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HARD X-RAY EMISSION FROM THE GALAXY CLUSTER A3667

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ABSTRACT

We report the results of a long *BeppoSAX* observation of Abell 3667, one of the most spectacular galaxy clusters in the southern sky. A clear detection of hard X-ray radiation up to ~35 keV is reported, while a hard excess above the thermal gas emission is present at a marginal level that should be considered as an upper limit to the presence of nonthermal X-ray radiation. The strong, hard excesses reported by *BeppoSAX* in Coma and A2256 and the only marginal detection of nonthermal emission in A3667 can be explained in the framework of the inverse Compton model. We argue that the nonthermal X-ray detections in the Phoswich Detection System energy range are related to the radio index structure of halos and relics present in the observed clusters of galaxies.

Subject headings: cosmic microwave background — galaxies: clusters: individual (Abell 3667) — magnetic fields — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

Abell 3667 is one of the most intriguing clusters of galaxies. It contains one of the largest radio sources in the southern sky with a total extent of ~30′ that corresponds to ~2.6 h_{50}^{-1} Mpc. This diffuse radio emission is located to the northwest (NW), well outside the central core of the cluster. A similar but weaker radio region is also present to the southeast, yielding a very peculiar structure not observed in any other cluster (Robertson 1991; Röttgering et al. 1997). The megaparsec-scale radio relics may have originated from the ongoing merger that is visible in the optical (Sodré et al. 1992), in X-ray (Knopp, Henry, & Briel 1996), and in the weak lensing mass map (Joffre et al. 2000). In the optical, A3667 shows strong galaxy concentrations around the two brightest D galaxies (Proust et al. 1988; Sodré et al. 1992). The main optical component is coincident with the peak of the X-ray emission. The *ASCA* observation reports an average gas temperature of 7.0 ± 0.6 keV with a constant radially averaged profile up to ~22′. The *ASCA* temperature map shows that the hottest region is in between the two groups of galaxies, confirming the merger scenario (Markevitch, Sarazin, & Vikhlinin 1999). Recently, a *Chandra* observation reported a sharp X-ray brightness edge near the cluster core (Vikhlinin, Markevitch, & Murray 2001) that was due to a large cool gas cloud moving through the hot intracluster medium (ICM).

Major cluster mergers can produce large-scale shocks and turbulence in the ICM, establishing conditions for in situ particle reacceleration and magnetic field amplification (Tribble 1993; Longair 1994 and references therein). The nonthermal electron population produces emission in various energy bands. Extended radio sources are the most evident signatures of nonthermal processes in clusters of galaxies. More recently, the detections in the Coma Cluster (Fusco-Femiano et al. 1999; Rephaeli, Gruber, & Blanco 1999) and A2256 (Fusco-Femiano et al. 2000) of a hard X-ray excess with respect to the thermal emission represent further evidence of nonthermal processes in some clusters of galaxies. This allows us to derive additional information on the physical conditions of the ICM environment, which cannot be obtained by studying the thermal plasma emission only.

