HARD X-RAY RADIATION IN THE COMA CLUSTER SPECTRUM

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ABSTRACT

Hard X-ray radiation has been detected for the first time in the Coma Cluster by BeppoSAX. Thanks to the unprecedented sensitivity of the Phoswich Detection System (PDS) instrument, the source has been detected up to ~80 keV. There is clear evidence (4.5σ) for nonthermal emission in excess of thermal emission above ~25 keV. The hard excess is very unlikely to be the result of X Comae, the Seyfert 1 galaxy that is present in the field of view of the PDS. A hard spectral tail that is due to inverse Compton scattering on cosmic microwave background photons is predicted in clusters, like Coma, with radio halos. Combining the present results with radio observations, a volume-averaged intracluster magnetic field of ~0.15 μG is derived, while the electron energy density of the emitting electrons is ~7 × 10^{-14} ergs cm^{-3}.

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

1 INTRODUCTION

Nonthermal hard X-ray radiation (HXR) is predicted in galaxy clusters with radio halos, such as Coma C in the central region of the Coma Cluster (Willson 1970), because of inverse Compton (IC) scattering by relativistic electrons of the cosmic microwave background (CMB) photons. The combined radio and HXR detections directly yield an estimate of the mean volume-averaged intracluster magnetic field, B, and of the electron energy density, ρ_e. Actually, to obtain information on ρ_e, knowledge of the size of the radio source and of the distance of the cluster are also needed. It is worth remarking that the procedure is based essentially only on observables. An accurate estimate of magnetic fields and electron and proton densities present in clusters of galaxies is essential for a clearer picture of the intracluster environment. In particular, these quantities are crucial to establish the role of magnetic fields on the dynamical history and the contribution of the relativistic particles to the intracluster gas heating (Rephaeli 1979).

Here we present the first detection of hard X-ray emission from the Coma Cluster obtained by BeppoSAX (Boella et al. 1997). Preliminary results have already been presented by Fusco-Femiano et al. (1998). The Coma Cluster was observed in 1997 December for an exposure time of ~91 ks. Here we discuss results from the two passively collimated instruments, the High-Pressure Gas Scintillation Proportional Counter (HPGSPC), whose energy range is 4–120 keV, and the Phoswich Detection System (PDS), working in the 15–200 keV energy range.

The main aim of this long observation was to search for nonthermal hard X-ray radiation that exploited the unique capabilities of the PDS: an overall sensitivity better than a few times 10^{-6} photons cm^{-2} s^{-1} keV^{-1} in the 40–80 keV energy band, a relatively small field of view (FWHM = 1′), a wide 15–200 keV energy range, and a low and stable background thanks to the equatorial orbit.

The cluster was also observed with the Medium-Energy Concentrator/Spectrometer (MECS), an imaging instrument working in the 1.5–10 keV energy range. Here we briefly summarize the results that will be discussed in detail in a forthcoming paper. Spatially resolved spectroscopy was performed on the core of the cluster with concentric annuli of 2′ within a region 8′ in radius (~325 kpc). There is no evidence for variations of the intracluster medium (ICM) temperature and metallicity in the observed region. The average temperature was determined to be 9.1 ± 0.1 keV, while the average iron abundance is 0.26 ± 0.02.

Throughout this Letter, we assume a Hubble constant of H_0 = 50 km s^{-1} Mpc^{-1} h, and q_0 = 1/2, so that an angular distance of 1′ corresponds to 40.6 kpc (z_{Coma} = 0.0232). Quoted confidence intervals are at a 68% level, if not otherwise specified.

2 PDS AND HPGSPC DATA REDUCTION

The PDS and the HPGSPC instruments use the rocking collimator technique for background subtraction with angles of 3′5 and 3′, respectively. In the PDS, the standard observation strategy is to observe the X-ray target with one collimator and to monitor the background level on both sides of the source position with the other, so that a continuous monitoring of the source and background is obtained. The standard dwell time in each position of both collimators is 96 s. The background level of the PDS is the lowest obtained thus far with high-energy instruments on board satellites, thanks to the equatorial orbit. In the 15–300 keV energy band, the background is ~2 × 10^{-4} counts cm^{-2} s^{-1} keV^{-1} (Frontera et al. 1997). The background is very stable, again thanks to the favorable orbit, and no modeling of the time variation of the background is required. Counts are excluded from the analysis for 300 s after the passage of the satellite through the trapped radiation of the South Atlantic Geomagnetic Anomaly. In the HPGSPC, the collimator assumes an on- and off-source position with the same dwell time as the PDS (Manzo et al. 1997).

