NONTHERMAL HARD X-RAY EXCESS IN THE COMA CLUSTER: RESOLVING THE DISCREPANCY BETWEEN THE RESULTS OF DIFFERENT PDS DATA ANALYSES

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ABSTRACT

The detection of a nonthermal excess in the Coma Cluster spectrum by two BeppoSAX observations analyzed with the XAS package (Fusco-Femiano et al.) has been disavowed by an analysis (Rossetti & Molendi) performed with a different software package (SAXDAS) for the extraction of the spectrum. To resolve this discrepancy we reanalyze the PDS data considering the same software used by Rossetti & Molendi. A correct selection of the data and the exclusion of contaminating sources in the background determination show that the SAXDAS analysis also reports a nonthermal excess with respect to the thermal emission at about the same confidence level of that obtained with the XAS package (~4.8σ). In addition, we report the lack of the systematic errors investigated by Rossetti & Molendi and Nevalainen et al., taking into account the whole sample of the PDS observations off the Galactic plane, as already shown in our data analysis of Abell 2256 (Fusco-Femiano, Landi, & Orlandini). All this eliminates any ambiguity and confirms the presence of a hard tail in the spectrum of the Coma Cluster.

Subject headings: cosmic microwave background — galaxies: clusters: individual (Coma) — magnetic fields — radiation mechanisms: nonthermal — X-rays: galaxies

1 INTRODUCTION

Nonthermal hard X-ray (HXR) emission was predicted in the 1970s in clusters of galaxies showing extended radio regions, radio halos, or relics, since the same radio synchrotron electrons can interact with the cosmic microwave background photons to give inverse Compton (IC) X-ray radiation (Perola & Reinhardt 1972; Rephaeli 1979). Several attempts to detect hard tails in the spectrum of a few clusters of galaxies were performed with various experiments (Bazzano et al. 1984, 1990; Rephaeli et al. 1987; Rephaeli & Gruber 1988; Rephaeli et al. 1994) that reported only upper limits to the nonthermal flux. A significant breakthrough in the measurement of nonthermal HXR emission was obtained thanks to the improved sensitivity and wide spectral capabilities of the BeppoSAX and Rossi X-Ray Timing Explorer (RXTE) satellites. As pointed out by Petrosian (2003), the discovery of nonthermal HXR radiation has led to a remarkable increase of the theoretical investigations regarding the possible acceleration mechanisms and origin of the relativistic electrons responsible for the nonthermal emission, although the presence of nonthermal phenomena in the intracluster medium of some clusters was established decades ago (Willson 1970).

Nonthermal HXR radiation was detected in excess of the thermal emission in the Coma Cluster by the first BeppoSAX observation (Fusco-Femiano et al. 1999) using the Phoswich Detection System (PDS) and confirmed by a second independent observation with a time interval of about 3 yr (Fusco-Femiano et al. 2004, hereafter FF04). The presence of a second component in the X-ray spectrum of the cluster has also been reported by two RXTE observations (Rephaeli et al. 1999; Rephaeli & Gruber 2002). A2256 is the second cluster in which a nonthermal excess has been measured by two BeppoSAX observations (Fusco-Femiano et al. 2000, 2005) and by RXTE (Rephaeli & Gruber 2003). At a lower confidence level, with respect to Coma and A2256, nonthermal HXR radiation has been detected by BeppoSAX in A754 (Fusco-Femiano et al. 2003b). An upper limit to the nonthermal flux has been reported in A3667 (Fusco-Femiano et al. 2001), A119 (Fusco-Femiano et al. 2003a), and A2163 (Feretti et al. 2001). For the last cluster an RXTE observation shows instead the presence of a HXR excess (Rephaeli et al. 2006). RXTE also reports some evidence of nonthermal emission by the Bullet Cluster (Petrosian et al. 2006).

The PDS spectra of all the BeppoSAX observations were extracted using the XAS version 2.1 package (Chiappetti & dal Fiume 1997) specifically created to handle the PDS peculiarities. However, a PDS data analysis performed with a different software package (SAXDAS) does not report evidence for the presence of a hard tail in the spectrum of the Coma Cluster (Rossetti & Molendi 2004, hereafter RM04).

To solve this contradiction we reanalyzed the PDS data of the two BeppoSAX observations using the SAXDAS version 2.0.2 package, and in this Letter we present our results and conclusions. In §2 we show the results of this analysis that are compared with those reported in FF04 using the XAS package, and we examine the possible systematic errors investigated by RM04 and Nevalainen et al. (2004, hereafter NE04). In §3 we discuss the reasons that have led to controversial results using different software packages. Finally, §4 is devoted to the conclusions regarding the presence of a hard tail in the spectrum of the Coma Cluster.

