SOFT AND HARD X-RAY EXCESS EMISSION IN ABELL 3112 OBSERVED WITH CHANDRA

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ABSTRACT

Chandra ACIS-S observations of the galaxy cluster Abell 3112 feature the presence of an excess of X-ray emission above the contribution from the diffuse hot gas, which can be equally well modeled with an additional nonthermal power-law model or with a low-temperature thermal model of low metal abundance. We show that the excess emission cannot be due to uncertainties in the background subtraction or in the Galactic HI column density. Calibration uncertainties in the ACIS detector that may affect our results are addressed by comparing the Chandra data to XMM-Newton MOS and PN spectra. While differences between the three instruments remain, all detect the excess in similar amounts, providing evidence against an instrumental nature of the excess. Given the presence of nonthermal radio emission near the center of Abell 3112, we argue that the excess X-ray emission is of nonthermal nature and distributed throughout the entire X-ray bandpass, from soft to hard X-rays. The excess can be explained with the presence of a population of relativistic electrons with \( \sim 7\% \) of the cluster’s gas pressure. We also discuss a possible thermal nature of the excess and examine the problems associated with such interpretation.

Subject headings: galaxies: clusters: individual (Abell 3112) — X-rays: galaxies: clusters

Online material: color figures

1. INTRODUCTION

The detection of excess extreme-ultraviolet and soft X-ray photons \((\sim 0.1 – 1 \text{ keV})\) in the spectra of galaxy clusters indicates the presence of nonthermal processes, or of warm gas \((T \sim 10^6 – 10^7 \text{ K})\) near clusters (e.g., Lieu et al. 1996; Bowyer et al. 1996; Sarazin & Lieu 1998; Nevalainen et al. 2003; Bonamente et al. 2005b).

The excess emission above the contribution from the hot intracluster medium was originally discovered with EUVE (Lieu et al. 1996), and confirmed by ROSAT (e.g., Bonamente et al. 2002), BeppoSAX (e.g., Bonamente et al. 2001), and XMM-Newton (e.g., Nevalainen et al. 2003) for a large number of clusters. Some detections were subject to criticism ranging from issues with the EUVE data analysis (Bowyer et al. 1999) to effects of the Galactic HI absorption (Bregman & Lloyd-Davies 2006); such critiques were addressed by dedicated reobservations and reanalyses, which confirmed the presence of the excess (e.g., Lieu et al. 1999a; Bonamente et al. 2002; Nevalainen et al. 2007). A tentative detection of emission lines associated with the soft emitter was reported by Kaastra et al. (2003) using XMM-Newton data. Recently, Werner et al. (2007) confirmed the soft excess emission in Abell S1101 using Suzaku data, but did not confirm the earlier finding of emission lines associated with the excess emitter. The presence of hard X-ray excess emission in some clusters (e.g., Fusco-Femiano et al. 1999; Nevalainen et al. 2004) provides further indication that additional physics is required in order to interpret X-ray cluster spectra.

Interpretation of the soft excess emission has been the subject of an active debate. Thermal emission from warm gas \((kT \sim 0.1 – 1 \text{ keV})\) is a viable model (e.g., Lieu et al. 1996; Bonamente et al. 2002; Finoguenov et al. 2003), which indicates the presence of an additional phase in the intergalactic medium (e.g., Cheng et al. 2005). The thermal interpretation is not consistent with the Cen & Ostriker (1999) model of diffuse filaments, which are too tenuous to produce the observed radiation (Mittaz et al. 2004; Bonamente et al. 2005b). Another viable model is nonthermal emission as inverse Compton scattering of the cosmic microwave background (e.g., Sarazin & Lieu 1998; Lieu et al. 1999b).

Given that all major X-ray missions with soft X-ray sensitivity since EUVE have reported a detection of cluster soft excess, in this paper we investigate the presence of the phenomenon in the Chandra data of Abell 3112, a cluster for which XMM-Newton detected the presence of strong soft X-ray excess emission (Nevalainen et al. 2003). The investigation is made possible by the recent calibration efforts by the Chandra team to correct the effects of the contaminant on the optical filter of ACIS. The scope of this paper is primarily that of assessing if, with the current calibration of the soft X-ray channels of ACIS-S, Abell 3112 has evidence for the soft excess, above the calibration uncertainties, as reported by XMM-Newton. This paper is structured as follows: in §2 we present the Chandra observations of Abell 3112, in §3 the reduction and analysis of the observations with particular attention to removal of periods of high background, and in §4 we present the spectral analysis of the Abell 3112 data, revealing the presence of the excess emission, including a comparison between Chandra and XMM-Newton spectra. In §5 we discuss the effect of the instrumental background and of projection effects, and in §6 we report our interpretation of the spectral analysis. Section 7 contains our discussion and conclusions.

