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HARD X-RAY EMISSION IN CLUSTERS OF GALAXIES

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The recent discovery in some clusters of galaxies of soft and hard excesses with respect to the thermal bremsstrahlung emission by the hot intracluster medium has opened a new window in the study of this class of objects. For the hard excess, the spectral capabilities of *BeppoSAX* and *RXTE* have led to a significant breakthrough in the discovery of this new spectral component predicted in clusters showing radio halos. Various interpretations have been proposed since the discovery of nonthermal emission in the Coma cluster. We discuss future observations to search for hard X-ray tails in clusters of galaxies.

1 Introduction

The study of clusters of galaxies has benefited greatly by extensive X-ray measurements of thermal emission from hot intracluster medium (ICM). Spectral and imaging observations of clusters have resulted in direct determinations of the gas temperature, density and abundances, and in reliable estimates of the baryonic and total masses of clusters. The sample of observed X-ray clusters has given us some insight into the determination of the cosmological parameters. These important results have been obtained in large part from measurements of X-rays at energies ≤ 10 keV.

Recent researches on clusters of galaxies have unveiled new radiation components in the intracluster medium (ICM) of some clusters, namely a cluster soft excess (CSE) and a hard excess (HEX) with respect to the thermal emission. The soft excess has been discovered by the *Extreme Ultraviolet Explorer* (*EUVE*) in the 69-190 eV energy range in a few clusters and confirmed by *ROSAT* and *BeppoSAX* in the 0.1-0.4 keV energy range[20,4,19]. The hard excess refers to the discovery of hard X-ray (HXR) emission in the Coma cluster by the PDS onboard *BeppoSAX* [12] and *RXTE* [28] and to a second HXR excess detected by *BeppoSAX* in the galaxy cluster A2256[14]; a marginal evidence is also reported for A2199[18] in the external regions of the cluster. Observations of clusters at low and high X-ray energies are of considerable interest considering that we can derive significant additional information on physical conditions in the ICM environment, due to the different emission mechanism with respect to the thermal bremsstrahlung by the hot gas.

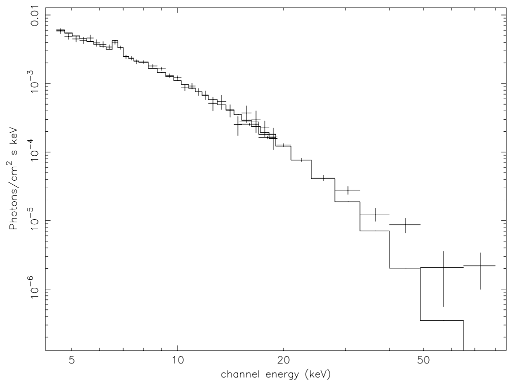

Figure 1: HPGSPC and PDS data. The continuous line represents a thermal component at the average cluster temperature of $8.5^{+0.6}_{-0.5}$ keV.

2 Hard X-ray Excess

Hard X-ray radiation was predicted in clusters showing radio halos attesting the presence of relativistic electrons in the intracluster space due to inverse Compton (IC) scattering of relativistic electrons by the cosmic microwave background (CMB) photons. The attempts to detect radiation at energies above ∼30 keV with ballon experiments[1], with *HEAO-1*[26] and with the OSSE experiment[27] reported essentially flux upper limits. The much improved spectral capabilities of *BeppoSAX* and *RXTE* satellites have recently led to a significant breakthrough in the measurement of an additional spectral component in clusters. HXR radiation has been detected for the first time in the Coma cluster up to ∼ 80 keV[12,28] and in the galaxy cluster A2256 by *BeppoSAX* [14], while a marginal evidence is reported for A2199 in the external regions of the MECS detector onboard *BeppoSAX* [18].

2.1 Coma Cluster

The PDS detected hard X-ray emission in the 15-80 keV energy range in the Coma cluster spectrum. The analysis was performed combining the PDS data with the HPGSPC data in the 4.5-20 keV energy range. A clear excess above the thermal intracluster emission is present at a confidence level of $\sim 4.5\sigma$, as shown in fig. 1.