Throughout this Letter we assume a ΛCDM cosmology with \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) \( h_{70} \), \( \Omega_m = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \). An angular distance of 1’ corresponds to 29.0 kpc (\( z_{\text{Coma}} = 0.0232 \)). Quoted confidence intervals are at 90% level, if not otherwise specified.

2 PDS DATA REDUCTION AND RESULTS

The Coma Cluster was observed for the first time by the PDS instrument (Frontera et al. 1997) in 1997 December for ~91 ks and reobserved in 2000 December for ~300 ks. The pointing coordinates of BeppoSAX are at \( \alpha = 12^\mathrm{h}58^\mathrm{m}52^\mathrm{s}, \delta = +27^\circ58’54” \) (J2000.0). To resolve the discrepancy between the results shown by FF04 and RM04 regarding the presence of a nonthermal component in the HXR Coma spec-
trum, we have reanalyzed the PDS data with the SAXDAS package used by RM04. However, we start by reporting the procedure used in the XAS analysis and the main results obtained. More details can be found in FF04.

2.1. XAS Analysis

The PDS data used in the XAS analysis were selected by a first automatic procedure followed by a visual check in order to eliminate all the remaining spikes that can significantly affect the analysis results. The effective exposure times in the two PDS observations were 44.5 and 122.2 ks, respectively (hereafter OBS1 and OBS2). Since the source is rather faint in the PDS band (∼5 mcrab in 15–100 keV), a careful check of the background subtraction was performed, making use of the default rocking law of the two PDS collimators that samples ON/ON−OFF/ON−OFF fields for each collimator with a dwell time of 96 s (Frontera et al. 1997). When one collimator is pointing ON-source, the other collimator is pointing toward one of the two OFF positions. Initially, we used the standard procedure to obtain PDS spectra (Dal Fiume et al. 1997); this procedure consists of extracting one accumulated spectrum for each unit for each collimator position. We then checked the two independently accumulated background spectra in the two different +/−OFF sky directions, offset by 210′ with respect to the on-axis pointing direction (+OFF pointing: α = 12°58′57.8″, δ = +24°28′55.1″; −OFF pointing: α = 12°58′47.0″, δ = +31°28′54.7″). The comparison between the two accumulated backgrounds (difference between the +OFF and −OFF count rate spectra) showed that for OBS1 the difference was compatible with zero (0.044 ± 0.047 counts s−1 for a background level of 21.66 ± 0.02 counts s−1 in 15–100 keV), while for the longer, more sensitive OBS2, there was an excess of 0.064 ± 0.021 counts s−1 (background 16.76 ± 0.01 counts s−1). As reported in FF04, a careful check of possible variable sources in the PDS offset fields led the attention to the BL Lac source 1ES 1255+244, present in the +OFF field, that was observed by BeppoSAX in 1998 May in the framework of a spectral survey of BL Lac objects by Beckmann et al. (2002). Because of the very short exposure time (∼3 ks), our analysis of the source has determined only a 2σ upper limit of 0.26 counts s−1 in 15–100 keV, corresponding to 1.6 mcrab, however compatible with the background excess measured in OBS2. Moreover, just in the center of the +OFF field the extremely weak ROSAT source RX J125847.1+242741 is also present. The presence of these contaminating sources justified the decision to exclude the +OFF field in the background evaluation and consider only the −OFF field as the “uncontaminated” background for both the Coma observations.

The combined spectrum, obtained by summing the spectra of the two observations (OBS1 and OBS2), shows a nonthermal hard excess with respect to the thermal component at the confidence level (c.l.) of ∼4.8 σ in the 20–80 keV energy range considering only the −OFF background spectrum. The spectrum is reported in Figure 1. FF04 also reported the confidence level of the nonthermal excess considering the standard procedure, i.e., by using as background the average of the spectra extracted from both of the two offset fields. The c.l. is lower (∼3.9 σ) due to the contamination in the +OFF background. The average gas temperature used in the analysis is that measured by Ginga of 8.11 ± 0.07 keV (David et al. 1993) in a field of view comparable to that of the PDS (FWHM ∼1.3′). This value of the average temperature is confirmed by a determination of RXTE that reports a best-fit temperature of 7.90 ± 0.03 keV (Rephaeli & Gruber 2002) in a field of view of ∼1′ comparable to the field of view of Ginga and PDS.