Both clusters for which nonthermal X-ray emission has been detected show extended radio halos in the center. Moreover, a relic region is present in A2256, at ~8′ from the center, more extended and brighter than the halo source (Bridle et al. 1979). Marginal evidence of nonthermal radiation is reported in the external regions of A2199 using the Medium-Energy Concentrator/Spectrometer (Kaastra et al. 1999); this cluster does not show any extended radio region. Therefore, the most direct explanation for the detected hard X-ray excesses is that they are due to inverse Compton (IC) scattering of cosmic microwave background photons by the relativistic electrons responsible for the radio emission. Alternative interpretations of the IC model for the nonthermal radiation detected in the Coma Cluster have been proposed. Blasi & Colafrancesco (1999) suggest a secondary electron production. However, this model implies a γ-ray flux considerably larger than the EGRET upper limit, unless the hard X-ray excess and the radio halo emission in Coma are not due to the same population of electrons. A different mechanism is given by nonthermal bremsstrahlung from suprathermal electrons formed through the current acceleration of the thermal gas (Ensslin, Lieu, & Biermann 1999; Dogiel 2000; Sarazin & Kempner 2000; Blasi 2000). At present, due to the low efficiency of the proposed acceleration processes and of the bremsstrahlung mechanism, these models would require an unrealistically high energy input, as recently pointed out by Petrosian (2001). Besides, this interpretation seems to be in conflict with the *BeppoSAX* detection of A2256 since the derived flat power-law spectrum of the electrons gives a negligible nonthermal bremsstrahlung contribution to the Phoswich Detection System (PDS) flux (Fusco-Femiano et al. 2000). These alternative models are motivated by the discrepancy between the value for the intracluster magnetic field derived by the *BeppoSAX* observation of the Coma Cluster ($B_X \sim 0.16$ μG; Fusco-Femiano et al. 1999) and the value derived from the Faraday rotation (FR) of polarized radiation

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toward the radio galaxy NGC 4869 ($B_{\rm FR} \sim 6$ μG; Feretti et al. 1995). However, this discrepancy could be resolved considering that Feretti et al. (1995) also inferred the existence of a weaker and larger scale magnetic field in the range of 0.1–0.2 $h_{50}^{1/2}$ μG consistent with the value measured by *BeppoSAX*, and therefore the component of ~6 μG could be local. Goldshmidt & Rephaeli (1993) suggested that the discrepancy between $B_{\rm X}$ and $B_{\rm FR}$ could be alleviated by taking into consideration the expected spatial profiles of the magnetic field and relativistic electrons. More recently, it has been shown that IC models that include the effects of more realistic electron spectra, combined with the expected spatial profiles of the magnetic field, and anisotropies in the pitch angle distribution of the electrons allow higher values of the intracluster magnetic field, in better agreement with the FR measurements (Brunetti et al. 2001; Petrosian 2001).

In this Letter, we present the results of a long observation of A3667, exploiting the unique capabilities of the PDS (Frontera et al. 1997) on board *BeppoSAX* to search for hard X-ray radiation (HXR) emission. We also discuss a possible explanation for the marginal detection of the nonthermal hard excess with respect to the thermal emission reported in this observation.

Throughout this Letter, we assume a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1} h_{50} and $q_0 = \frac{1}{2}$, so that an angular distance of 1′ corresponds to 87 kpc ($z_{\rm A3667} = 0.055$; Sodré et al. 1992). Quoted confidence intervals are at a 90% level, if not otherwise specified.

2. PDS DATA REDUCTION AND RESULTS

The pointing coordinates of *BeppoSAX* are at J2000 $\alpha = 20^{\rm h}11^{\rm m}30\overset{\rm s}{.}0$, $\delta = -56°40'0\overset{''}{.}0$, in proximity to the secondary galaxy concentration, and the PDS field of view (1°.3) includes only the radio region to the north of the cluster. The total effective exposure time for the PDS was ~1.13×10^5 s in the two observations of 1998 May and 1999 October.

Since the source is rather faint in the PDS band (approximately 0.44 mcrab in 15–40 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 s (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); 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. The comparison between the two accumulated backgrounds ([+OFF] vs. [−OFF]) does not show a difference in the two pointings. The background level of the PDS is the lowest and most stable obtained so far with the high-energy instruments on board satellites thanks to its equatorial orbit. No modeling of the time variation of the background is required. 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 ~35 keV.