The correctness of the PDS background subtraction has been
checked by verifying that the counts fluctuate at about zero flux as the signal falls below detectability. This happens at energies greater than ~80 keV. Two broad, strong features that peaked at ~30 and ~60 keV are present in the PDS background spectrum (Frontera et al. 1997). However, even excluding the counts in the energy bands of these features, hard X-ray radiation is still detectable.

3. PDS AND HPGSPC DATA ANALYSIS AND RESULTS

The PDS detected hard X-ray emission in the 15–80 keV energy range in the Coma Cluster spectrum, as shown in Figure 1. We started the spectral analysis by working only with the PDS data in order to have a robust indication of the presence of a nonthermal component in the observed HXR. The MECS data are not very helpful in this respect since its field of view is much smaller than that of the PDS. With the PDS data alone, however, it is not possible to perform complex spectral fits, and one has to resort to fixing the temperature of the intracluster medium. Different temperatures, in the range of 7.5–8.5 keV, have been reported by previous X-ray observations for the Coma Cluster (Hughes, Gorenstein & Fabricant 1988a; Hughes et al. 1988b; Watt et al. 1992; Hughes et al. 1993), but with a clear pattern: the larger the field of view, the lower the measured temperature. By fixing the temperature of the thermal component to the average cluster value of 8.21 keV, as determined by the Large Area Counter experiment on board *Ginga* (whose field of view of $1^\circ \times 2^\circ$ is not much different from that of the PDS), we obtain the fit shown in Figure 1. Adopting a temperature as high as 9.1 keV, as observed by the MECS in the cluster core, the results are substantially the same. The flux of the thermal component is $\sim 3.3 \times 10^{-5}$ ergs cm$^{-2}$ s$^{-1}$ in the 2–10 keV energy range; the reduced $\chi^2$ of the fit is 3.2 for 9 degrees of freedom (dof), mainly because of a clear excess above 25 keV at a 4.5 $\sigma$ level. Leaving the temperature as a free parameter, a value of $kT = 10.73^{+0.81}_{-0.71}$ is obtained; the reduced $\chi^2$ is 2.14 for 8 dof. The $\chi^2$ value decreases significantly when a second component is added. Modeling this further component as a power law, as for nonthermal emission, the reduced $\chi^2$ value is 0.92 for 7 dof. The confidence interval for the power-law spectral index is rather large, 0.7–3.6, but the flux ($\sim 2.2 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the 20–80 keV energy range) does not depend much on the power-law index. On the other hand, if we consider a second thermal component, instead of the nonthermal one, the fit requires a temperature greater than 40 keV. This unrealistic value may be interpreted as a strong indication that the detected hard excess is due to a nonthermal mechanism. It is worth remarking that the X-ray fluxes measured by *Ginga* and PDS coincide, within the errors, in their common energy range of 15–20 keV, where the flux is still dominated by the IC M thermal component. The contribution of the nonthermal component is not greater than 20% at 20 keV, even adopting the rather steep value of 2.34 (see § 4) for the spectral index of the hard flux.

The analysis of the PDS data alone cannot provide a precise estimate of the nonthermal spectral index. A tighter constraint can be obtained by including in our analysis the HPGSPC data in the 4.5–20 keV energy range, as shown in Figure 2. The HPGSPC instrument has a field of view ($1^\circ \times 1^\circ$) comparable to that of the PDS ($1^\circ 3$, hexagonal) and therefore can be used for a global spectral fit. Combining HPGSPC and PDS data, it is then possible to leave the temperature of the intracluster medium as a free parameter in the fit procedure. The relative normalization of the two instruments has been left free, to account for the slightly different field of views and the remaining uncertainties in the intercalibration. We obtain an IC M temperature of 8.5$^{+0.5}_{-0.4}$ keV, which is consistent with the *Ginga* determination, and an iron abundance of 0.15$^{+0.06}_{-0.04}$. The reduced $\chi^2$ is 0.80 for 34 dof. The resulting allowed spectral index range is 0.7–2.5, which is smaller than the previous one determined by using only the PDS data but still is not sufficient to distinguish between different emission mechanisms. If we fix the parameters of the thermal component to their best-fit values, we obtain 1.57$^{+0.36}_{-0.39}$ (90%) for the photon index of the nonthermal radiation, corresponding to a contribution of the nonthermal emission to the 2–10 keV flux between ~2% and 10%.