2.2. SAXDAS Analysis

The first combined spectrum was extracted considering the PDS data resulting by the automatic selection operated by the SAXDAS package. The confidence level of the excess, in the range 20–80 keV and for an average gas temperature of 8.11 keV, is ∼2.9 σ (observed count rate = 0.1717 ± 0.0146 counts s−1, model predicted rate = 0.1295 counts s−1), taking into account only the uncontaminated −OFF position. The effective exposure time is 42.8 ks in OBS1 and 119.3 ks in OBS2 for a total exposure time of 162.1 ks. To resolve the discrepancy between these results and those obtained by FF04 with a XAS analysis (see § 2.1), a new combined spectrum was extracted considering the same time windows used in the XAS analysis. These time windows are different from those used by RM04 in their SAXDAS analysis. The reason is in the different criterion for eliminating the spurious spikes produced by the charged particles that interact with the PDS detectors: a semi-automated procedure (i.e., an automated procedure followed by a visual check) for XAS and a completely automated procedure for SAXDAS (Guainazzi & Matteucci 1997). With the same time windows used by XAS, the c.l. of the excess in the SAXDAS spectrum raises at ∼4.2 σ (observed count rate = 0.1902 ± 0.0148 counts s−1, model predicted rate = 0.1280 counts s−1), while the total exposure time reduces to 160.9 ks (it was 162.1 ks).

The two packages, starting from the same time windows, produce a difference in the total effective exposure time of 5.8 ks (tXAS = 166.7 ks, tSAXDAS = 160.9) essentially due to (1) the different Earth angle above which data are selected (the Earth angle is defined as the angle between the Earth limb and the BeppoSAX pointing direction). The Earth angle is 5° for XAS and 10° for SAXDAS. And (2) the removal of observational time after any South Atlantic Geomagnetic Anomaly (SAGA)
passage. The SAXDAS package removes 5 minutes after any passage, while XAS eliminates the time necessary to reach the correct voltage of the instruments after their shut-down during the SAGA passage.

In conclusion, we have a lower exposure time for the SAXDAS analysis, which may imply a lower c.l. of the nonthermal excess. To quantify this difference we have extracted a further combined spectrum using the same time windows selected in the XAS analysis but imposing an Earth angle of 5° in the SAXDAS package. The total effective time exposure of the two observations is now $t_{\text{SAXDAS}} = 169.1$ ks instead of $160.9$ ks. The excess results to be at the c.l. of $\sim 4.6 \sigma$ (observed count rate $= 0.1944 \pm 0.0144$ counts s$^{-1}$, model predicted rate $= 0.1280$ counts s$^{-1}$). This HXR spectrum is reported in Figure 2. The difference in the initial energy of the SAXDAS and XAS spectra (SAXDAS spectrum starts at 12 keV, while XAS at 15 keV) gives insignificant variations in the c.l. values of the nonthermal excess.

2.3. Possible Systematic Errors

The systematic errors examined by RM04 and NE04 have already been discussed by us in the PDS analysis of A2256 (Fusco-Femiano et al. 2005), but considering their importance in the analysis results we intend to report here again the main parts of the discussion:

1. RM04 claim the presence of an “instrumental background residual” (see § 2.1 of their paper) derived from the analysis of 15 “blank fields,” i.e., fields that do not contain sources showing significant emission in the PDS energy range. By summing the spectra from these observations they find that the spectrum differs from zero: the count rate is $(1.45 \pm 0.77) \times 10^{-2}$ counts s$^{-1}$ in the 12–100 keV energy range. This seems to indicate that the background in the ON position is larger than that in the ±OFF positions, producing an instrumental contribution not removed by the background subtraction procedure. This effect has been studied by Landi (2005) considering the complete sample of 868 PDS pointings with galactic latitude $|b| > 15^\circ$, and selecting the 15–100 keV net count spectra for which there is source detection below 1 σ (that is, “blank fields”). These spectra have been summed imposing a net exposure greater than 20 ks. A net count rate of $(1.67 \pm 5.30) \times 10^{-3}$ counts s$^{-1}$ has been derived, consistent with the definition of blank field. Also, NE04 do not report evidence for an instrumental residual.

2. The other effect evaluated by RM04 regards the systematic differences between the background fields. They analyze a sample of 69 observations whose target is outside the galactic plane and with a long exposure time (see the Appendix of their paper). RM04 find that the mean value of the difference between ON and the two ±OFF and +OFF sky positions is significantly different from zero and positive. This effect has also been investigated by Landi (2005) on the whole sample of PDS observations. The obtained value of $(5.3 \pm 6.3) \times 10^{-3}$ counts s$^{-1}$ is consistent with no contamination at all. We presume that the value found by RM04 could be due to the small sample of observations they considered. NE04, analyzing a larger sample of data with respect to that used by RM04 (164 PDS observations), found a systematic difference between ON and the two offset pointings that cancels out in the standard usage of both offsets.

