### Hard X-ray emission from the galaxy cluster A2256

Roberto Fusco-Femiano

Istituto di Astrofisica Spaziale, C.N.R., via del Fosso del Cavaliere, I-00133 Roma, Italy dario@saturn.ias.rm.cnr.it

> Daniele Dal Fiume TESRE, C.N.R., via Gobetti 101, I-40129 Bologna, Italy

> > Sabrina De Grandi

Osservatorio Astronomico di Brera, via Bianchi 46, I-23807 Merate, Italy

Luigina Feretti

Istituto di Radioastronomia, C.N.R., via Gobetti 101, I-40129 Bologna, Italy

Gabriele Giovannini

Istituto di Radioastronomia, C.N.R., via Gobetti 101, I-40129 Bologna, Italy Dip. di Fisica, Univ. Bologna, via B. Pichat 6/2, I-40127 Bologna, Italy

Paola Grandi Istituto di Astrofisica Spaziale, C.N.R., via del Fosso del Cavaliere, I-00133 Roma, Italy

> Angela Malizia BeppoSAX SDC, via Corcolle 19, I-00131 Roma, Italy

> > Giorgio Matt

Dip. Fisica, Univ. Roma Tre, via della Vasca Navale 84, I-00146 Roma, Italy

Silvano Molendi Istituto di Fisica Cosmica, C.N.R., via Bassini 15, I-20133 Milano, Italy

## ABSTRACT

After the positive detection by  $BeppoSAX$  of hard X-ray radiation up to ∼80 keV in the Coma cluster spectrum, we present evidence for nonthermal emission from A2256 in excess of thermal emission at a  $4.6\sigma$  confidence level. In addition to this power law component, a second nonthermal component already detected by ASCA could be present in the X-ray spectrum of the cluster, not surprisingly given the complex radio morphology of the cluster central region. The spectral index of the hard tail detected by the PDS onboard BeppoSAX is marginally consistent with that expected by the inverse Compton model. A value of  $\sim 0.05 \mu G$  is derived for the intracluster magnetic field of the extended radio emission in the northern regions of the cluster, while a higher value of  $\sim 0.5 \mu G$  could be present in the central radio halo, likely related to the hard tail detected by ASCA .

Subject headings: cosmic microwave background — galaxies: clusters: individual  $(A2256)$  — magnetic fields — radiation mechanisms: non-thermal — X-rays: galaxies

### 1. Introduction

Nonthermal hard X-ray (HXR) radiation has been detected for the first time in the Coma cluster by BeppoSAX (Fusco-Femiano et al. 1999) and RXTE (Rephaeli, Gruber & Blanco 1999), while marginal evidence is reported for A2199 (Kaastra *et al.* 1999). These observations are only first steps towards assessing the general existence of this new component in the X-ray spectra of clusters of galaxies. The search for nonthermal emission in more clusters is of high importance as it will allow to derive additional informations on the physical conditions of the intracluster medium (ICM) environment, which cannot be obtained by studying the thermal plasma emission only.

Various interpretations of the HXR emission have been presented since its discovery in the Coma cluster spectrum. The most direct explanation is inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by the relativistic electrons responsible of the extended radio emission present in the central region of Coma (Willson 1970). The combined radio synchrotron and IC HXR fluxes (e.g., Rephaeli 1979) allow to estimate a volume-averaged intracluster magnetic field of  $\sim 0.16 \mu G$  (Fusco-Femiano *et al.* 1999). One of the problems with the IC model is that this value of the magnetic field in the ICM seems to be at odd with the value determined from Faraday rotation of polarized radiation toward the head tail radio galaxy NGC4869 that gives a line-of-sight  $B \sim 6 \mu G$  (Feretti *et al.* 1995), and with the equipartition value in the radio halo, which is ~ 0.4  $h_{50}^{2/7}$   $\mu$ G (Giovannini *et al.* 1993). We note, however, that Feretti et al. (1995) also inferred the existence of a weaker and larger scale magnetic field component in the range of 0.1 – 0.2  $h_{50}^{1/2}$  µG, and therefore the ~ 6 µG field could be local. A low average magnetic field is also consistent with the model developed by Brunetti et al. (1999), which predicts a magnetic field strenght decreasing with the distance from the cluster centre.

