0.1$ keV) with Extreme Ultraviolet Explorer (EUVE) observations of the Virgo and Coma clusters, and then confirmed with several other instruments, notably in the ROSAT 1/4 keV band (see Durret et al. 2008 for a recent review of the literature; detections in Coma include Bowyer et al. 1999, 2004; Finoguenov et al. 2003; Bonamente et al. 2003; Nevalainen et al. 2003). The excess emission is usually modeled as an additional thermal component of lower temperature ($kT \sim 10^4-10^5$ keV) or as a nonthermal power law. An additional thermal model may arise from cooler gas inside the cluster (Lieu et al. 1996b), possibly in pressure equilibrium as in the Cheng et al. (2005) model, or from warm filaments seen in projection toward clusters (e.g., Mittaz et al. 2004; Bonamente et al. 2005). A nonthermal power law is indicative of relativistic electrons that scatter the cosmic microwave background (CMB) photons and emit by Compton scattering (e.g., Sarazin & Lieu 1998; Lieu et al. 1999). Given the limited spectral resolution of the current CCD detector technology, it has not been possible to prove conclusively which additional model is a better fit to the data (see, e.g., Nevalainen et al. 2003; Bonamente et al. 2005; Werner et al. 2007).

In the main X-ray band ($0.5-10$ keV), cluster spectra in annular regions are typically well fitted by single-temperature models. Recently, it has become evident that the best-fit temperature of the hot plasma is band-dependent, with a trend of lower temperatures when lower energy bands are used in the fit (Nevalainen et al. 2003; Cavagnolo et al. 2008; Bonamente et al. 2007); this behavior is naturally explained by the presence of an additional soft component.

In the absence of conclusive spectral evidence on the origin of the excess emission, clues can be found from the spatial distribution of the excess. The excess emission typically increases with radius, with respect to the hot ICM (e.g., Lieu et al. 1999; Bonamente et al. 2001a), indicating that the excess component is likely unrelated to the hot ICM. Attempts at resolving the emission have so far been unsuccessful (e.g., Bonamente et al. 2003), and thus a truly diffuse origin for the excess emission is favored. To date, the excess emission was detected out to a maximum radius of 1.7 Mpc (Bonamente et al. 2003), and typically around $0.5-1$ Mpc; at these radii, the hot plasma has a density of $\sim 10^{-4}-10^{-5}$ cm$^{-3}$, and can support $\sim \mu$G magnetic fields that give rise to radio halos (e.g., Feretti et al. 2001; Brunetti et al. 2007; Clarke & Ensslin 2006). Therefore, a nonthermal origin of the excess can be justified.

Detection of the excess emission is particularly sensitive to the background subtraction process. The soft X-ray sky is known to have gradients on the scales of degrees (e.g., Snowden et al. 1997), requiring that the background is estimated from a region that is spatially contiguous to the cluster. Moreover, temporal variability can be induced by solar flares, which cause charge–exchange radiation that varies on timescales of hours; the most accurate background subtraction is therefore performed when a simultaneous background measurement is available, e.g., from peripheral regions of the detector. Such time- and space-contiguous background was used in the early EUVE and ROSAT works, thanks to the large field of view of those instruments. In the case of XMM-Newton and Chandra, the local background is only available for high-redshift clusters of smaller angular size. An incorrect background subtraction caused by time variability was shown by Takei et al. (2008) to be the reason for an earlier claim of detection of O VII emission lines associated with the soft excess emission. In the case of the Coma cluster, even the 1° radius of the PSPC emission is entirely filled by cluster emission, and therefore a time-contiguous background was not available in our earlier analysis based on pointed observation (Bonamente et al. 2003).

In this paper, we analyze ROSAT All-Sky Survey (RASS) data in the direction of the Coma cluster. Thanks to the all-sky nature of the observations, these data are the only observations of Coma to feature a background that is spatially and temporally contiguous, and with unlimited radial coverage. We therefore aim to show that excess emission is present when this local

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background is used, and determine the maximum radius of detection of the excess emission. This paper is structured in the following way. In Section 2, we describe the RASS data, the data analysis and the detection of the soft excess emission, in Section 3, we interpret the emission using thermal and nonthermal models, and in Section 4, we discuss our results and present our conclusions.