Abell 3112 is a southern cluster located near R.A. = \( 03^h17^m52.4^s \), decl. = \( -44^\circ14'35'' \) (J2000.0) and at redshift \( z = 0.075 \), with an X-ray luminosity of \( L_X = 7.4 \times 10^{44} \text{ ergs s}^{-1} \) in the 0.1–2.4 keV band (Reiprich & Böhringer 2002). In this paper we assume a cosmology of \( h = 0.72, \Omega_m = 0.3 \), and \( \Omega_L = 0.7 \), for which \( l \) corresponds to approximately 85 kpc. The Galactic HI column density toward this cluster was measured by Dickey & Lockman (1990) as \( N_H = 2.6 \times 10^{20} \text{ cm}^{-2} \).

2. CHANDRA OBSERVATIONS OF ABELL 3112

Chandra observed Abell 3112 in two separate exposures in 2001 September (ObsID 2516, 16.9 ks exposure time) and 2001...
May (ObsID 2216, 7.2 ks exposure). The two Chandra observations of Abell 3112 analyzed in this paper were first published by Takizawa et al. (2003). They found that the putative cooling-flow gas in Abell 3112 is present in more modest amounts (44.5$_{-32.5}^{+52.1}$ $M_\odot$ yr$^{-1}$) than previously thought based on ROSAT data (Allen & Fabian 1997; Peres et al. 1998). In each of the annuli investigated by Takizawa et al. (2003) the cooling component is detected with low significance and is certainly confined to the central $\sim 60''$ region. Takizawa et al. (2003) detected the presence of the central source PKS 0316$-$444, a radio source detected by the same authors at 1.4 GHz, which features thermal and nonthermal X-ray emission. For these reasons, in this paper we do not investigate the diffuse emission in the central 60'' region.

Our study of the diffuse X-ray emission from Abell 3112 differs from that of Takizawa et al. (2003; who use the 0.5–10 keV band) in that more accurate calibration information is now available, which results in a better correction for the time-variable charge transfer inefficiency and the spatially dependent build-up of contaminants in the optical filter of the instrument. We chose not to use energies below 0.5 keV, given that the effects of the optical filter contaminant are still not well calibrated at these energies (A. Vikhlinin 2007, private communication). The soft excess detected in several clusters becomes stronger at lower X-ray energies; this study therefore probes the presence of the excess emission only in those channels allowed by the current Chandra calibration.

It is worthwhile to point out that Takizawa et al. (2003) did detect a sub-Galactic column density toward Abell 3112, an effect which may be indicative of excess soft X-ray photons, as shown in Bonamente et al. (2005b) and Nevalainen et al. (2007). They attributed this effect to an overcorrection of the Chandra effective area by the Chandra data analysis tools available at the time of their study.

3. DATA REDUCTION

The data reduction was performed with CIAO 3.4, using the calibration information available in CALDB 3.3.4 Level 1 event files were reprocessed to apply the latest calibration (using the acis_process_events tool), including the time- and space-dependent correction due to the contaminant on the ACIS optical filter, which affects the detection of soft X-ray photons. ACIS observations of bright sources can also be affected by a readout artifact also known as out-of-time events (e.g., Markevitch 2003). It is caused by source photons that hit the detector during the $\sim 40$ ms that are necessary for one ACIS frame (accumulated over a $\sim 3.2$ s integration) to be transferred to the readout electronics. Although our observations feature neither a strong point source nor a peaked distribution of the cluster surface brightness, we follow the additional reduction step described by Markovich (2003) in order to account for this effect.

The ACIS-S3 background was studied in detail by Markovich et al. (2003), who provide a detailed set of prescriptions useful to excise times with high background count rates. Since the cluster occupies the entire S3 chip, the S1 chip was used to investigate the presence of background flares. Following the Markovich et al. (2003) prescription, the quiescent background rate in the 2.5–6.5 keV band was determined from the flare-free blank-sky data set provided with CIAO and applicable to the A3112 observations.

4. SPECTRAL ANALYSIS

The ACIS spectrum is initially fit to an optically thin plasma emission code (mekal in XSPEC), modified by the photoelectric absorption (wabs in XSPEC); the Galactic $N_H$ was fixed at the measured values, except in a model in § 4.1 in which a variable $N_H$ is explicitly stated.5 The background is measured from blank-sky observations, as described in § 3. The spectral range used in this paper for the ACIS data is 0.5–7 keV. Errors are 68% confidence intervals, obtained with the $\chi^2$min + 1 method.