An alternative explanation is nonthermal bremsstrahlung (NTB) emission from suprathermal electrons currently accelerated at energies greater than ∼10 keV by shocks or turbulence (Kaastra et al. 1998; Ensslin, Lieu, & Biermann 1999; Sarazin & Kempner 1999). Another and more trivial possibility is that the HXR radiation is due to a hard X-ray source present in the external regions of the field of view of the  $BeppoSAX$  PDS (FWHM=1.3°, hexagonal), as for example a highly obscured Seyfert 2 galaxy like the Circinus galaxy (Matt *et al.* 1999). In the central region ( $\sim 30'$ in radius), the MECS image does not show evidence of this kind of sources (Fusco-Femiano 1999). Hovewer, the detection of a hard nonthermal component in other clusters should strongly reduce the probability of this last interpretation.

In this letter we present the results of a long observation of A2256, exploiting the unique

capabilities of the PDS, onboard  $BeppoSAX$ , to search for HXR emission (Frontera *et al.* 1997). The cluster was also observed with the MECS, an imaging instrument working in the 1.5-10 keV energy range (Boella *et al.* 1997). The galaxy cluster A2256 is similar to the Coma cluster in many X-ray properties, as luminosity and presence of substructures. The ROSAT PSPC observations showed that  $A2256$  is a double X-ray cluster (Briel *et al.* 1991), suggesting that a subcluster may be merging with a larger cluster, although there is no strong evidence in the temperature map in favour of an advanced merger (Markevitch & Vikhlinin 1997), as it is for Coma. The average gas temperature is ∼7 keV, as measured by several X-ray instruments (David et al. 1993; Hatsukade 1989; Markevitch & Vikhlinin 1997; Henriksen 1999). Both clusters show a radio halo in the central and periferal regions. However, the radio emission from A2256 is notably complex. The region around the cluster centre is occupied by an unusual concentration of radio galaxies: at least five discrete sources have been identified with cluster galaxies, but there also two extended emission regions which have linear sizes  $\leq$ 1 Mpc (Bridle & Formalont 1976; Bridle *et al.* 1979; Rottgering et al. 1994).

Throughout the Letter we assume a Hubble constant of  $H_o = 50$  km s<sup>-1</sup> Mpc<sup>-1</sup> h<sub>50</sub> and  $q_0 = 1/2$ , so that an angular distance of 1' corresponds to 92 kpc ( $z_{A2256} = 0.0581$ ; Struble & Rood 1991). Quoted confidence intervals are at 90% level, if not otherwise specified.

## 2. PDS and MECS Data Reduction

The total effective exposure time was  $\sim 1.3 \times 10^5$  sec for the MECS and  $\sim 7.1 \times 10^4$  sec for the PDS in the two observations of February 1998 and February 1999. The observed count rate for A2256 was  $0.497\pm0.002$  cts/s for the 2 MECS units and  $0.27\pm0.04$  cts/s for the PDS instrument.

Since the source is rather faint in the PDS band (approximately 1.5 mCrab in 15-150 keV) a careful check of the background subtraction must be performed. The background sampling was performed using 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" (Frontera et al. 1997). When one collimator is pointing ON source, the other collimator is pointing toward one of the two OFF positions. We used the standard procedure to obtain PDS spectra (Dal Fiume et al. 1997), which consists in 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. The comparison between the two accumulated backgrounds  $([-OFF] - [OFF])$  shows a difference with a marginal excess below 30 keV in the  $[+OFF]$  pointing. This excess is much lower than the signal from the source, but it must not be neglected. The total excess in the first two equalized energy channels (15-33.5 keV) is  $0.048 \pm 0.024$  cts s<sup>-1</sup>, i.e. approximately  $2\sigma$ . This concentration in only the lowest energy channels implies that the excess is likely due to contamination by a point source rather than to a statistical fluctuation. The total source spectrum was therefore obtained using only the uncontaminated background accumulated pointing at the [-OFF] field. Hovewer, in Section 3 we

report the confidence level of the nonthermal emission in excess of the thermal one considering the average of the two background measurements. The background level of the PDS is the lowest obtained thus far with high-energy instruments on board satellites thanks to the equatorial orbit and is very stable again thanks to the favorable orbit. No modeling of the time variation of the background is required.

MECS data preparation and linearization was performed using the Saxdas package under FTOOLS environment. We have extracted a MECS spectrum from a circular region of 8' radius (corresponding to about 0.8 Mpc) centered on the primary emission peak. From the ROSAT PSPC radial profile, we estimate that about 70% of the total cluster emission falls within this radius. The background subtraction has been performed using spectra extracted from blank sky event files in the same region of the detector as the source.