2. DATA REDUCTION AND ANALYSIS

2.1. The ROSAT All-Sky Survey Data

The angular resolution of the ROSAT X-ray telescope in combination with the PSPC camera is approximately 1.8 (50% encircled energy radius averaged over the field of view), and the energy resolution is approximately ΔE/E = 0.43(E/0.93 keV)^{−0.3} FWHM, corresponding to a ΔE ~ 0.2 keV in the 1/4 keV band, and ΔE ~ 0.5 keV at 1.5 keV. The field of view of PSPC is circular with approximately 1° radius. During the first year of operation, ROSAT performed an all-sky X-ray survey, which included an exposure of ~850 s in the direction of the Coma cluster (Briel et al. 1992). Snowden et al. (1997) analyzed the RASS and provided maps on the diffuse soft X-ray emission in seven bands (R1–R7), with linear pixel of size 12”. The R2 band is the softest band with reliable calibration (90% of peak response 0.14–0.284 keV), and band R7 (1.05–2.04 keV) is the highest energy band available with the PSPC detector.

The maps exclude bright pointlike sources identified from the RASS data themselves, using a flux threshold for which the RASS source catalog is complete over 90% of the sky. In the R1+R2 band, the flux threshold is 0.025 counts s^{−1}, and in the R6+R7 band it is 0.020 counts s^{−1} (Snowden et al. 1997). This choice resulted in the exclusion of the central pixel of the Coma cluster in the R2 band, which appears pointlike at the resolution of these data. The units of the emission maps are 10^{−6} PSPC counts s^{−1} arcmin^{−2} (a detector-specific measure of the intensity of radiation, proportional to the surface brightness), and take into account the effects of vignetting, different exposure times of a given sky region, detector artifacts, obscuration by the window support structure, and other efficiency variations. The maps of the diffuse emission are complemented by matching maps of the estimated uncertainty in the intensity, needed in order to determine the statistical significance of the emission above the local background (Snowden et al. 1997).3

These X-ray data represent a unique opportunity for the detection of diffuse emission associated with the Coma cluster. These are in fact the only observations that feature both a large radial coverage and a simultaneous background measurement. The latter feature is especially significant, in an effort to avoid background subtraction problems caused by the charge-exchange radiation induced by solar activity (Takei et al. 2008). Owing to the scanning mode in which ROSAT was operated during the survey, any enhancement caused by solar wind-induced emission will be present in both cluster and background regions. No other X-ray mission has performed a survey of the X-ray sky, or has a field of view, which covers such a large area of the sky. The pointed RASS observations of Coma, which we analyzed in a previous paper (Bonamente et al. 2003), covered only a region of 1° radius, and thus could not investigate the emission beyond that distance, or with a local background.

2.2. Calibration Accuracy of the ROSAT PSPC

Initial calibration of the ROSAT PSPC was performed on the ground (Pfeffermann et al. 1987). Of particular interest to the results of this paper is the calibration of the effective area in the R2 band. Snowden et al. (1995) compared PSPC observations of the diffuse soft X-ray background with observations from the Wisconsin survey (e.g., McCammon et al. 1983; Garmire et al. 1992); the comparison revealed that the PSPC effective area was well calibrated within a 10% uncertainty. More recently, Beuermann et al. (2006) compared the extreme-ultraviolet and soft X-ray fluxes of three standard candles observed by the Chandra LETG, EUVE, and ROSAT PSPC, and found that the agreement between the various instruments indicate that the PSPC effective area is calibrated within a few percent error. These results indicate that the uncertainties in the R2 band effective area are of the order of few percent; as it will be shown in the following, this level of uncertainty will not affect any of the results presented in this paper.