Figure 1 shows a clear detection of hard X-ray emission up to ~35 keV, at a confidence level of ~10 σ. The observed count rate was 0.134 ± 0.013 counts s^{-1}. The fit to the PDS data with a thermal component (*solid line*) at the fixed average gas temperature of 7 keV derived from the *ASCA* observation (see § 1)

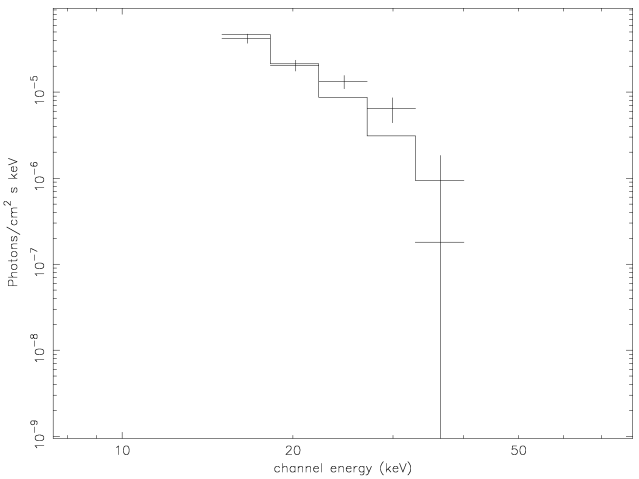

FIG. 1.—PDS data. The continuous line represents a thermal component at the average cluster gas temperature of 7 keV (Markevitch et al. 1998). The errors bars are quoted at a 1 σ level.

indicates the marginal presence of a hard excess at a confidence level of ~2.6 σ. If we introduce a second nonthermal component, modeled as a power law, we obtain an insignificant improvement with respect to the previous model, according to the *F*-test. The low statistics do not allow us to perform a fit with a thermal component at the fixed average cluster gas temperature and a second thermal component. The only possible fit is with a thermal bremsstrahlung model that gives a best-fit temperature of ~11 keV with a large confidence interval (7.7–16.8 keV; 90%). The average cluster gas temperature is only slightly different from this interval. Therefore, the ~2.6 σ excess should be considered as an upper limit to the presence of nonthermal HXR. The analysis of the two observations with effective exposure times of ~44 ks (1998 May) and ~69 ks (1999 October) for the PDS does not show significant flux variations.

3. DISCUSSION

Using the long observation by *BeppoSAX* of Abell 3667, we report robust evidence for hard X-ray emission in the PDS energy range of 15–35 keV and an upper limit for a hard nonthermal excess with respect to the thermal emission at the average gas temperature of 7 keV.

As pointed out in § 1, the most striking feature of Abell 3667 is the diffuse arc-shaped radio region located to the NW of the X-ray core with a total extent of ~30′ (~2.6 Mpc), one of the largest radio sources known in the southern sky. The total flux density is 5.5 ± 0.5 Jy at 843 MHz. Also, the spectral index structure is very interesting: a region with a flat spectrum ($\alpha_r \sim 0.5$) on the NW rim of the source with considerable steepening toward $\alpha_r \sim 1.5$ to the southwest (Röttgering et al. 1997). The overall radio spectral index of ~1.1 is consistent with the flux density measurements (Mills, Slee, & Hills 1961; Bolton, Gardner, & Mackey 1964; Robertson 1991). Fitting the PDS data with a thermal component, at a temperature of 7 keV, and a power law component, with an index of 2.1 ($1 + \alpha_r$), we derive a nonthermal IC flux upper limit of ~4.1×10^{-12} ergs cm^{-2} s^{-1} in the 15–35 keV energy range. Extrapolating this flux in the energy range of 20–80 keV, we obtain $F_{\rm X} \sim 6.4 \times 10^{-12}$ ergs cm^{-2} s^{-1}, which is a factor of ~3.4 and ~2 lower than the nonthermal fluxes detected in Coma and A2256, respectively. In the IC interpretation, this flux upper limit, combined with the radio

synchrotron emission, determines a lower limit to the volume-averaged intracluster magnetic field of 0.41 μG.