A numerical relative normalization factor among the two instruments has been included in the fitting procedure (see next Section) to account for: a) the fact that the MECS spectrum includes emission out to ∼0.8 Mpc from the X-ray peak, while the PDS field of view (1.3 degrees FWHM) covers the entire emission from the cluster; b) the slight mismatch in the absolute flux calibration of the MECS and PDS response matrices employed (September 1997 release; Fiore, Guainazzi & Grandi 1999); c) the vignetting in the PDS instrument, (the MECS vignetting is included in the response matrix). The estimated normalization factor is ∼1.1. In the fitting procedure we allow this factor to vary within 15% from the above value to account for the uncertainty in this parameter.

### 3. PDS and MECS Data Analysis and Results

The spectral analysis of the MECS data alone, in the energy range 2-9.7 keV and in the central ~0.8 Mpc region, gives a gas temperature of  $kT = 7.41 \pm 0.23$  keV ( $\chi^2$ =154.5 for 162 degrees of freedom; hereafter dof), using an optically thin thermal emission model (MEKAL code on the XSPEC package), absorbed by a galactic line of sight equivalent hydrogen column density,  $N_H$ , of  $4.01\times10^{20}$  cm<sup>-2</sup>. This value of the temperature is consistent with the ASCA GIS measurement (6.78-7.44 keV; Henriksen 1999), and with the values obtained by previous observations : the *Einstein* MPC  $(6.7-8.1 \text{ keV}; \text{David } et \text{ al. } 1993)$  and  $Ginga (7.32-7.70 \text{ keV}; \text{Hatsukade } 1989)$ . Also the flux of  $\sim 5.3 \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> in the 2-10 keV energy range is consistent with the previous measurements. The iron abundance is  $0.26 \pm 0.03$ , in agreement with the ASCA results (Markevitch & Vikhlinin 1997).

The analysis of the PDS data with a thermal bresstrahlung component gives a temperature of ∼30 keV. Fitting the data with two thermal components, one of these at the fixed temperature of 7.4 keV, we obtain a temperature greater than ∼90 keV for the second component. These unrealistic high values for the gas temperature obtained in both the fits are interpreted as a strong indication that the detected hard excess is due to a nonthermal mechanism.

Figure 1 shows the simultaneous fit to the MECS and PDS data with a thermal component at the temperature of 7.47±0.35 keV and a normalization factor of ∼1.2 for the two data sets. The  $\chi^2$  is 180.5 for 167 dof. Hard X-ray radiation at energies greater than ∼20 keV is in excess with respect to the thermal component at a level of  $\sim 4.6\sigma$  and this value is rather stable against variation of the normalization factor. It results slightly lower ( $\sim 4.5\sigma$ ) considering the average of the two background measurements. Besides, also fitting the PDS data alone with a thermal component at the fixed temperature of 7.47 keV we obtain an excess at a level of  $4.3\sigma$ . If we introduce a second nonthermal component, modeled as a power law, we obtain the fit shown in figure 2. The  $\chi^2$  is 156.6 for 165 dof. The improvement with respect to the previous model is significant at more than the 99.99% confidence level, according to the F-test. The confidence contours of the parameters kT and photon spectral index  $(\alpha_X)$  show that, at 90% confidence level. the temperature is well determined, 6.8-7.5 keV, while  $\alpha_X$  describes a large interval 0.3-1.7. The presence of the nonthermal component has the effect to slightly decrease the best fit value of the temperature  $(6.95^{+0.45}_{-0.35}~\text{keV})$ , with respect to the temperature obtained considering only the MECS data. The flux of the nonthermal component is rather stable,  $\sim 1.2 \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> in the 20-80 keV energy range, against variations of  $\alpha_X$ . The contribution of the nonthermal component to the thermal flux in the 2-10 keV energy range is  $\leq 10\%$  for  $\alpha_X \leq 1.70$ . The analysis of the two observations with effective exposure times of ∼23 ksec (February 1998) and ∼48 ksec (February 1999) for the PDS does not show significant flux variations. These results and the fact that the two clusters with a detected hard X–rays excess (Coma and A2256) both have radio halos, strongly support the diffuse nonthermal mechanism as responsible for the excess, as discussed in the next section.