2.3. Images and Radial Profiles of the X-ray Surface Brightness

In Figure 1, we show the diffuse surface brightness in a region of 400 deg^2 around the Coma cluster. The R2 band map features the northern edge of the North Polar Spur in the bottom right quadrant of panel (a); the two black pixels indicate the location of two pointlike features removed by the Snowden et al. (1997) data reduction. The R7 band image indicates that the 1–2 keV background in the neighborhood of Coma does not feature any large-scale gradients.

We obtained azimuthally averaged radial profiles of the surface brightness in the two bands (Figure 2), centered at R.A. = 12°59′50″, decl. = +27°58′59″, located at the center of Figure 1.4 Analysis of the R2 profile in Figure 2(a) shows that the North Polar Spur region is likely to affect the level of emission at distances ≥6′ from Coma. We therefore estimate the local background in two ways: as the average of the 4°–6° region, and as the average of the 4°–10° region (Table 1). Given that the two estimates of the background are statistically consistent with one another in each band, we use the 4°–6° background in the following analysis; all results presented in this paper are unchanged if the 4°–10° background is used instead. The choice of 4° as the minimum distance is motivated by the fact that the emission appears to fade into the background between 3° and 4°, consistent with the fact that Coma is not known to emit X-rays at such large distances. For a Hubble constant of H_0 = 73 km s^{-1} Mpc^{-1}, 1° corresponds to 1.67 Mpc at the redshift of the Coma cluster (z = 0.024).

The radial profiles indicate that the 1–2 keV emission reaches the local background at a radius of ~2′, while the softer R2 band has emission above the local background out to (at least) 3′. The radial profiles therefore indicate that the Coma cluster has an additional soft emission component at large radii. Measurements of the virial radius of Coma were recently obtained by weak lensing measurements (Kubo et al. 2007, r_{200} = 2.7 ± 0.3 Mpc for H_0 = 73 km s^{-1} Mpc^{-1}), galaxy kinematics (Lokas & Mamon 2003, r_v = 2.8 ± 0.8 Mpc for H_0 = 73 km s^{-1} Mpc^{-1}), and redshift survey of cluster galaxies (Geller et al. 1999, r_{200} ≃ 2.1 Mpc for H_0 = 73 km s^{-1} Mpc^{-1}). These

3 The maps of the diffuse X-ray emission can be found at http://www.xray.mpe.mpg.de/rosat/survey/sxrb/12/ass.html. The R2 and R7 bands used in this work are g000p90h2b120pm.fits and g000p90h2b120pm.fits for R2 band, and g000p90c7b120pm.fits and g000p90c7b120pm.fits for R7 band.

4 This position corresponding to pixel (247.80, 251.08) in the Snowden maps.
measurements are in agreement with earlier X-ray measurements by Briel et al. (1992, based on these ROSAT data) and Hughes (1989, based on Einstein data), which detected X-ray emission at radial distance of \( \leq 100 \) arcmin. The present detection of soft X-ray emission out to (at least) 3° or 5 Mpc, therefore tracks the soft X-ray emission out to the virial radius, and also constitutes the largest continuous halo of X-ray emission detected to date in any galaxy cluster.

### 2.4. The Soft X-ray Excess Emission

Further analysis of the soft emission must take into account the contribution of the hot intracluster medium to the R2 band emission. Given the limited spectral resolution and narrow bandpass (\( \sim 0.2–2 \) keV), the RASS PSPC data are not ideal for the determination of hot plasma temperatures. We therefore rely on other X-ray studies of Coma, which consistently measure a plasma temperature of \( kT \simeq 8 \) keV in the central 20' (e.g., Arnaud et al. 2001; Lutovinov et al. 2008). At larger radii, Finoguenov et al. (2001) measure temperatures in the range of 15–3 keV for regions between 0.5 and 1.5 from the cluster center, consistent with the decrease of temperature at large radii observed in other clusters (Vikhlinin et al. 2006).