3. In addition, NE04 introduce a systematic error in the net source count rates due to unresolved and not significantly detected point sources present in the PDS field of view. They find that an excess of 0.019 counts s$^{-1}$ has to be added to the net count rate spectra (no errors are given on this measurement), when the standard method of background evaluation is used, and 0.027 counts s$^{-1}$ has to be added when the background is evaluated from only one offset field. We performed this same analysis on a set of 868 observations (NE04 use 164 fields) and find that the contribution of background fluctuations due to unresolved and not significantly detected sources in the offset fields (in other words, the PDS confusion limit) introduces a variance $\sigma^2_{\text{fluc}} = (9.5 \pm 10.3) \times 10^{-4}$ (counts s$^{-1}$)$^2$ consistent with zero (see also Fusco-Femiano et al. 2005). Therefore, PDS data are not affected by this systematic effect.

3. DISCUSSION

Figure 2 also shows that the PDS combined spectrum extracted with the SAXDAS package reveals the presence of a nonthermal excess with respect to the thermal emission at about the same c.l. reported by the XAS analysis (FF04) ($\sim 4.8 \sigma$ for XAS and $\sim 4.6 \sigma$ for SAXDAS). The discrepancy between the results reported in FF04 and RM04 is mainly due to (1) an accurate selection of the events (in fact, we have shown that the SAXDAS analysis of the same PDS time windows used with the XAS software leads to a significant increase of the c.l. of the excess [from $\sim 2.9 \sigma$ to $\sim 4.2 \sigma$]) and (2) a correct determination of the background. The XAS and SAXDAS spectra shown in Figures 1 and 2, respectively, are obtained considering only the ±OFF background. The exclusion of the ±OFF position in the background determination implies a more pronounced detection of nonthermal radiation from the Coma Cluster. The check regarding the presence of contaminating sources in the ±OFF field was not operated by RM04.

An increase of $\sim 0.4 \sigma$ in the c.l. value is obtained adopting in the SAXDAS analysis the same Earth angle of 5° used in the XAS procedure. The lower Earth angle implies a greater exposure time that justifies an improvement in the c.l. value of the nonthermal excess. Considering in the SAXDAS analysis the same time windows and the same Earth angle used in the XAS analysis, the difference in the total exposure time is 2.4 ks in favor of the SAXDAS package ($t_{\text{XAS}} = 166.7$ ks, $t_{\text{SAXDAS}} = 169.1$ ks) due to the different removal of the time operated by the two packages after any SAGA passage. The XAS package
results to be more conservative waiting more time than SAXDAS to allow the PDS high voltage to reach the correct levels. Thus, some spurious events could be present in the SAXDAS analysis, in particular for the longer OBS2 observation.

In order to reproduce the results obtained by RM04, we have computed the c.l. of the excess for OBS1 and OBS2 spectra (RM04 do not report the c.l. value for the combined spectrum) using the automatic selection of the events operated by the SAXDAS package and the standard procedure for the background determination. The c.l. values are 2.90 and 1.34 for OBS1 and OBS2, respectively, in the energy range 25–80 keV and for an average gas temperature of 8.21 keV. These values are not much distant from those reported in Table 2 of RM04 (2.84 σ for OBS1 and 1.11 σ for OBS2), confirming that the selection procedure of the PDS events and the exclusion of the +OFF position for the background determination are the main reasons for the different results reported in FF04 and RM04.

The PDS data analysis of very weak sources like Coma in the HXR band requires a rigorous selection of the events in order to eliminate the presence of any spikes able to introduce noise that hides the presence of a nonthermal excess with respect to the thermal radiation. The presence of contaminating sources in the offset fields does not allow the use of the standard procedure for the background evaluation.

4. CONCLUSIONS

We have shown that the presence of a nonthermal excess with respect to the thermal emission in the spectrum of the Coma Cluster does not depend on the used software package (XAS or SAXDAS) for the PDS data analysis. The spectra extracted with XAS and SAXDAS, reported in Figures 1 and 2, respectively, show both a nonthermal excess at about the same c.l. value when in the SAXDAS analysis the same time windows used in the XAS analysis (FF04) are adopted and the +OFF sky direction is not taken into account in the background determination for the presence of contaminating sources. The systematic effects claimed by RM04 and NE04 can be excluded, considering the whole sample of the PDS observations off the Galactic plane.

This reanalysis of the PDS data, using the SAXDAS package, explains the different results reported in FF04 and RM04, confirming the presence of a nonthermal component in the Coma Cluster spectrum.

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5 These values of the c.l. of the excess refer to the line “No Subtraction” (no subtraction of the instrumental residual that Landi (2005) find consistent with zero; see § 2.3).