CONFIRMATION OF NONTHERMAL HARD X-RAY EXCESS IN THE COMA CLUSTER FROM TWO EPOCH OBSERVATIONS

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Received 2003 November 21; accepted 2004 January 9; published 2004 February 5

ABSTRACT

We report the hard X-ray spectrum of the Coma Cluster obtained using the Phoswich Detection System data of two independent BeppoSAX observations performed with a time interval of about 3 yr. In both the spectra a nonthermal excess with respect to the thermal emission is present at a confidence level of ~3.4 σ. The combined spectrum obtained by adding up the two spectra allows a measurement of the excess at the level of ~4.8 σ at energies above 20 keV. The analysis of the full BeppoSAX data set provides a revised nonthermal X-ray flux that is slightly lower than that previously estimated (Fusco-Femiano et al.) and in agreement with that measured by two Rossi X-Ray Timing Explorer observations. The analysis of the offset fields in our Coma observations provides a possible flux determination of the BL Lac object 1ES 1255+244.

Subject headings: BL Lacertae objects: individual (1ES 1255+244) — cosmic microwave background — galaxies: clusters: individual (Coma) — magnetic fields — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

In the hierarchical scenario of structure formation, clusters of galaxies form by the gravitational merger of subclusters and groups. Numerical simulations of large-scale structure formation indicate that this class of objects undergo several merger processes as they form (West, Villumsen, & Dekel 1991; Katz & White 1993). Cluster mergers are highly energetic events, and the associated large-scale shocks and turbulence could provide the ingredients necessary to the formation of extended radio regions (radio halos or relics) detected so far in a limited number of clusters, namely, a magnetic field amplification and particle reacceleration (Tribble 1993; Roettiger, Burns, & Stone 1999a; Roettiger, Stone, & Burns 1999b; Cavaliere, Menci, & Tozzi 1999; Brunetti et al. 2001; Fujita, Takizawa, & Sarazin 2003). Clusters of galaxies with detected diffuse radio emission indeed show significant evidence of merger activity. The existence of megaparsec-scale radio halos or relics combined with the relatively short radioactive lifetimes of the electrons (~10^7 yr) suggests an in situ electron reaccelerated induced by a very recent or current merger event (Markevitch & Vikhlinin 2001). The presence of large radio regions could be related to the origin of the nonthermal hard X-ray (HXR) emission detected in the Coma Cluster (Fusco-Femiano et al. 1999; Rephaeli, Gruber, & Blanco 1999; Rephaeli & Gruber 2002) and A2256 (Fusco-Femiano et al. 2000; Rephaeli & Gruber 2003) by BeppoSAX and the Rossi X-Ray Timing Explorer (RXTE) and, at lower confidence level, by BeppoSAX in A754 (Fusco-Femiano et al. 2003b). The most likely interpretation of the nonthermal HXR radiation is inverse Compton (IC) emission by the same radio synchrotron electrons scattering the cosmic microwave background (CMB) photons. However, one cannot completely exclude the possibility that the nonthermal emission detected by BeppoSAX and RXTE may be due to the presence of obscured sources in the field of view of the detectors. The BeppoSAX/MECS images test this possibility only in the cluster central region of size ~30′ in radius, while the BeppoSAX/Phoswich Detection System (PDS; Frontera et al. 1997a), which is able to detect HXR radiation in the energy range 15–200 keV, has a larger field of view (FWHM ~1′3). The probability to find obscured sources, such as Circinus (Matt, Guinanazzi, & Maiolino 1999), very active at high energies in the field of view of the PDS is estimated to be of the order of 10% (Kaastra 1999; Fusco-Femiano et al. 2003a). Future deep observations by the Imager on Board the INTEGRAL Satellite (IBIS) with a spatial resolution of ~12′ can definitely resolve this uncertainty.

In this Letter, we present the results of a long BeppoSAX observation of ~300 ks that confirms the presence of a nonthermal HXR tail in the spectrum of the Coma Cluster in agreement with the detection obtained by a previous shorter observation of ~91 ks, after data reanalysis of the first observation slightly modified the numerical results reported in Fusco-Femiano et al. (1999) but not the general conclusions. Finally, we show the combined spectrum obtained by summing the spectra of the two observations. Throughout this Letter we assume a Hubble constant of H_0 = 50 km s^{-1} Mpc^{-1} and q_0 = 3/2, so that an angular distance of 1′ corresponds to 40.6 kpc (z_{Coma} = 0.0232). Quoted confidence intervals are at the 90% level, if not otherwise specified.