In order to assess the possible impact of calibration uncertainties on the Chandra data analysis, we also analyze XMM-Newton MOS and PN spectra of the same region of Abell 3112. The XMM-Newton data analysis is described in detail in Nevalainen et al. (2003), to which the reader is referred for details. We reduced the available XMM-Newton observation of Abell 3112 to obtain 22.3 ks of MOS data, and 16.6 ks of PN data. The XMM-Newton data analysis was performed with the SAS 7.0.0 software, using the calibration information available as of 2007 May. The XMM-Newton reduction follows the same steps as the Chandra data, including flagging of high-background time intervals and the use of background accumulated from blank-sky observations (see Nevalainen et al. 2005). Data from the two MOS units were averaged to yield one MOS spectrum. The XMM-Newton spectra are fit in the 0.3–8 keV band.

4.1. Single-Temperature Model

First, we fit the ACIS spectrum with a simple one-temperature model in the 0.5–7 keV band. The fit is poor, with positive residuals at low and high energy, and negative residuals in the central band around 2 keV (Fig. 1 and Table 1). The presence of residuals is such that a fit of the spectrum in the hard band (2–7 keV) provides a significantly higher temperature than the 0.5–7 keV fit, and its extrapolation to low energies does not match the observed spectrum (Fig. 2 and Table 2). Likewise, a fit to the low-energy band alone (0.5–4 keV) provides a lower temperature, and highlights the presence of high-energy residuals (Fig. 3 and Table 2). We provide similar fits to the XMM-Newton spectra, in which the

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4 The analysis was initially performed using CIAO 3.3 and CALDB 3.2. The later release of the Chandra CALDB included changes to the calibration of the charge transfer inefficiency (CTI) for back-illuminated chips; such changes did affect the Abell 3112 spectra, but did not change the overall results presented in this paper.

5 The normalization of the spectra in Tables 1–4 follows the customary XSPEC units, $N = 10^{-11} \left(1 + z^2 D_L^2 \right)^{-1} n_e n_H dV$, where $D_L$ is the angular diameter distance (cm), and $n_e$ and $n_H$ are the electron and hydrogen densities (cm$^{-3}$), respectively.
The 0.3–8 keV band is used for the full-band fit, and the 2–8 and 0.3–4 keV bands, respectively, for the low-energy and high-energy band fits. Finally, a joint fit to all available data (ACIS, MOS, and PN) is also performed for comparison.

In § 5.2 we show that the poor fit to a single-temperature model cannot be due to the decrease of the hot gas temperature at large radii. From these narrowband fits alone it is not possible to establish whether the poor single-temperature fit is due to an additional high-energy component (e.g., a hard excess) or to a low-energy component (e.g., a soft excess). What these fits do indicate is the need for a more accurate modeling than a simple single-temperature model, if one wants to satisfactorily fit the whole-band spectrum.

Before proceeding with multicomponent models, we investigate the possibility that the poor single-temperature fit is caused by variations in the H\textsc{i} absorbing column, and therefore repeat the single-temperature fits with a variable $N_{\text{H}}$. The fits to a free-$N_{\text{H}}$ single-temperature model are somewhat improved (Table 1).

The fact that the best-fit $N_{\text{H}}$ is significantly sub-Galactic, and that high-energy residuals remain, indicates that the fit residuals cannot be explained as a Galactic absorption effect. We therefore proceed with the addition of a second emission component in order to provide a better fit to the data.

### 4.2. Two-Component Models: Nonthermal Model and Two-Temperature Model

We now add a nonthermal power-law component to the thermal model. The addition results in acceptable fits, with a significant improvement to the $\chi^2$ statistic (Table 3).
The power-law model of the 1′–2.5′ region contributes to \( \sim 50\% \) of the X-ray luminosity in the same region (Fig. 4). This results in higher metal abundances for the hot gas, now with an emission integral reduced by \( \sim 50\% \) with respect to the single-temperature model. If the excess emission is described by this nonthermal power-law model, the excess emission would extend throughout the X-ray band and into the hard X-ray band.

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(\sim 0.3 \text{ keV}) and with low metal abundance, with spectral fits of similar quality to the nonthermal model (Table 4).