In order to estimate the hot ICM contribution to the R2 band, we assume that the average plasma temperature has the distribution shown in Table 2, decreasing from 8 keV to 2 keV between the center and the outskirts. We estimate the ratio of R2–R7 band count rates using the method described in Snowden et al. (1997), which consists of using the on-axis PSPC response function in conjunction with an optically thin plasma emission model.\(^5\) The distribution of Galactic H\(\text{I}\) in the direction of Coma was investigated in Bonamente et al. (2003), by means of the Dickey & Lockman (1990) and Hartmann & Burton (1997) 21 cm data, and IRAS 100 \(\mu\)m data. For a region within 5° from the cluster center, the H\(\text{I}\) column density is between \( N_{\text{H}} = 0.8–1.1 \times 10^{20} \) cm\(^{-2}\), with no evidence of large-scale gradients; for the count-rate ratios in Table 2, we assumed \( N_{\text{H}} = 0.9 \times 10^{20} \) cm\(^{-2}\).

\(^5\) This procedure was also confirmed by S. Snowden (2009, private communication). The PSPC-C camera was used for the All-Sky Survey.

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**Table 1**

| Background Levels in \(10^{-6}\) PSPC Counts s\(^{-1}\) arcmin\(^{-2}\) |
|-----------------|-----------------|
| \(4°–6°\)       | \(555.7 \pm 2.3\) |
| \(4°–10°\)      | \(558.0 \pm 1.2\) |

**Figure 1.** Images of the diffuse emission of Coma in bands R2 (a) and R7 (b). Units of the emissions are \(10^{-6}\) PSPC counts s\(^{-1}\) arcmin\(^{-2}\).

(A color version of this figure is available in the online journal.)

**Figure 2.** Radial profiles of the diffuse emission near Coma in R2 (a) and R7 band (b). Units of the surface brightness are \(10^{-6}\) PSPC counts s\(^{-1}\) arcmin\(^{-2}\).
which is appropriate for the radial range of interest. The count-
rate ratio is also sensitive to the chemical composition of the
plasma; in particular, a higher abundance $A$ of metals results in a
lower $R2$–$R7$ ratio, due to emission lines processes. We therefore
used a conservative value of $A = 0$ in deriving the estimates of
Table 2; if an abundance of $A = 0.3$ was used instead, the
count-rate ratio would decrease respectively to 1.03 (8 keV),
1.20 (4 keV), and 1.48 (2 keV), causing a lower prediction
for the contribution of the hot ICM in the $R2$ band and higher
soft X-ray fluxes. For each annulus, we thus estimate the hot
ICM contribution to the $1/4$ keV band by multiplication of the
background-subtracted $R7$ intensity (Figure 2) by the factor in
Table 2.

In Figure 3, we show the $R2$ band excess emission above the
contribution of the hot ICM. This determination of the excess
emission clearly depends on our choices in the modeling of
the thermal plasma. If the plasma temperature in the $0:5$–$2:0$
region is higher, then our estimates are a strict lower limit. The
excess emission is still detected at high significance by using a
region—which is less affected

| Region (°) | $kT$ (keV) | $R2/R7$ ratio |
|-----------|------------|--------------|
| 0–0.5     | 8          | 1.04         |
| 0.5–2     | 4          | 1.28         |
| 2–4       | 2          | 1.80         |

Table 2. Average Temperature of the Coma Plasma, and Ratio of R2-to-R7 Count Rate for PSPC

in the $1$–$2$ keV band, in a circular area of approximate radius
0.78. We can use these numbers to estimate the contribution of
unresolved point sources in our RASS data. First, we rescale
the EPIC count rate to the PSPC count rate in the same energy
band, taking into account that the PSPC camera has an average
effective area that is $\sim 8$ times smaller than that of the
EPIC detector. Then, assuming (conservatively) that an equivalent population
of X-ray sources is present at larger radii, we can estimate that
the average brightness due to point sources in the $R7$ band is of
the order of $S = 7.2 \times 10^{-6}$ PSPC counts s$^{-1}$ arcmin$^{-2}$. The
contribution of these point sources to the $R2$ band depends on their spectrum; for an X-ray thermal spectrum with $kT = 1$
keV, typical of galaxies, the $R2$ count rate is approximately
$2$–$2.5$ times that in the $R7$ band, i.e., $\sim 1 \times$ higher than the
$R2$-to-$R7$ conversion factor used at radii $\geq 0.5$ in converting
the $R7$ emission to the $R2$ band (see Table 2). Unresolved point
sources would therefore reduce the soft excess fluxes of Figure 3
by approximately $7.2 \times 10^{-6}$ PSPC counts s$^{-1}$ arcmin$^{-2}$, which
corresponds to $10\%$ of the detected excess at radii less than $2'$,
and by $10\%–20\%$ in the $2'$–$3'$ region. We therefore conclude
that unresolved point source do not contribute significantly, if
at all, to the detected signal.