# 4. Discussion

A2256 is the second cluster, after Coma (Fusco-Femiano *et al.* 1999), which shows hard X-ray radiation up to ∼80 keV in the PDS spectrum, with a clear excess above the thermal intracluster emission. (A2199 shows only a marginal evidence in the external region of the MECS detectors, Kaastra et al. 1999). We have investigated the possibility that the observed excess in A2256 could be due by a confusing source in the field of view of the PDS. The most qualified candidate is the QSO 4C +79.16 observed by ROSAT PSPC with a count rate of ∼0.041 c/s (WGA Catalogue). With a typical photon index of 1.8 (ROSAT reports a steeper index of  $\sim$ 2.5), about 1.2 c/s are necessary to account for the observed HXR emission of  $\sim 1.2 \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> in the 20-80 keV energy range of the PDS. Considering that the QSO is  $\sim$  52′ off-axis, an unusual variability of about two orders of magnitude is required. There is still the possibility that an obscured source, like Circinus (Matt et al. 1999), be responsible of the detected HXR radiation. Unless the obscured source is within 2′ of the central bright core of A2256, our analysis of the MECS image excludes the presence of this kind of sources in the central region ( $\sim 30'$  in radius) of the cluster.

The application of the inverse Compton model, based on the scattering of relativistic electrons

with the 3K background photons, appears less straightforward in A2256 than in the Coma cluster. The radio morphology is remarkably complex (Bridle & Fomalont 1976; Bridle et al. 1979; Rottgering et al. 1994). There are at least four radio sources classified as head-tail radio galaxies, an ultra steep spectrum source and a diffuse region in the north with two diffuse arcs  $(G,H)$ according to Bridle *et al.* 1979), at a distance of  $\sim 8'$  from the cluster centre. The extent of this diffuse region is estimated to be  $1.0 \times 0.3$  Mpc, with a total flux density of 671 mJy at 610 MHz and a rather uniform spectral index of  $0.8\pm0.1$  between 610 and 1415 MHz (Bridle *et al.* 1979). The percentage polarization is uniform with an average value of 20%. The alignement of the electric field vectors suggests a well ordered magnetic field. The equipartition magnetic field is 1-2  $\mu$ G (Bridle et al. 1979). A fainter extended emission permeates the cluster centre (diffuse emission around D in Bridle et al. 1979) with a steeper radio spectral index of  $\sim$ 1.8 as estimated by Bridle et al. (1979) and in agreement with the 327 MHz data from the Westerbork Northern Sky Survey (Rengelink *et al.* 1997). The total flux density is 100 mJy at 610 MHz and no polarized emission have been detected from this region. We note that the physical and morphological properties of the diffuse D emission are consistent with those of central halo sources while those in the  $G - H$ region are consistent with the properties of peripheral relic sources as 1253+275 in the Coma cluster.

In addition to the thermal emission, a second component in the X-ray spectrum of A2256 was noted by Markevitch & Vikhlinin (1997) in their spectral analysis of the ASCA data in the central r=3′ spherical bin. Although they were not able to firmly establish the origin of this emission, their best fit is a power law model with photon index  $2.4\pm0.3$ , therefore favouring a nonthermal component. The contribution of this component to the total flux is not reported in the paper. Considering that there are no bright point sources in the  $ROSAT$  HRI image, they argued for an extended source. Also the joint ASCA GIS & RXTE PCA data analysis is consistent with the detection of a nonthermal component in addition to the thermal component. The contribution of this nonthermal component to the total X-ray flux in the 2-10 energy range is  $\leq 4\%$ . However, a second thermal component (0.75-1.46 keV), instead of a nonthermal one, provides a better description of the data (Henriksen 1999). The MECS data do not show evidence of this steep nonthermal component in the central bin of 2′ because the energy range is truncated to a lower limit of 2 keV (Molendi, De Grandi, & Fusco-Femiano 2000), while a joint fit to the LECS & MECS data within 4′ does not show a significant evidence for an additional component at energies lower than 2 keV.

