XXIst Moriond Astrophysics Meeting - Les Arcs March 10-17, 2001

HARD X-RAY EMISSION FROM THE GALAXY CLUSTERS A3667 AND A1367

R. FUSCO-FEMIANO
Istituto Astrofisica Spaziale, CNR, Area Ricerca Tor Vergata, via del Fosso del Cavaliere 100, Roma, Italy

We report the results of *BeppoSAX* observations of Abell 3667, one of the most spectacular galaxy clusters in the southern sky, and of Abell 1367. A clear detection of hard X-ray radiation up to ∼35 keV is reported for A3667, 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. A negative detection is instead reported for A1367. The strong hard excesses reported by *BeppoSAX* in Coma and A2256 and the marginal or negative detection of nonthermal emission in A3667 and A1367, respectively, can be explained in the framework of the inverse Compton model. We argue that the nonthermal X-ray detections in the PDS energy range are related to the radio index structure of halos and relics present in the observed clusters of galaxies.

1 Introduction

Clusters of galaxies are the largest organized structures present in the universe. They generally form by the gravitational merger of groups and subclusters. X-ray observations at energies ≤10 keV of thermal bremsstrahlung emission from the hot, relatively dense intracluster gas, have already contributed in an essential way to our understanding of the cluster environment. Recent researches on clusters of galaxies have unveiled new radiation components in the intracluster medium (ICM) of some clusters, namely a cluster soft excess discovered by the *EUVE* [1,2,3] and a hard X-ray (HXR) excess detected in the Coma cluster by *BeppoSAX* [4] and *RXTE* [5]. A second HXR excess was detected by *BeppoSAX* in the galaxy cluster A2256[6] while a marginal evidence is also reported for A2199[7] in the external regions of the cluster.

The extended radio sources are the most evident signatures of nonthermal phenomena in some ∼30 clusters of galaxies and the recent detections of nonthermal emission in the Coma cluster (see Fig. 1) and in A2256 (see Fig. 2) represent a further evidence of nonthermal processes in the intracluster space of some clusters of galaxies. Also the soft excess could be attributed to a nonthermal mechanism[8]. An improved knowledge of this class of objects implies the inclusion of nonthermal processes for a more precise physical description of the intracluster environment. The basic nonthermal quantities (magnetic field, relativistic electrons and protons) may interact with the gas and thereby affect its thermal state. The likely origin of the nonthermal processes responsible for the radio and hard X-ray emissions is in the major cluster mergers that can produce large-scale shocks and turbulence in the ICM establishing conditions for in-situ particle reacceleration and magnetic field amplification[9,10].

Both the Coma cluster and A2256 where nonthermal X-ray emission has been detected show extended radio halos or relics or both. A2199, where *BeppoSAX* reported a marginal

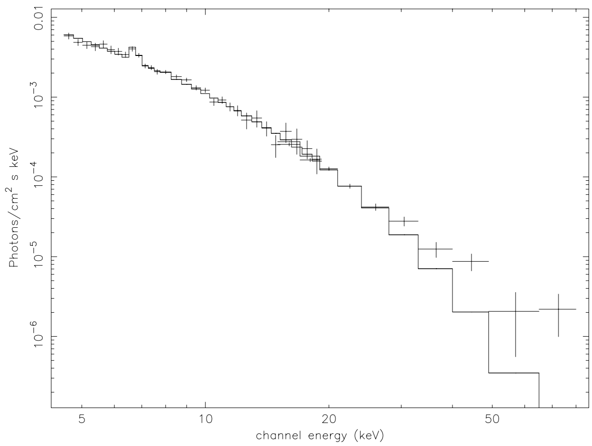

Figure 1: Coma cluster : HPGSPC and PDS data. The continuous line represents a thermal component at the average cluster gas temperature of $8.5^{+0.6}_{-0.5}$ keV.