2. PDS DATA REDUCTION AND RESULTS

The Coma Cluster was observed for the first time in 1997 December for ~91 ks and reobserved in 2000 December for ~300 ks. The pointing coordinates of BeppoSAX are at α = 12^h58^m52s, δ = +27°58′54″ (J2000.0). The total effective exposure times of the PDS in the two observations were 44.5 and 122.2 ks, respectively (hereafter OBS1 and OBS2). The PDS spectra of both the observations were extracted using the XAS version 2.1 package (Chiappetti & Dal Fiume 1997). The choice of using this software is dictated by the nonstandard pipeline needed to extract the net count spectra (see below). Because our Institute (i.e., IASF/Bologna) was in charge of the design, construction, and maintenance of the PDS, and we developed and

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tested the XAS package, specifically created to handle the PDS peculiarities (while the SAXDAS package, used for the standard analysis, is more suitable for handling imaging instruments, such as MECS and LECS), we felt more confident in using XAS for the PDS analysis. Since the source is rather faint in the PDS band (<5 mcrab in 15–100 keV), a careful check of the background subtraction must be performed. The background sampling was performed by making use of the default rocking law of the two PDS collimators that samples ON/OFF, ON/OFF fields for each collimator with a dwell time of 96 s (Frontera et al. 1997a). 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: \( \alpha = 12^h58^m57^s, \delta = +24^\circ28'55'' \); OFF pointing: \( \alpha = 12^h58^m47^s, \delta = +31^\circ28'54'' \)). The comparison between the two accumulated backgrounds (difference between the +OFF and −OFF count rate spectra) shows that for OBS1, the difference is 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 is an excess of 0.064 ± 0.021 counts s\(^{-1}\) (background 16.76 ± 0.01 counts s\(^{-1}\)). A careful check of possible variable sources in the PDS offset fields leads our attention to the BL Lac source 1ES 1255+244, present in the +OFF field. Luckily, this same source was observed by BeppoSAX in 1998 May in the framework of a spectral survey of BL Lac objects by Beckmann et al. (2002), who, surprisingly, state that “for 1ES 1255+244 there are no PDS data.” Indeed, we retrieved the raw data from the ASI Scientific Data Center, extracted the PDS spectrum (the background has to be evaluated only on one offset field because the other is pointed exactly on Coma—the two sources are contaminating each other), and found that the source is quite faint, consistent with zero flux being detected. Because of the very short exposure time (\( \sim 3 \) ks), it is only possible to give a 2 σ 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. It is worth noting that it is possible to derive a more stringent upper limit on the X-ray flux from 1ES 1255+44 at the time of our Coma OBS2 by assuming that all the contamination in the +OFF field comes from this source. It is straightforward to show that the 0.064 ± 0.021 counts s\(^{-1}\) excess translates into 428 ± 424 net counts when one takes into account the much shorter

| Observation | Epoch   | PDS Exposure (ks) | Observed Rate (counts s\(^{-1}\)) | Predicted Rate (counts s\(^{-1}\)) | Excess (c.l.) | Flux\(^{b}\) (10\(^{-11}\) ergs cm\(^{-2}\) s\(^{-1}\)) |
|------------|---------|-------------------|-------------------------------|-----------------------------------|--------------|---------------------------------|
| OBS1       | 1997 Dec| 44.5              | 0.390 ± 0.033                 | 0.278                             | 3.4 σ        | 2.3 ± 1.0                       |
| OBS2       | 2000 Dec| 122.2             | 0.333 ± 0.017                 | 0.275                             | 3.4 σ        | 1.3 ± 0.1                       |
| Combined   |         | 166.7             | 0.349 ± 0.015                 | 0.276                             | 4.8 σ        | 1.5 ± 0.5                       |

Note.—Quoted errors at 90% confidence level for a single parameter.

\( a \) Excess with respect to a 8.1 keV (David et al. 1993) thermal bremsstrahlung component for energies above 20 keV (see text for details).

\( b \) A photon index of 2 was used to derive the flux (see text for details).

BL Lac observation (3340 s) compared to our OBS2 and an upward factor of 2 correction due to the ~40′ off-axis position of the source, corresponding to a 50% intensity reduction because of the triangular collimator response (Frontera et al. 1997b). At its face value, this is consistent with the run of PDS counts as compared to the MECS counts in the BL Lac sample studied by Beckmann et al. (2002), barring time variability effects.