### 4.3. Comparison to XMM-Newton Results and Effect of Calibration Uncertainties

The XMM-Newton study of Nevalainen et al. (2003) found soft excess emission in Abell 3112 at the level of \sim 20\%–40\% above the hot thermal component. The analysis of Chandra and XMM-Newton calibration is an ongoing effort, and changes to the XMM-Newton calibration since the publication of the Nevalainen et al. (2003) resulted in changes to the derived soft excess properties (also noted by Nevalainen et al. 2007), although the presence of the excess itself was confirmed.

In order to provide a more up-to-date comparison between the Chandra and the XMM-Newton data, we also analyzed the MOS and PN spectra of the 1.0–2.5\text{ keV} region reduced with the latest available calibration information (see Table 1 for details, and Figs. 1–3 and Tables 1–4 for results). Such a comparison indicates clearly that both MOS and PN detect a behavior similar to the ACIS spectra: the spectra are not consistent with a single-temperature model, and feature residuals at both low and high energy. The addition of a power-law or of a low-temperature thermal model results in significant improvements to the $\chi^2$, as was the case for the Chandra data.

Differences between the three instruments (ACIS, PN, and MOS) remain, as the best-fit hot gas temperatures from XMM-Newton are somewhat lower than Chandra’s, and the PN excess is \sim 10\% higher than those in ACIS and MOS. Since a wrong hot gas temperature may affect the detection of the excess emission, we also perform a joint fit between all three instruments (Figs. 1–3, bottom right panels). This exercise indicates that even using XMM-Newton-driven temperatures, the Chandra data are not satisfactorily fit by a single-temperature emission model. Comparison of the best-fit nonthermal models (Table 3) between the three instruments indicates that a power law of index $\alpha \sim 1.8$ is a viable model for both Chandra and XMM-Newton data of Abell 3112. The two-temperature model (Table 4) also provides a significant reduction in $\chi^2$ for all data sets, although the three instruments do not agree on the temperature of the warm phase.

### 5. Background Subtraction and Projection Effects

#### 5.1. Background Subtraction

We used the blank-sky data sets provided with the CIAO software for the purpose of background subtraction, as described in §. The quiescent X-ray background present in the data has two main components: a stable particle background and a variable sky signal. The former is present in the blank-sky data set, and therefore accurately removed from our cluster data. The latter is a soft X-ray background which varies with position in the sky and is the dominant source of background at energies \leq 1\text{ keV}. The background in this Abell 3112 observation is \sim 4\% at soft energies (0.5–2\text{ keV}) and \sim 25\% at energies 5–7\text{ keV} (Fig. 5).

Our choice of investigating only the central—and brightest—regions of the cluster (excluding the core) was motivated precisely by the presence of this variable soft X-ray background component, and the need to minimize its effects. If the \sim 20\% soft X-ray excess was due to an anomalous background in this observation, it is required that the background exceed the blank-sky estimate by a factor of 5. This exceeds the observed variability of the soft X-ray sky background by more than 1 order of magnitude, which is \sim 25\%–50\% in the \sim 0.5–1\text{ keV} band (e.g., Bonamente et al. 2005a).

In the high-energy band ($E \geq 4\text{ keV}$), the diffuse sky background is expected to be negligible (Markevitch et al. 2003), and the X-ray background is of detector origin. We established that the background subtraction in this band was accurate by ensuring that the signal at high energy ($E \geq 10\text{ keV}$), where Chandra has no effective area to detect photons, was consistent between the Abell 3112 observations and the blank-sky observations, thereby resulting in a null background-subtracted spectrum at those energies. The fact that the background is not responsible for the apparent excess of hard photons (Figs. 1 and 3) was established by performing a fit to the spectrum in which the instrumental background was artificially increased by 20\%; this test resulted in no significant changes to the fit parameters or the high-energy residuals. Markevitch et al. (2003) also shows that the high-energy background usually does not vary between observations by more than a few percent.

#### 5.2. Projection Effects

Most clusters feature a radial temperature profile that decreases at large radii, as found, e.g., by Vikhlinin (2006) and Vikhlinin et al. (2005). The temperature profile is typically flat over the range \sim (0.1–0.3)R_{500}, where $R_{500}$ indicates the radius within which the mean cluster density is 500 times higher than the critical density.

One of the major sources of uncertainty in the ACIS calibration at low energies is the presence of a contaminant on the optical blocking filter of Chandra. At present, the Chandra calibration team has developed a model for the contaminant with an estimated uncertainty on its optical depth of 10\% at 0.7\text{ keV}. Such an uncertainty will not be sufficient to explain the 20\% soft X-ray residuals shown in this paper. The contaminant contains elements with absorption edges in the 0.5–0.7\text{ keV} range, and we estimated that an optical depth of the contaminant that is higher by a factor of 30\% is necessary in order to explain the soft X-ray residuals present in this Abell 3112 observation. The fact that the XMM-Newton data show residuals of similar nature and in comparable amount (and even in larger amount according to the PN data) argues against such an instrumental nature of the Chandra excess.