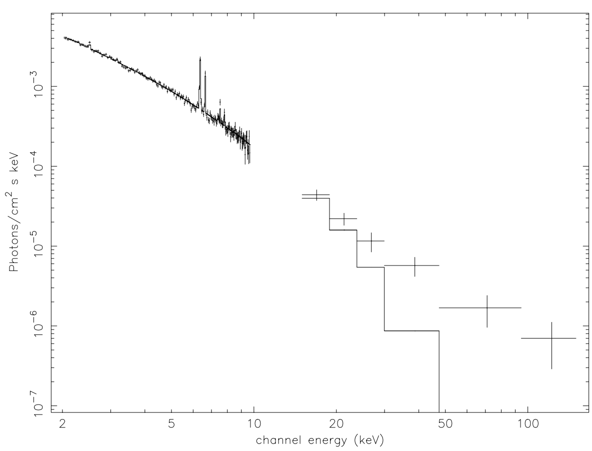

Figure 2: Abell 2256 : MECS and PDS data. The continuous line represents a thermal component at the average cluster gas temperature of 7.47±0.35 keV.

detection of nonthermal X-ray emission, does not show any extended radio region. So, the most natural explanation for the detected HXR excesses is that they are due to inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by the relativistic electrons responsible for the radio emission. However, alternative interpretations to the IC model for the nonthermal radiation detected in the Coma cluster have been proposed. Blasi & Colafrancesco[11] suggest a secondary electron production due to the interactions of cosmic rays within the ICM. However this model implies a γ-ray flux considerably larger than the EGRET upper limit unless the HXR 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[12,13,14,15] At present, due to the low efficiency of the proposed acceleration processes and of the bremsstrahulung mechanism, these models would require an unrealistically high energy input as recently pointed out by Petrosian[16]. Besides, this interpretation seems to be in conflict with the *BeppoSAX* detection of A2256 since the derived flat power-law spectrum of the electrons (2.4) gives a negligible nonthermal bremsstrahlung contribution to the PDS flux[6]. This model requires steep electron spectrum. Finally, we cannot exclude a trivial explanation for the detected hard excesses. A point source can be present in the FOV of the PDS onboard *BeppoSAX* . For example, a source like Circinus[17], a very obscured Seyfert II galaxy but very active at energies above 10 keV. We can exclude its presence only in the central region of size $R \sim 30'$ thanks to the MECS images.

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 ($B_{XR} \sim 0.16\mu G$[4]), obtained combining the radio flux and the IC X-ray flux using only observables[18], and the value derived from Faraday rotation (FR) of polarized radiation toward the radio galaxy NGC4869 ($B_{FR} \sim 6\mu G$[19]). However, this discrepancy could be resolved considering that Feretti *et al.* [19] inferred also the existence of a weaker and larger scale magnetic field in the range 0.1-0.2 $h_{50}^{1/2}$ μG consistent with the value measured by *BeppoSAX* , and therefore the component of $\sim 6\mu G$ could be local. Goldshmidt & Rephaeli[20] suggested that this discrepancy could be alleviated taking into consideration the expected spatial profiles of the magnetic field and relativistic electrons. More recently, it has been shown that IC models which include the effects of more realistic electron spectra, combined with the expected spatial profiles of the magnetic field, and anysotropies in the pitch angle distribution of the electrons allow higher values of the intracluster magnetic field in better agreement with the Faraday rotation measurements[21,16].

2 *BeppoSAX* Observation of A3667 and A1367

More recently, *BeppoSAX* observed other two clusters, namely A3667 and A1367. We report the results of the data analysis regarding the PDS operating in the 15-200 keV energy range[22].

2.1 A3667

Abell 3667 is one of the most spectacular clusters of galaxies. It contains one of the largest radio source in the southern sky with a total extent of $\sim 30'$ which corresponds to $\sim 2.6 h_{50}^{-1}$ Mpc. This diffuse radio emission is located to the north-west, well outside the central core of the cluster. A similar but weaker radio region is present also to the south-east[23,24] (see Fig. 3).

The Mpc-scale radio relics may be originated by the ongoing merger visible in the optical region, the cluster shows strong galaxy concentrations around the two brightest D galaxies[25,26], in the X-ray region[27], as shown by the elongated isophotes, and in the weak lensing mass map[28]. The *ASCA* observation reports an average gas temperature of 7.0$\pm$0.6 keV with a constant radially averaged profile up to $\sim 22'$ and a temperature map showing that the hottest region is in between the two groups of galaxies confirming the merger scenario[29].