Returning to the Coma observations, to remain on the safe side we decided to exclude the +OFF field in the background evaluation and consider only the −OFF field as the “uncontaminated” background for both the Coma observations. Moreover, just in the center of the +OFF field is also present the extremely weak ROSAT source RX J125847.1+242741. However, in § 3 we also report the level of confidence of the nonthermal excess considering the average of the measured backgrounds in the two positions. The observed count rate of OBS1 is 0.78 ± 0.03 counts s\(^{-1}\) in the 15–100 keV energy range, at a confidence level of ~26 σ. In the first analysis the nonthermal excess with respect to the thermal bremsstrahlung emission reported by the PDS was at the confidence level of ~4.5 σ. The derived nonthermal flux was \( \sim 2.2 \times 10^{-11} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 20–80 keV energy band (assuming a photon index \( \Gamma_x = 1.5 \)). By relating the radio and the nonthermal fluxes it was then possible to estimate a volume-averaged intracluster magnetic field \( B \sim 0.15 \) μG, using only observables (Fusco-Femiano et al. 1999). It should be pointed out that a reanalysis of these data has evidenced a trivial mistake in the previous data analysis (summing three spectra, one of them was summed twice), so that the correct spectrum obtained from OBS1 shows an excess with respect to the thermal component with the average gas temperature measured by Ginga (8.11 ± 0.07, 90%; David et al. 1993) at a somewhat lower confidence level of ~3.4 σ (see Table 1). The fit with a single temperature gives ~9.9\(^{+1.3}_{-1.1}\) keV, above the average gas temperature measured by Ginga (with a field of view comparable to that of the PDS), implying the presence of a second spectral component. The fit with two thermal components (one fixed at 8.1 keV) requires an unrealistic second temperature (>50 keV) that strongly supports a nonthermal mechanism for the additional component present in the spectrum of the Coma Cluster. If we consider a power law for the second component, the PDS data are not able to fix the photon index, but the nonthermal flux is rather stable against index variations. We assume a photon index \( \Gamma_x = 2.0 \) to derive the nonthermal flux that results to be ~2.5 ± 1.0 × 10\(^{-11}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 20–80 keV energy range.

The observed count rate of OBS2 is 0.72 ± 0.02 counts s\(^{-1}\) in the 15–100 keV energy range, at the confidence level of ~36 σ. At energies above 20 keV, the spectrum shows an excess with respect to the thermal emission (\( kT = 8.1 \) keV) at a con-
fidence level of $\sim 3.4 \sigma$ (see Table 1). The fit with a single temperature gives $9.5^{+0.8}_{-0.6}$ keV. Also, OBS2 indicates the presence of an additional spectral feature, and also, in this case, the fit with a second thermal component requires unrealistic values for the temperature. The nonthermal flux ($\Gamma_1 = 2.0$) is $1.3^{+0.6}_{-0.8} \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the band 20–80 keV, consistent with the flux reported in OBS1. The nonthermal fluxes are (marginally) consistent also at a 68% confidence level: $(2.3 \pm 0.7) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the first observation and $1.3^{+0.3}_{-0.4} \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the second one.

The combined spectrum is obtained by summing the spectra of the two observations (see Fig. 1). The total count rate is $0.740 \pm 0.017$ counts s$^{-1}$ in the 15–100 keV energy range, at the confidence level of $\sim 44 \sigma$. At energies greater than 20 keV, the HXR excess is at the confidence level of $\sim 4.8 \sigma$ (see Table 1). Even the inclusion of a 1% systematic to the data, necessary for sources with high signal-to-noise ratio but not for faint sources such as Coma (Frontera et al. 1997b), does not change the significance of our nonthermal HXR excess. The fit with a single thermal component gives $9.7 \pm 0.6$ keV, well above the average gas temperature measured by Ginga, with a statistically unacceptable $\chi^2$ value ($= 2.1$ for 8 degrees of freedom [dof]). The presence of a second component is more evident from the $\chi^2$-value that has a significant decrement when a second component, a power law, is added to the thermal component with $kT = 8.1$ keV. The improvement passing from the first model ($\chi^2 = 4.10$ for 9 dof) to the second one ($\chi^2 = 1.2$ for 7 dof) is significant at more than 99.4% confidence level, according to the $F$-test. Also, the combined spectrum cannot be fitted with a second thermal component unless an unrealistic value for the temperature is assumed, thus supporting the nonthermal origin for this additional spectral feature. The nonthermal flux for $\Gamma_1 = 2.0$ is $(1.5 \pm 0.5) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the 20–80 keV energy range, and it is rather stable, assuming reasonable different values of the photon index. In fact, for $\Gamma = 1.5$ the flux is $\sim 6\%$ lower, and for $\Gamma = 2.5$ it is $\sim 15\%$ higher.