### Table 2: Narrowband Single-Temperature Models with Fixed $N_H$

| Data        | $\chi^2$/dof ($\chi_1^2$) | $kT$ (keV) | $A$ | Norm ($10^{-5}$) |
|-------------|---------------------------|------------|-----|-----------------|
| **Fit to 2–7 keV Band (2–8 keV for XMM-Newton Data)** |               |            |     |                 |
| ACIS ....... | 179.7/166 (1.08)          | 5.86$^{+0.57}_{-0.36}$ | 0.45 ± 0.07 | 0.94 ± 0.03     |
| PN .......... | 73.4/105 (0.70)           | 5.25$^{+0.23}_{-0.21}$ | 0.32 ± 0.04 | 0.82 ± 0.02     |
| MOS ......... | 115.4/105 (1.10)          | 5.34$^{+0.19}_{-0.19}$ | 0.37 ± 0.04 | 0.97 ± 0.02     |
| Joint* ........ | 365.6/394 (0.93)         | 5.31$^{+0.14}_{-0.13}$ | 0.36 ± 0.03 | 0.98 ± 0.02     |
| **Fit to 0.5–4 keV Band (0.3–4 keV for XMM-Newton Data)** |               |            |     |                 |
| ACIS ....... | 261.3/210 (1.24)          | 4.54 ± 0.14 | 0.29 ± 0.06 | 1.04 ± 0.02     |
| PN .......... | 137.0/108 (1.29)          | 3.46$^{+0.07}_{-0.06}$ | 0.13 ± 0.02 | 1.01 ± 0.01     |
| MOS ......... | 165.6/116 (1.43)          | 4.24 ± 0.08 | 0.26 ± 0.03 | 1.08 ± 0.01     |
| Joint* ........ | 638.6/437 (1.46)        | 3.93$^{+0.06}_{-0.05}$ | 0.20$^{+0.01}_{-0.03}$ | 1.07 ± 0.01     |

* For the joint fit, the three normalizations apply respectively to the ACIS, PN, and MOS data.

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7 See, e.g., http://cxc.harvard.edu/cal/Acis/Cal Wonderland/seqDeg/index.html.
We examined whether the soft excess signal in the 1.0′–2.5′ annulus analyzed in this paper could be due to projection effects of gas at different temperatures along the line of sight. For this purpose, we modeled the three-dimensional temperature profile of Abell 3112 using the average model found in the analysis of several Chandra clusters (eq. [9] in Vikhlinin 2006). Using a mean temperature of 5 keV and a redshift of \( z = 0.075 \), we find that \( r_{500} \approx 1.1 \) Mpc, or \( \sim 12' \) (assuming the concordance cosmology), and therefore the inner radius of 1′ corresponds to approximately 0.1\( r_{500} \). For the gas density distribution we used the \( \beta \)-model with

\[
\rho(r) = \frac{\rho_0}{(1 + (r/r_c)^2)^{3/2}}
\]

\( \rho \) is the gas density, \( r \) is the radial distance, \( \rho_0 \) is the central density, and \( r_c \) is the scale radius. The parameters were determined to fit the observed temperature and density profiles.

### Table 3

**Nonthermal Model**

| Data    | \( \chi^2 \text{dof} (\chi^2) \) | \( kT \) (keV) | \( A \) | Normalization \( (\times 10^{-2}) \) | \( \alpha \) | \( L_{42}^a \) (10^{42} ergs s\(^{-1}\)) |
|---------|----------------------------------|----------------|--------|--------------------------------------|--------|------------------|
| ACIS    | 295.4/267 (1.10)                 | 5.36 ±0.40     | 0.87 ±0.25 | 0.50 ±0.14                         | 1.79 ±0.11 | 74.4             |
| PN      | 118.6/159 (0.74)                 | 4.12 ±0.24     | 0.47 ±0.03 | 0.57 ±0.05                         | 1.83 ±0.07 | 61.0             |
| MOS     | 185.1/172 (1.08)                 | 4.44 ±0.19     | 0.48 ±0.05 | 0.74 ±0.06                         | 1.74 ±0.07 | 49.8             |
| Joint\(^b\) | 643.7/604 (1.07)               | 4.59 ±0.08     | 0.50 ±0.02 | 0.69 ±0.10                         | 1.85 ±0.04 | 46.0             |

\( L_{42}^a \) is the unabsorbed luminosity of the nonthermal model in the 0.5–7 keV band.