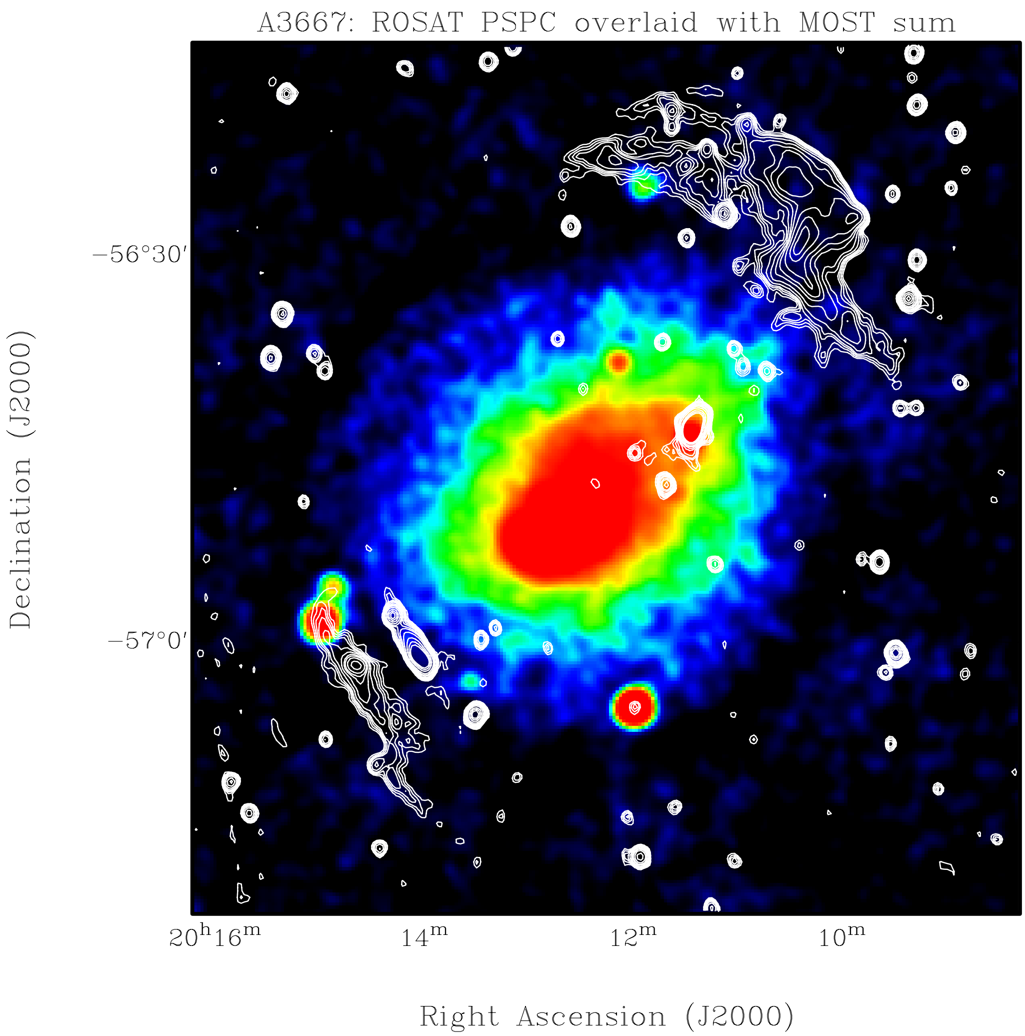

Figure 3: A3667. *ROSAT* PSPC image overlaid with the radio map obtained by Röttgering *et al.* 1997[24].