3. DISCUSSION

Nonthermal HXR emission has been reported in two BeppoSAX observations of the Coma Cluster performed with a time interval of about 3 yr. Both the observations indicate the presence of a nonthermal excess with respect to the thermal emission at a confidence level of $\sim 3.4 \sigma$. The combined spectrum obtained by adding up the two spectra gives an excess at the confidence level of $\sim 4.8 \sigma$. The spectra of the two observations have been obtained using only the uncontaminated background-accumulated pointing at the ($\sim$OFF) field. However, by considering the average of the background measurements in the two sky directions in both the observations, the excess is still significant at the level of $\sim 3.9 \sigma$ (observed count rate $= 0.324 \pm 0.013$ counts s$^{-1}$, model predicted rate $= 0.273$ counts s$^{-1}$). The nonthermal fluxes measured in the two observations are consistent at the 90% confidence level and marginally at the 68% confidence level. The nonthermal fluxes obtained using the Ginga measurement of $8.11 \pm 0.07$ keV (David et al. 1993) for the average gas temperature that is in good agreement with the XMM-Newton determination (Arnaud et al. 2001) of $8.25 \pm 0.10$ keV in the central region ($R < 10'$) of the cluster. In fact, all the X-ray observations of Coma (Hughes, Fabricant, & Gorenstein 1998a; Hughes et al. 1993, 1988b; Watt et al. 1992) have indicated a clear pattern: the larger the field of view, the lower the measured temperature. Besides, RXTE reports a best-fit temperature of $7.90 \pm 0.03$ keV (Rephaeli & Gruber 2002) in a field of view of $\sim 1'$ comparable to that of the PDS. However, also considering $kT = 8.25$ keV for the average gas temperature in the field of view of the PDS, the nonthermal excess is at the level of $\sim 4.6 \sigma$ (observed count rate $= 0.349 \pm 0.015$ counts s$^{-1}$, model predicted rate $= 0.280$ counts s$^{-1}$), and the derived nonthermal flux has a negligible variation. Recent PDS data analysis of Coma performed with the SAXDAS software has led to controversial results: an analysis of both observations has not reported evidence for a nonthermal excess (Rossetti & Molendi 2004), while the analysis of the first one (OBS1) by Nevalainen et al. (2004) confirms our published HXR detection, albeit at a lower confidence level for the systematic uncertainties of their work. A systematic comparison between PDS spectra extracted by means of the two software packages (XAS, used here, and SAXDAS) is under way. Preliminary results on the analysis performed on sources of different luminosities show that the spectral parameters do not change when computed with different packages. On the other hand, the errors associated to the spectral parameters are smaller when using XAS. This effect is more accentuated for faint sources. We suspect that this could be due to differences in filtering of good data and/or in the spectral equalization (i.e., conversion from spectral channels to energy channels) that for SAXDAS is performed after summing the four PDS units, while for XAS it is performed before. These effects will be discussed in detail in a forthcoming paper.

As discussed in the Introduction, the likely origin of the nonthermal HXR excesses detected by BeppoSAX and RXTE is IC emission by the same relativistic electrons responsible for the diffuse radio emission scattering the CMB photons, as predicted in the 1970s (see Perola & Reinhardt 1972; Rephaeli 1979).

On behalf of the PDS group, see ftp://ftp.tesre.bo.cnr.it/pub/sax/doc/software_docs/xas_vs_saxdas.ps.
et al. (1999) favoring a central magnetic field strength of 1–6 \mu G; Feretti et al. 1995). Newman, Newman, & Rephaeli (2002) have recently pointed out that many and large uncertainties are associated with the determination of \( B_{FR} \) (see also Govoni et al. 2003 and Govoni & Murgia 2004). The present value of the nonthermal HXR flux is slightly lower than that reported in Fusco-Femiano & Murgia 2004). The present value of the nonthermal X-ray flux is consistent with the confidence level of the nonthermal excess is in the interval \( \sim 3.9 \sigma \). In the framework of the IC model, the combination of the radio and nonthermal X-ray fluxes allows an estimate for a volume-averaged intracluster magnetic field \( B_x \) of \( \sim 0.2 \mu G \) (see Fusco-Femiano et al. 1999). This value seems to be in contrast with the line-of-sight magnetic field derived from the Faraday rotation of polarized radiation of sources through the intracluster medium (ICM; \( B_{FR} \sim 6 \mu G \); Feretti et al. 1995). The IBIS on board INTEGRAL with its \( \gamma \) detection at a confidence level slightly above 3 \sigma by BeppoSAX, and the derived value of the magnetic field is of the same order of that determined in Coma (Fusco-Femiano et al. 2003b). The PDS detection should be confirmed by a deeper observation with imaging instruments for the presence of the radio galaxy 26W20 located at a distance of \( \sim 27' \) from the BeppoSAX pointing. The IBIS on board INTEGRAL with its spatial resolution of \( \sim 12' \) has the possibility to eliminate this ambiguity and to detect the excess at a higher confidence level with respect to that obtained by BeppoSAX.

We wish to thank F. Frontera for stimulating discussions and the referee for the useful suggestions.

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