\(^b\) For the joint fit, the three normalizations apply respectively to the ACIS, PN, and MOS data.
parameters obtained from ROSAT PSPC data (Vikhlinin et al. 1999), i.e., $\beta = 0.63$ and $r_{\text{core}} = 1.0'$. We divided the cluster in concentric shells of 0.5' width and assigned each shell with density and temperature values given by the above models. We then intersected the spherical shells with a hollow cylinder of inner and outer radii of 1.0' and 2.5', representing our line of sight to Abell 3112, and computed the volume of these portions of shell using exact analytical formulas. Finally, we calculated the emission measure of each shell at different temperatures along the line of sight.

We found that $\sim$90% of the emission in the projected 1.0'–2.5' region of Abell 3112 originates from three-dimensional distances of $(0.1–0.3)r_{500}$ from the cluster center, where the gas temperature is nearly isothermal, i.e., varies by less than 10%. Due to the dominance of the isothermal component the effect of the projected lower temperatures is expected to be small, as we further investigate in the following. Using the emission measures and temperatures of our three-dimensional model described above, we simulated PN spectra (the most sensitive instrument available) for different portions of the line of sight (1) from a three-dimensional radial range of $(0.1–0.3)r_{500}$ (inner isothermal region), (2) from a radial range $(0.3–1.0)r_{500}$ (outer region), and (3) a radial range of $(0.1–1.0)r_{500}$ (full region, assuming that the X-ray emission extends to $r_{500}$); all spectra were projected onto the 1'–2.5' annulus. The best-fit temperature of the emission originating from the outer region is 20% lower than that in the inner isothermal region, and its emission measure is only $\sim$10% of that of the hotter one (Fig. 6). The full-region spectrum is fitted perfectly with a single-temperature model with a best-fit temperature 3% lower than that within the inner isothermal region (Fig. 6). There are no soft or hard X-ray residuals, even when considering the channels at the lowest energy of 0.1 keV, and thus the projection of different temperatures along the line of sight does not explain the soft excess detected in the 1'–2.5' region of Abell 3112.

6. INTERPRETATION OF THE EXCESS EMISSION

Having ruled out the H i column density and the background as sources of the excess emission and addressed other sources of systematic errors, we now turn to the physical interpretation of the excess emission, as in the XMM-Newton observation of Abell S1101 of Bonamente et al. (2005b).

6.1. Nonthermal Interpretation

Relativistic electrons in the intergalactic medium will cause cosmic microwave background (CMB) photons to Compton-scatter into the X-ray band (the so-called inverse Compton scattering). The Lorentz factor $\gamma$ of the electrons is related to the observed energy $E$ (0.5–7 keV) of the photons via $E = 75(\gamma/300)^2$ eV, (e.g., Sarazin 1988). Assuming that each annulus is representative of a spherical shell, one can calculate the pressure of the thermal and of the nonthermal component. For the hot gas pressure, $p = n k T$, the number density $n$ is estimated from the measured normalization $N$ of the spectrum, $N \propto \int n^2 dV$, where $V$ is the volume of the spherical shell.

The nonthermal pressure is calculated as $p_{\text{nt}} = \frac{1}{3} u$, where $u$ is the energy density of the relativistic electrons, calculated as

$$u = \frac{1}{V} \left(8 \times 10^{61}\right) \frac{L_{\text{nt}}}{10^{42} \text{ ergs s}^{-1}} \frac{\left(\frac{3 - \mu}{2 - \mu}\right)}{\left(\frac{\gamma_{\text{max}}^3 - \gamma_{\text{min}}^3}{\gamma_{\text{min}}^3 - \gamma_{\text{min}}^3}\right)} \text{ ergs cm}^{-3}, \quad (1)$$

| Data    | $\chi^2$/dof ($\chi^2$) | $kT$ (keV) | $A$ | Normalization ($10^{-2}$) | $kT_{\text{warm}}$ (keV) | $A$ | Normalization ($10^{-3}$) |
|---------|-------------------------|------------|-----|--------------------------|--------------------------|-----|--------------------------|
| ACIS    | 296.6/266 (1.11)        | 5.61\pm0.27 | 5.51\pm0.07 | 0.94 \pm 0.03 | 0.34\pm0.12 | \leq 2.5 | 0.14\pm0.17 |
| PN      | 117.8/158 (0.74)        | 5.34\pm0.23 | 0.38\pm0.04 | 0.78 \pm 0.04 | 0.89\pm0.12 | \leq 0.17 | 0.90\pm0.04 |
| MOS     | 178.8/170 (1.05)        | 4.68\pm0.07 | 0.39 \pm 0.03 | 1.03 \pm 0.01 | \leq 0.10 | \leq 0.04 | 3.39\pm1.02 |
| Joint   | 654.5/603 (1.09)        | 5.12\pm0.09 | 0.39\pm0.02 | 0.94 \pm 0.01 | 0.62\pm0.04 | \leq 0.01 | 0.24 \pm 0.01 |