4. DISCUSSION

The PDS on board the *BeppoSAX* satellite detected hard X-ray emission up to energies of ~80 keV in the spectrum of the Coma Cluster, with a clear excess above the thermal intracluster
emission, which is best explained as a nonthermal component. One possible explanation for the observed excess is emission by a different source in the field of view. The most qualified candidate is the Seyfert 1 galaxy X Comae at $z = 0.092 \pm 0.002$ (Bond & Sargent 1973). The ROSAT PSPC observation (Dow & White 1995) reports a power-law spectrum with a photon index of $2.50 \pm 0.16$ and a flux of $3.6 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.4–2.4 keV band (corresponding to $\sim 1.6 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ in the range of 2–10 keV). X Comae has also been observed by EXOSAT (Branduardi-Raymont et al. 1985) and by the Einstein IPC Slew Survey (Elvis et al. 1992) at approximately the same flux level. The steep photon index reported by ROSAT requires an unusual variability of a factor $\sim 65$ to explain the detected hard excess, considering that the source is $\sim 27''$ off-axis and $N_{\text{H,gal}} = 9 \times 10^{20}$ cm$^{-2}$. With a more typical photon index of 1.8, the variability factor is $\sim 11$, no longer extreme but still large. Luckily enough, X Comae is located just on the edge of the field of view of the MECS, and part of the point-spread function of the source lies within the field of view of the detector. Considering the location of X Comae and the lack of detection, it is possible to estimate an upper limit to the flux of the source on the order of $\sim 4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (2–10 keV), which is much lower than the flux of $\sim 2.9 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ (photon index = 1.8) required to account for the HXR.

If, instead, we assume that the hard spectral tail detected at energies above 25 keV is due to relativistic electrons scattering the CMB photons, it is possible to derive, using only observables, the value of the mean volume-averaged intracluster magnetic field, $B$. In the Coma Cluster, the radio halo Coma C has an extension of $\sim 1$ Mpc in radius and is located in the central region of the cluster. Relating the observed synchrotron radio flux to the X-ray IC flux, we obtain

$$f_s = C(\alpha)F_s B^{-\alpha} \nu^{-\alpha} n_e^{-\alpha},$$

where $\alpha$ is the slope of the radio halo spectrum and $F_s$ is the radio flux at the frequency $\nu_s$ for $C(\alpha)$, see Rephaeli (1979).

The value of the radio halo spectral index is still uncertain for Coma C. Considering all the radio fluxes measured between 30.9 MHz and 1.4 GHz, Kim et al. (1990) and Giovannini et al. (1993) determined a value of $\alpha = 1.34 \pm 0.06$, while $\alpha = 1.16 \pm 0.03$ is obtained using the flux measured at 1.4 GHz by Deiss et al. (1997). We have remodeled the radio flux spectrum of Coma C between 30.9 MHz and 2.7 GHz using the data set given in Giovannini et al. (1993), taking into account the electron energy losses due to synchrotron and IC emission (see Fig. 3). The best fit indicates an electron injection spectrum of $2.92 \pm 0.20$ ($\alpha = 0.96 \pm 0.10, 90\%$), while curvature of the radio spectrum is detected at $\nu > 100$ MHz because of electron aging. Considering that the electron energy range should be $2.4–4.9$ GeV in order to give IC emission in the 20–80 keV band and that the radio spectrum begins to steepen at $\nu > 100$ MHz, $\alpha = 0.96$ for values of $B \leq 25$ $\mu$G. The radio data and the X-ray spectrum detected by the PDS then imply a value of $B = \sim 0.14$ $\mu$G, while $B = \sim 0.16$ $\mu$G is obtained if the extreme value of 1.34 is adopted for $\alpha$. Using the size, $R$, and the distance, $d$, of the radio source, it is possible to estimate the electron energy density. Assuming a radio halo size $R = 1$ Mpc ($\sim 25'$) and a distance $d = 138$ Mpc, the energy density of electrons with energies $\geq 500$ MeV is $\sim 7 \times 10^{-14}$ ergs cm$^{-3}$. The estimated value of $B$ is not very different from the lower limit of 0.1 $\mu$G derived from the 2 $\sigma$ upper bounds on the HXR reported by the OSSE experiment (Rephaeli, Ulmer, & Gruber 1994). Binning the PDS data between $\sim 40$ and $\sim 80$ keV, the HXR flux ($\sim 4 \sigma$) is lower by a factor of $\sim 2$ with respect to the upper limit (see Fig. 1).