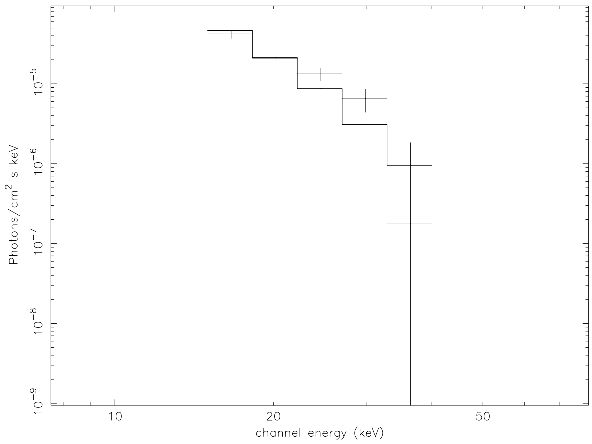

Figure 4: Abell 3667 : PDS data. The continuous line represents a thermal component at the average cluster gas temperature of 7 keV (Markevitch *et al.* 1998). The errors bars are quoted at 1σ.

The PDS FOV (1.3°) onboard *BeppoSAX* includes only the radio region in the north of the cluster. We have a long observation composed of two observations of May 1998 and October 1999. The observation reports a clear detection of hard X-ray emission up to $\sim$ 35 keV, at a confidence level of $\sim 10\sigma$. The observed count rate was 0.134±0.013 cts/s. Instead the fit to the PDS data with a thermal component (see Fig. 4) indicates a marginal presence of a hard excess at the confidence level of $\sim 2.6\sigma$. 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 to perform a fit with a thermal component at the fixed average cluster gas temperature and a second thermal component. The only possibile fit is with a thermal bremsstrahlung model that gives a best fit temperature of $\sim$ 11 keV with a large confidence interval (7.7-16.8 keV, 90%). The average cluster gas temperature is only slightly out of this interval. Therefore, the $\sim 2.6\sigma$ excess should be considered as an upper limit to the presence of nonthermal HXR radiation. 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.

2.2 A1367

The recent *BeppoSAX* observation of A1367 for an effective exposure time of ~42 ks reports a negative detection of hard X-ray emission in the PDS energy range, i.e. above 15 keV (Rephaeli *et al.* , in preparation).

3 Discussion

The long observation by *BeppoSAX* of Abell 3667 reports a robust evidence for hard X-ray emission in the PDS energy range 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 Section 2.1, 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 $\sim 30'$ ($\sim$ 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 ($\alpha_r \sim 0.5$) in the NW rim of the source with a considerable steepening to $\alpha_r \sim$1.5 toward the SW[24]. The overall radio spectral index of ~1.1 is consistent with the flux density

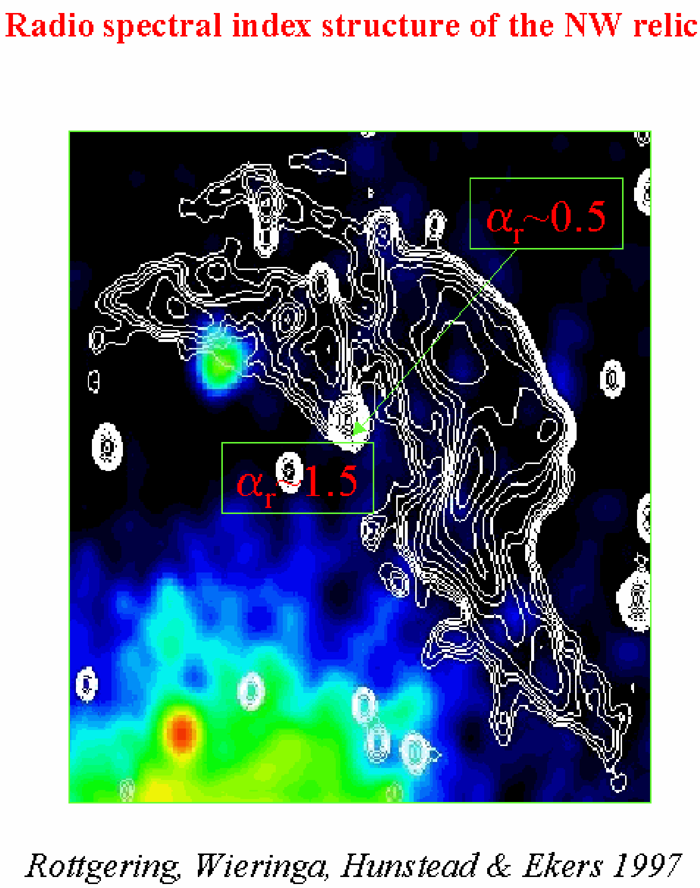

Figure 5: Radio spectral index structure of the NW relic of Abell 3667[24].