TABLE 4
Two-Temperature Model

Fig. 4.—Left: Nonthermal fit to ACIS data; the dotted lines are individual model components. Right: Two-temperature fit to ACIS data. Models have the parameters of Table 3.
in which $L_{\text{all}}$ is the unabsorbed nonthermal luminosity in the 0.5–7 keV band and $\mu$ is the electron differential number index ($dN_e/dE \propto E^{-\mu}$) related to the observed spectral power-law index by $\mu = -1 + 2\alpha$. The results are that the nonthermal pressure accounts for a small fraction ($\sim 7\%$) of the hot gas pressure (Table 5).

The relativistic particles, or cosmic rays, could be provided by jets of a central active galaxy, then transported outwards while undergoing second-order Fermi acceleration by turbulent Alfvén waves (Lieu & Quenby 2006). If the acceleration of relativistic electrons occurs at diffuse shocks (e.g., Bell 1978a, 1978b), then a typical electron spectral index is $\mu \simeq 2.5$, corresponding to a photon index of $\alpha \simeq 1.75$, as observed by both Chandra and XMM-Newton. A steepening of the power-law index toward larger radii is naturally explained as a result of radiative losses (Lieu et al. 1999b). Presence of nonthermal phenomena in the core of Abell 3112 is also confirmed by the low-frequency radio emission associated with the central galaxy, and with a double-tailed source within $\sim 30''$ of the cluster’s center (Takizawa et al. 2003).

### 6.2. Thermal Interpretation

If the excess is of thermal nature, the mass of the warm phase can be estimated for two simple geometries, one in which the warm gas coexists with the hot gas in spherical shells (case 1), the other in which the gas is in diffuse filaments (a la Cen & Ostriker 1999) of fixed density or length, projected toward the cluster (case 2):

1. In the first case, the warm gas may be clumped with a volume filling factor $f = V_{\text{cl}}/V$, where $V_{\text{cl}} \ll V$ is the effective volume occupied by the gas, and the detected emission integral is $I = \int n^2 f \, dV$. The gas density $n$ can therefore be estimated for a fixed volume filling factor $f$, $n \propto f^{-1/2}$ (Table 5). The ratio of warm-to-hot gas mass is given by $M_{\text{warm}}/M_{\text{hot}} = f^{1/2}(I_{\text{warm}}/I_{\text{hot}})^{1/2}$, corresponding to $39^{+47}_{-45} \%$; therefore, the warm gas may account for a significant fraction of the cluster’s total baryon mass, depending on its filling factor. Alternatively, the volume filling factor can be estimated directly by requiring that the warm and hot gas are in pressure equilibrium, $p = n_{\text{hot}} kT_{\text{hot}} = n_{\text{warm}} kT_{\text{warm}}$. In this case one can show that the ratio of warm-to-hot gas mass in each annular region is $M_{\text{warm}}/M_{\text{hot}} = (I_{\text{warm}}/I_{\text{hot}})^{3/2}(T_{\text{warm}}/T_{\text{hot}})$. This results in a warm-to-hot gas mass ratio of $0.35^{+0.05}_{-0.04} \%$. The putative warm gas will have a cooling time that is shorter than the Hubble time, thereby requiring a replenishment or heating mechanism in order to be sustained. The cooling time can be estimated using the isobaric cooling formula of Sarazin (1988). Assuming a diffuse warm gas of filling factor $f = 1$, the cooling time is 1.9 Gyr; if the warm gas is denser because of a smaller filling factor, or because it is in pressure equipartition with the hot gas, the cooling time is further reduced.

2. In the second case, the volume occupied by the gas is $A \times L$, where $A$ is the area of the annulus and $L$ the filament’s length along the line of sight, and the detected emission integral becomes $I = \int n^2 (AdL)$. In this case, one needs to fix either the density $n$ or the length $L$ in order to interpret the detected emission integral $I$. In this paper, we assume filaments of a fixed fiducial length of 1 Mpc, and estimate accordingly the density of the warm filaments projected toward the cluster (Table 5). The density derived...
attributed to uncertainties in the Galactic H.