The nonthermal contribution to the 2–10 keV flux is $\sim 10\%$, $\sim 16\%$, and $\sim 24\%$ for $\alpha = 0.96, 1.16$, and 1.34, respectively. This contribution has implications for the determination of the intracluster gas properties.

The value of the magnetic field derived here seems to be inconsistent with the measurements of Faraday rotation of polarized radiation through the hot ICM that give a line-of-sight value of $B$ in the range of $\sim 2–6 h_{50}^{1/2}\mu G$ (Kim et al. 1990; Feretti et al. 1995). We note, however, that Feretti et al. (1995) also inferred the existence of a weaker magnetic field component, ordered on a scale of about a cluster core radius, with a line-of-sight strength in the range of $\sim 0.1–0.2 h_{50}^{1/2}\mu G$. From the results obtained here with the IC model, we can argue that the strongly tangled magnetic field component of $6 \mu$G is likely present in local cluster regions, while the overall cluster magnetic field may be more reasonably represented by the weaker and ordered component, whose strength is in good agreement with the present estimate. Other determinations (or lower limits) of $B$ that are based on different methods are in the range of 0.2–0.4 $\mu$G (Hwang 1997; Bowyer & Berghöfer 1998; Sreekumar et al. 1996; Henriksen 1998). In particular, the equipartition magnetic field is $\sim 0.4 h_{50}^{1/2}\mu G$ (Giovannini et al. 1993). Very attractive suggestions have been proposed regarding the origin of the IC magnetic field, such as the one suggesting that galaxy motion may be driving a turbulent dynamo that amplifies faint seed fields to an average value of $\sim 0.1–0.2 h_{50}^{1/2}\mu G$. The seed fields are supplied through gas loss by galaxies (Goldman & Rephaeli 1991; De Young 1992). Larger magnetic fields require different amplification mechanisms, such as merger activity.

Different interpretations have also been proposed to explain the nonthermal hard X-ray emission. Ensslin, Lieu, & Biermann (1998) suggest that it might be bremsstrahlung emission by
suprathermal electrons in the ICM, accelerated by turbulences within the medium. Another proposed emission mechanism is given by IC scattering of a large population of cosmic rays by the CMB photons (Lieu et al. 1999). In this model, the relativistic component could also be responsible for the soft excess discovered in a few clusters in the 69 eV–0.4 keV energy band (Lieu et al. 1996a; Bowyer, Lampton, & Lieu 1996; Fabian 1996; Mittaz, Lieu, & Lockman 1998; Bowyer, Lieu, & Mittaz 1998; Kaastra 1998). In particular, the remodeled EUV and soft X-ray data by Lieu et al. (1999) lead to a photon index of ~1.75. An extrapolation of the EUV spectra to higher energies gives an excess flux between 20 and 80 keV of \( \sim 1 \times 10^{-11} \) ergs cm\(^{-2}\) s\(^{-1}\), only a factor of \( \sim 2 \) lower than the PDS excess, suggesting a possible physical connection between the soft and hard excesses.

The next step in studying the hard X-ray emission would be a precise estimate of its spectral shape, which would help in discriminating between competing emission mechanisms. A longer BeppoSAX observation of the Coma Cluster would be valuable in this respect. Sarazin \& Lieu (1998) suggest that a relic population of very low energy cosmic-ray electrons may be responsible for the IC EUV excess detected also in clusters of galaxies in which radio halos are absent. It would be of great interest to investigate radio-quiet clusters of galaxies to verify whether or not hard X-ray excesses are common in galaxy clusters.