Given the presence of such a large radio region to the NW of A3667, a robust detection of a nonthermal X-ray component might be expected instead of the upper limit reported by *BeppoSAX*. This result cannot be attributed to the shift ($\sim 17'$) of the PDS pointing with respect to the centroid of the radio relic ($\alpha = 20^h10^m30^s$, $\delta = -56°25'0\farcs0$). Instead, one possible explanation may be related to the radio spectral index structure of the NW relic. As indicated by Roettiger, Burns, & Stone (1999), the sharp edge of the radio source is the site of particle acceleration, while the progressive index steepening with the increase of the distance from the shock would indicate particle aging due to radiative losses. In the narrow shocked region, where particle reacceleration is at work, the magnetic field is expected to be amplified by adiabatic compression, with the consequence that the synchrotron emission is enhanced, thus giving a limited number of electrons the ability to produce IC X-rays. In the postshock region of the relic, the electrons suffer strong radiative losses with no reacceleration, considering also that the relic is well outside the cluster core. Therefore, their energy spectrum develops a high-energy cutoff at $\gamma < 10^4$, and the electron energy is not sufficiently high to emit IC radiation in the hard X-ray band. Synchrotron emission is detected in the postshocked region because the magnetic field is still strong due to its likely long relax time.

The Coma Cluster, where nonthermal HXR emission is present at a significant level (Fusco-Femiano et al. 1999), shows a quite different radio index structure (Giovannini et al. 1993; Deiss et al. 1997). The cluster exhibits a central plateau ($R \sim 10'$) with a radio spectral index of $\sim$0.7 (in the core, it appears to be lower; Deiss et al. 1997) and a progressive spectral steepening with the increasing radius in the external regions of the radio halo. Moreover, the total extent of the radio halo ($R \sim 80'$) and the lack of a clear shocked region are not compatible with the scenario of the pure spectral aging of the emitting electrons. Thus, in situ reacceleration processes are required, probably because of turbulence related to recent mergers (Colless & Dunn 1996; Donnelly et al. 1999; Arnaud et al. 2001) with a possible additional contribution from the gas motion originating from the massive galaxies orbiting in the cluster core (Deiss & Just 1996). Brunetti et al. (2001) have recently shown that the radio observational properties of the Coma halo and the nonthermal HXR emission can be accounted for by a population of reaccelerated relativistic electrons with an energy break $\gamma_b \gtrsim 10^4$ emitting in a magnetic field that is smoothly decreasing from the center toward the periphery.

Similar considerations can be applied to Abell 2256, which is the second cluster that shows clear evidence of a hard excess above the thermal intracluster emission (Fusco-Femiano et al. 2000). Abell 2256 exhibits a large diffuse radio region (1.0×0.3 Mpc) to the north, at a distance of $\sim 8'$ from the cluster center (relic), with a rather uniform and flat spectral index of 0.8 ± 0.1 between 610 and 1415 MHz. A fainter extended emission (halo) permeates the cluster center with a steeper radio spectral index of $\sim$1.8 (Bridle & Fomalont 1976; Bridle et al. 1979; Röttgering et al. 1994; Rengelink et al. 1997). The low and uniform value of α_r in the cluster relic indicates a broad reacceleration region, probably the result of an ongoing merger event (Sun et al. 2001). Moreover, the presence of the central radio halo would favor the hypothesis that in situ reacceleration processes are active in the cluster volume. As discussed by Fusco-Femiano et al. (2000), in the framework of the IC model, the probable source of the nonthermal HXR emission is the large relic if the associated magnetic field is on the order of $\sim$0.1 μG. An additional contribution could be provided by the halo electrons if the radio index structure is similar to that of the Coma Cluster.

4. CONCLUSIONS

The positive detections of nonthermal HXR radiation in the Coma Cluster and A2256 and the upper limit reported in A3667 by *BeppoSAX* are explained in the framework of the IC model. In particular, these results appear to be related to the radio spectral index structure of the radio halos or relics present in these clusters. The essential requirement to detect nonthermal X-ray emission in the PDS energy range is the presence of large regions of reaccelerated electrons, with $\gamma \sim 10^4$, due to the balance between radiative losses and reacceleration gains in turbulence generated by recent merger events.

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