This paper feature an excess of X-ray photons which cannot be

Fabian 2006), instead of significantly subsolar as usually measured

of nearly solar abundances (as in the Perseus cluster; Sanders &

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Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1

Bregman, J. N., Novicki, M. C., Krick, J. E., & Arabadjis, J. S. 2003, ApJ, 597, 399

Bregman, J. N., & Lloyd-Davies, E. J. 2006, ApJ, 644, 167

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in this fashion scales as \( n \propto L^{-1/2} \), i.e., if the filaments are 10 Mpc long instead, the density will be reduced by a factor of \(~3\). The density and length of the putative filaments according to this inter-

pretation of the soft excess are orders of magnitude larger that predicted by simulations (e.g., Cen & Ostriker 1999; Davé et al. 2001), similar to the case of the soft excess in the XMM-Newton observation Abell S1101 (Bonamente et al. 2005b).

6.3. Effects on the Hot Intracluster Medium

The results of Tables 1, 3, and 4 show that the presence of an

undiagnosed additional component in X-ray spectra, regardless

of its origin, has an impact on the determination of the temper-

ature and metal abundance of the hot gas. The temperature is af-

fected by the presence of the excess component, which, if properly

modeled with either a thermal or nonthermal model, contains a

systematic shift in the measured \( T \) by up to \(~25\%\) in these obser-

vations of Abell 3112. The measurement of chemical abundances

will also experience a systematic change toward larger values. In

particular, if the excess is of nonthermal origin, the result is that

of nearly solar abundances (as in the Perseus cluster; Sanders &

Fabian 2006), instead of significantly subsolar as usually measured

(De Grandi & Molendi 2001).

7. DISCUSSION AND CONCLUSIONS

The Chandra ACIS-S observations of Abell 3112 analyzed in this paper feature an excess of X-ray photons which cannot be attributed to uncertainties in the Galactic \( H \) absorbing column or to the X-ray background emission. The excess emission is equally well fit by a nonthermal power-law model and by a thermal model of \(~0.2–0.7\) keV temperature and null metal abundance. The excess is

similar to that detected using XMM-Newton data (Nevalainen et al. 2003 and this paper).

Both interpretations point to additional physical mechanisms at work in galaxy clusters. The thermal interpretation of the ex-

cess is inconsistent with emission from diffuse filaments à la Cen

& Ostriker (1999) and indicates that the putative warm gas may be as massive as the hot gas.

The nonthermal interpretation, on the other hand, suggests that a significant fraction of the cluster’s X-ray emission may be associated with nonthermal processes, according to the original proposal of Felten & Morrison (1966), and not with the well-known hot gas at \( T \sim 10^8\) K. If a substantial fraction of the X-ray emission of some clusters is of nonthermal origin, it may also explain the less-than-expected Sunyaev-Zel’dovich effect that emerged from a comparison of WMAP and X-ray data for a large sample of nearby clusters (Lieut et al. 2006; Afshordi et al. 2007). In fact, for equal pressure of thermal and relativistic electrons, the Sunyaev-Zel’dovich decrement due to the latter is much less than the former (e.g., Enßlin & Kaiser 2000).

Does our detection then constitute a soft or a hard excess? From a pure data analysis viewpoint, the fact that a two-temperature fit to the spectra shifts the best-fit temperature of the hot phase to higher temperature and requires the introduction of a softer com-

ponent cannot alone be considered a proof that the data-model

mismatch is due to a soft excess of a thermal nature. In fact, the

nonthermal model has same goodness of fit as the two-temperature thermal model.

Moreover, the intrinsic paucity of hard X-ray photons com-
pared to soft X-ray photons is such that the latter drive the spectral

fit, and therefore a bona fide power-law component may be conf-

used for a low-temperature thermal emission, at the resolution of

these Abell 3112 observations. From an interpretational point of

view, the presence of nonthermal emission from radio observa-

tions and the difficulties with the thermal interpretation of the

excess emission (\( \S 6.2 \)) point at a nonthermal origin of the emis-

sion. We therefore argue in favor of a nonthermal origin of the

excess, and that the phenomenon is both a soft and hard excess or, simply, an excess emission throughout the X-ray bandpass.

The presence of this X-ray excess emission also affects the
determination of the hot gas parameters. Understanding the origin of this excess emission therefore promises not only the discovery of new physical phenomena in galaxy clusters, but also a better knowledge of the hot intergalactic medium.

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