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**REFERENCES**

Boella, G., et al. 1997, A&AS, 122, 299

Bond, H. E., \& Sargent, W. L. W. 1973, ApJ, 185, L109

Bowyer, S., \& Berghöfer, T. W. 1998, preprint (astro-ph/9804310)

Bowyer, S., Lampton, M., \& Lieu, R. 1996, Science 274, 1338

Bowyer, S., Lieu, R., \& Mittaz, J. P. D. 1998, in Proc. IAU Symp. 188, The Hot Universe, ed. K. Koyama, S. Kitamoto, \& M. Inoue (Dordrecht: Kluwer), 52

Branduardi-Raymont, G., Mason, K. O., Murdín, P. G., \& Martin, C. 1985, MNRAS, 216, 1043

Deiss, B. M., Reich, W., Lesch, H., \& Wielebinski, R. 1997, A&A, 321, 55

De Young, D. S. 1992, ApJ, 386, 464

Dow, K. L., \& White, S. D. M. 1995, ApJ, 439, 113

Elvis, M., Plummer, D., Schachter, J., \& Fabbiano, G. 1992, ApJS, 80, 257

Einslín, T. A., Lieu, R., \& Biermann, P. L. 1998, A&A, submitted (astro-ph/9808139)

Fabian, A. C. 1996, Science, 271, 1244

Feretti, L., Dallacasa, D., Giovannini, G., \& Tagliani, A. 1995, A&A, 302, 680

Frontera, F., Costa, E., Dal Fiume, D., Feroci, M., Nicastro, L., Orlandini, M., Palazzi, E., \& Zavattini, G. 1997, Proc. SPIE, 3114, 206

Fusco-Femiano, R., Dal Fiume, D., Feretti, L., Giovannini, G., Matt, G., \& Molendi, S. 1998, in Proc. 32nd COSPAR Scientific Assembly, Nagoja, Japan, ed. K. Makishima, L. Piro, \& T. Takahashi, in press

Giovannini, G., Feretti, L., Venturi, T., Kim, K. T., \& Kronberg, P. P. 1993, ApJ, 406, 399

Goldman, I., \& Rephaeli, Y. 1991, ApJ, 380, 344

Henriksen, M. 1998, PASJ, 50, 389

Hughes, J. P., Butcher, J. A., Stewart, G. C., \& Tanaka, Y. 1993, ApJ, 404, 611

Hughes, J. P., Gorenstein, P., \& Fabricant, D. 1988a, ApJ, 329, 82

Hughes, J. P., Yamashita, K., Okumura, Y., Tsunemi, H., \& Matsuoka, M. 1988b, ApJ, 327, 615

Hwang, C.-Y. 1997, Science, 278, 1917

Kaastra, J. S. 1998, in Proc. 32nd COSPAR Scientific Assembly, Nagoja, Japan, ed. K. Makishima, L. Piro, \& T. Takahashi, in press

Kim, K. T., Kronberg, P. P., Dewdney, P. E., \& Landecker, T. L. 1990, ApJ, 355, 29

Lieu, R., Ip, W.-H., Axford, W. L., \& Bonamente, M. 1999, ApJL, in press

Lieu, R., et al. 1996a, Science 274, 1335

———. 1996b, ApJ, 458, L5

Manzo, G., et al. 1997, A&AS, 122, 341

Mittaz, J. P. D., Lieu, R., \& Lockman, F. J. 1998, ApJ, 498, L17

Rephaeli, Y. 1979, ApJ, 227, 364

Rephaeli, Y., Ulmer, M., \& Gruber, D. E. 1994, ApJ, 429, 554

Sarazin, C. L., \& Lieu, R. 1998, ApJ, 494, L177

Sreekumar, P., et al. 1996, ApJ, 464, 628

Watt, M. P., Ponman, T. J., Bertram, D., Eyles, C. J., Skinner, G. K., \& Willmore, A. P. 1992, MNRAS, 258, 738

Willson, M. A. G. 1970, MNRAS, 151, 1