The power-law component (slope  $2.4 \pm 0.3$ ) found in the analysis of the ASCA data (Markevitch & Vikhlinin 1997), and the upper limit of 1.7 for  $a_X$ , determined by  $BeppoSAX$  data, suggest that two tails could be present in the X-ray spectrum of A2256. The former might due to the central diffuse radio source with the steep index  $\alpha_R \sim 1.8$ , and the last to the more extended radio emission in the northern region of the cluster with the flatter energy spectral index of  $0.8\pm0.1$ . Assuming that the contribution of the power-law component, detected by  $ASCA$ , to the total X-ray flux  $(F_X(2-10keV) \sim 5 \times 10^{-11} \ erg \ cm^{-2} \ s^{-1}$  ) is  $\sim 5\%$ , we obtain a negligible

contribution at PDS energies ( $\sim 4 \times 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>) and a magnetic field in the central radio region of ~ 0.5  $\mu$ G. For the external radio region, with spectral index 0.8, the nonthermal X-ray flux  $f_X(20 - 80keV) \simeq 1.2 \times 10^{-11}$  erg  $cm^{-2}$  s<sup>-1</sup>, derived by the PDS excess, leads to a low value of ~ 0.05  $\mu$ G. Even assuming that a large fraction (say 50%) of the HXR flux is due to the several point radio sources in the central region and/or to the contribution of different mechanisms, we obtain only a slightly greater value of  $\sim 0.08 \mu$ G. The combined fit of ASCA GIS and RXTE PCA data (Henriksen 1999) gives an upper limit of  $2.64 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> in the 2-10 keV energy range for the nonthermal component that corresponds to a lower limit for the volume-averaged intracluster magnetic field, B, of 0.36  $\mu$ G ( $\alpha_R = 1.8$ ). Considering that the HXR flux detected by the PDS is in agreement with the above value, we would obtain a value for B consistent with that derived by the GIS  $&$  PCA data, but the fit to the MECS  $&$  PDS data is unacceptable for  $\alpha_X = 1 + \alpha_R = 2.8$ .

The previous scenario of a decreasing intracluster magnetic field from the cluster center would be difficult to reconcile with the stronger periferal radio region and higher equipartition magnetic field with respect to the central radio halo. Therefore, we could consider the possibility, recently suggested by Brunetti *et al.* (1999), that the HXR IC spectrum may be flatter than the synchrotron radio spectrum because of the acceleration and energy loss processes that produce an electron spectrum with different slopes. A different electron spectrum index for HXR and radio emissions is more likely for low magnetic fields which require higher electron energies for synchrotron than for IC radiation. This could explain the better fit to the PDS data of A2256 with  $\alpha_X < 1 + \alpha_R = 1.8$ . Besides, this model suggests an alternative interpretation of the HXR excess of A2256. We can consider that a single hard tail is present in the X-ray spectrum of the cluster with index  $\alpha_X \leq 1.7$ , as detected by the PDS. The electron spectrum responsible of this HXR IC emission can produce radio emission with spectral index  $\alpha_R > \alpha_X$ -1=0.7 with a resulting mean volume-averaged intracluster magnetic field higher than the one we derive from the classical IC model.

A different mechanism which may produce HXR radiation is given by nonthermal bremsstrahlung. Sarazin & Kempner (1999) suggest that all or part of the HXR emission detected in the Coma cluster might be NTB from suprathermal electrons formed through current acceleration of the thermal gas, either by shocks or turbulence in the ICM. For A2256 the MECS & PDS measurements determine a power-law momentum spectrum of the electrons with index  $\leq 2\alpha_X - 1 = 2.4$  (90%). The consequence is that an accelerating electron model with flat spectrum produce more IC HXR emission than the NTB mechanism, unless the electron spectrum cuts-off or steepens at high energies. Besides, these models produce more radio emission than observed if B is  $\geq 1 \mu G$ .

We thank P. Giommi for useful suggestions regarding data analysis, G. Brunetti for discussions on the interpretation of the results, and the referee for valuable comments.

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Fig. 1.— MECS and PDS data. The continuous line represents a thermal component at the average cluster gas temperature of 7.47 $\pm$ 0.35 keV. The errors bars are quoted at  $1\sigma$  level.

Fig. 2.— The continuous line is the best-fit to the MECS (2-9.7 keV) and PDS (15-150 keV) data. The dashed line represents the thermal component  $(kT=6.95^{+0.45}_{-0.35}~\text{keV})$ , while the dot-dashed line is the non-thermal component with a spectral index of 1.4. A value of 1.21 takes into account the relative normalization of the two instruments. The reduced  $\chi^2_{red}$  is 0.95 for 165 degrees of freedom.