3. INTERPRETATION OF THE EXCESS EMISSION

In Section 2, we discussed possible sources of systematic
error that may affect the excess emission shown in Figure 3, and
concluded that the signal cannot be explained by errors in the
H $1$ column density, modeling of the hot plasma, or background
subtraction. We therefore proceed to investigate if the emission
can be due to unresolved point sources, and then discuss two
scenarios for a cluster origin of the emission.

3.1. Point-source Emission

Given the limited angular resolution of these RASS data, a
possible explanation for the detected excess is that the signal
is associated with a number of unresolved point sources (e.g.,
galaxies) in the Coma field. We address this possibility by using
the analysis of X-ray point sources detected by Finoguenov
et al. (2004) in an $XMM$-$Newton$ mosaic observation of the
central Coma cluster with the $XMM$-$Newton$ EPIC detector.
Their analysis detects a number of X-ray point sources for a
total combined flux of $F = 0.67 \pm 0.01$ EPIC counts per second

Figure 3. Radial profile of the excess emission in R2 band, above the contribution from the hot ICM. Units of the excess emissions are $10^{-6}$ PSPC counts s$^{-1}$ arcmin$^{-2}$. (A color version of this figure is available in the online journal.)
very spectacular detection of a ring of emission at a distance of \( \sim 1 \) Mpc from the center of the cluster Abell 3376, which is interpreted as the result of accretion shocks. There is theoretical (e.g., Cen & Ostriker 1999; Davé et al. 2001; Dolag et al. 2006) and observational evidence (e.g., Finoguenov et al. 2003; Werner et al. 2008) that diffuse filaments at \( kT \approx 10^5-10^6 \) K are present in the intercluster medium; these structures are therefore the ideal candidate for providing gas accreting into the deeper cluster potential. Shock acceleration, requires the presence of magnetic fields, in order to generate Alfvén waves that act as scattering centers (e.g. Bell 1978). Magnetic fields are clearly present in Abell 3376, as revealed by the nonthermal radio emission; it is however not clear, though, how magnetic fields would arise in an environment where the density of gas is expected to be very low (\( \lesssim 10^{-5} \) cm\(^{-3} \)).

Another interpretation is that optically thin soft X-ray emission from the filaments themselves is responsible for the detected emission. This scenario has been discussed in several prior papers (e.g., Bonamente et al. 2003, 2005; Mittaz et al. 2004), in which it was found that the column density of the filaments would exceed the expectations based on numerical simulations. We use the present RASS data to estimate the characteristics of the filaments that may be responsible for the excess emission. We assume filaments at a temperature of \( kT = 0.1 \) keV, and with null abundance of metals, typical of intergalactic filaments, and use the APEC emission code (Smith et al. 2001) to calculate the emissivity as \( \Lambda = 4.5 \times 10^{-18} \) counts cm\(^{-2} \) s\(^{-1} \) in the 0.14–0.284 keV (R2) band. We also assume a uniform electron density of \( n = 10^{-4} \) cm\(^{-3} \), corresponding to a baryonic overdensity of \( \delta \approx 200–300 \) (for \( H_0 = 73 \) km s\(^{-1} \) Mpc\(^{-1} \)), an average filament length of \( L = 5 \) Mpc in the direction of the observer. Using the average R2 band effective area of the PSPC detector \( (A_{\text{eff}} \approx 150 \) cm\(^2 \)) the R2 band surface brightness is calculated as

\[
S_X = \frac{1}{4\pi} \Lambda \cdot n^2 \cdot L \cdot A_{\text{eff}} = 70 \times 10^{-6} \text{ (counts s}^{-1} \text{ arcmin}^{-2} \). \ (1)
\]