measurements[30,31,23]. Fitting the PDS data with a thermal component, at the temperature of 7 keV, and a power law component, with index 2.1 ($1+\alpha_r$), we derive a nonthermal IC flux upper limit of $\sim 4.1 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 15-35 keV energy. Extrapolating this flux in the energy range 20-80 keV we obtain $F_X \sim 6.4 \times 10^{-12}$ erg cm^{-2} s^{-1} that is a factor $\sim$3.4 and $\sim$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 $0.41\mu G$.

Given the presence of such a large radio region in 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 (α : 20^h $10'$ $30''$; δ : $-56°$ $25'$ $0.0''$). Instead, one possibile explanation may be related to the radio spectral index structure of the NW relic (see Fig. 5). As indicated by Roettiger, Burns & Stone[32] 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 ageing because of 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 able to produce IC X-rays. In the post-shock 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 from the post-shocked region, because the magnetic field is still strong enough due to the likely long time to relax.

The Coma cluster, where nonthermal HXR emission is present at a significant level[4], shows a quite different radio index structure[33,34]. The cluster exhibits a central plateau (R$\sim 10'$) with radio spectral index $\sim$0.7 (in the core it appears to be lower[34]) and a progressive spectral steepening with the increasing radius in the external regions of the radio halo. Besides, the lack of a clear shocked region and the total extent of the radio halo (R$\sim 80'$) are not compatible with a scenario of pure spectral ageing of the emitting electrons. Thus, in situ reacceleration processes are required, probably due to turbulence related to recent mergers[35,36,37] with a possible additional contribution from the gas motion originating from the massive galaxies orbiting in the cluster core[38]. Brunetti *et al.* [21] 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 energy break $\gamma_b \gtrsim 10^4$ emitting in a magnetic field smoothly decreasing from the center toward the periphery.

Similar considerations can be applied to Abell 2256, that is the second cluster that shows a clear evidence of a hard excess above the thermal intracluster emission[6]. Abell 2256 exhibits a large diffuse radio region (1.0$\times$0.3 Mpc) in the north, at a distance of $\sim 8'$ from the cluster center (relic), with a rather uniform and flat spectral index of 0.8$\pm$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[39,40,41,42]. 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[43]. Moreover, the presence of the central radio halo would favour the hypothesis that in situ reacceleration processes are active in the cluster volume. As discussed by Fusco-Femiano *et al.* [6], in the framework of the IC model, the probable source of the non-thermal HXR emission is the large relic if the associated magnetic field is of the order of $\sim 0.1\ \mu$G. An additional contribution could be provided by the halo electrons if the radio index structure is similar to that of the Coma cluster.

Also the negative detection of hard X-ray emission reported by a recent observation of A1367 by *BeppoSAX* (Rephaeli, Dal Fiume, Fusco-Femiano & Orlandini, in preparation) can be explained using the IC interpretation. A1367 is a near cluster (z=0.0215) that shows a radio relic at a distance of $\sim 22'$ from the center and a low gas temperature of $\sim$ 3.7 keV[44] that explains lack of thermal emission at energies above 15 keV. We do not expect presence of nonthermal radiation for two reasons : the radio spectral index of 1.90$\pm$0.27[45] seems to indicate the absence of high energy reaccelerated electrons and besides the radio region has a limited extent of $8'$ corresponding to $\sim$300kpc.

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. The radio spectral index structure of the radio halos or relics present in these clusters reveals the essential condition to detect nonthermal X-ray emission in the PDS energy range, i.e. 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.

Acknowledgments

I am grateful to Dr. R.W.Hunstead who kindly provided the *ROSAT* PSPC image overlaid with the radio map of Abell 3667 (Figure 3).

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