(Comparison with Figure 3 shows that this is in fact the typical excess emission detected at the outskirts of the Coma cluster (radii \( \gtrsim 1.5 \) ). Since the surface brightness is proportional to \( n^2 \), lower density filaments would require to be substantially longer along the sightline, in order to explain the detected emission. Filaments of this density or length are more massive than typical filaments in numerical simulations (e.g., Mittaz et al. 2004). A possible explanation for the variance between observations and numerical models is that the filaments are actually magnified by gravitational lensing caused by the cluster potential, as discussed in Lieu & Bonamente (2009).

An additional interpretation can be provided by the Prokhorov (2008) model in which the soft excess emission is the result of a nonequilibrium state between electrons and ions present at the cluster’s outskirts. The model predicts soft X-ray excess from low-temperature electrons near the virial radius, which is approximately \( 2^\circ-3^\circ \) (see Section 2.3). These RASS observations are compatible with such scenario.

4. DISCUSSION AND CONCLUSIONS

These RASS data provide a unique view of the soft excess emission from the Coma cluster, which is now detected out to a \( \sim 5 \) Mpc radius. Diffuse filaments of warm gas provide the natural interpretation for the excess emission, either via particle acceleration at accretion shocks, or simply via their thermal emission. The scenario of thermal emission from filaments was tested using XMM-Newton observations of Abell S1101 (Bonamente et al. 2005); in that case, we determined that the filaments would be required to be even more massive than the ones discussed in this paper (for the same nominal density \( n = 10^{-4} \text{ cm}^{-3} \), the filament length would exceed 10 Mpc). In an upcoming paper (in preparation), we will show that the excess emission in Abell S1101 was overestimated, due to a significant revision of the \( \text{H} \) column density in the direction to the cluster (Kalberla et al. 2005); the reduced flux will make the estimates similar to the ones presented in this paper.

Current X-ray missions are not designed for studies of large-scale soft X-ray emission, given their narrow field of view and issues in the calibration of the 1/4 keV band (see Nevalainen et al. 2007 for a discussion on the XMM-Newton soft band, and Bonamente et al. 2007 on Chandra). The presence of filaments has therefore been mainly investigated in absorption, giving few tentative detections of absorption lines due to filaments. In particular, Nicastro et al. (2005) detected \( z > 0 \) absorption lines toward Markarian 421 with Chandra, although Rasmussen et al. (2007) did not confirm the detection with XMM-Newton. Of particular relevance to the Coma excess is the work of Takei et al. (2007), who used XMM-Newton ROSAT data to obtain a 3\( \sigma \) detection of absorption lines in the spectrum of X Comae, a background quasar at a projected distance of \( \sim 25' \) from the cluster center. Although that detection is of limited statistical significance, it provides support to the thermal interpretation of the soft excess emission we discussed in Section 2.4, at least in the central regions of the cluster.

The ROSAT mission continues to provide the most compelling detections of soft excess emission from galaxy clusters. Using pointed PSPC data, we were initially able to detect soft excess emission in several clusters (Bonamente et al. 2001a, 2001b, 2001c), confirming the discovery papers based on EUVE observation (Lieu et al. 1996a, 1996b). We then showed that a large fraction of clusters at high Galactic latitude feature the excess emission (Bonamente et al. 2002), used a mosaic of four pointed observations of Coma to detect the emission out to 1.7 Mpc (Bonamente et al. 2003) and now, based on the RASS data, out to 5 Mpc. In all cases, ROSAT’s unique combination of a reliable calibration in the 1/4 keV band, and the availability of contemporaneous background, rendered these detections possible. The main advantage of searching for filaments in emission is the insensitivity to the abundance of metals, and to clumping of the gas. The observations analyzed in this paper show that a very modest exposure time with a wide-field soft X-ray camera is a most efficient way to detect emission from warm filaments in the neighborhood of clusters.

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