The χ^2 value decreases significantly when a second component is added and in the case of a second thermal component the fit requires a temperature greater than 40 keV. This unrealistic value is interpreted as a strong indication that the detected hard excess is due to a nonthermal mechanism. The analysis cannot provide a precise estimate of the photon spectral index. The flux $\sim 2.2 \times 10^{-11}$ $erg\ cm^{-2}\ s^{-1}$ in the 20-80 keV energy range does not depend much on the power-law index. The contribution of the nonthermal emission to the X-ray flux in the canonical 2-10 keV energy range is not greater than 20%, depending on the assumed spectral index.

The most direct explanation of this hard excess is inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by the relativistic electrons responsible for the extended radio emission present in the central region of Coma[33]. The combined radio synchrotron and IC HXR fluxes[e.g.,25] allow to estimate a volume-averaged intracluster magnetic field of $\sim 0.16\ \mu G$[12], using only observables. Assuming a radio halo size R = 1 Mpc and a distance d = 138 Mpc ($H_0 = 50\ Km\ s^{-1}\ Mpc^{-1}$) of the radio source the electron energy density results to be $\rho_e \sim 7 \times 10^{-14}\ erg\ cm^{-3}$ for a radio spectral index of 1.2 [8]. One of the problems with the IC model is that the value of $\sim 0.16\ \mu G$ for the magnetic field in the ICM seems to be at odds with the value determined from Faraday rotation of polarized radiation toward the head tail radio

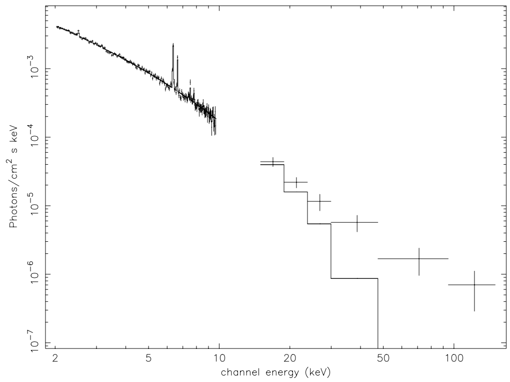

Figure 2: MECS and PDS data. The continuous line represents a thermal component at the average cluster gas temperature of 7.47±0.35 keV.

galaxy NGC4869[11] that gives a line-of-sight $B \sim 6$ μG, and with the equipartition value in the radio halo[15], which is ~ 0.4 $h_{50}^{2/7}$ μG. We note, however, that Feretti *et al.* [11] 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.

2.2 A2256

In the galaxy cluster A2256[14] we have measured non thermal emission in excess of thermal one at a confidence level of $\sim 4.6\sigma$ (see Fig. 2). A joint analysis of MECS and PDS data was performed, including a numerical relative normalization among the two instruments in the fitting procedure[see 14]. The confidence contours of the parameters kT and photon spectral index, α_X, give an upper limit for the spectral index of 1.7 (90%). The flux of the nonthermal component $\sim 1.2 \times 10^{-11}$ $erg\ cm^{-2}\ s^{-1}$ in the 20-80 keV energy range is rather stable against variation of α_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$1.7.

In addition to the nonthermal component detected by the PDS onboard *BeppoSAX* , a second nonthermal component already detected by *ASCA* [22] in the central r=3′ spherical bin could be present in the X-ray spectrum of the cluster, not surprisingly given the complex radio morphology of the cluster central region. Although Markevitch & Vikhlinin were not able to firmly establish the origin of this emission, their best fit is a power law model with photon index 2.4±0.3, therefore favouring a nonthermal component.

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[5,6,29]. 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.* [6]), at a distance of $\sim 8'$ from the cluster centre. The extent of this diffuse region is estimated to be 1.0×0.3 Mpc, with a total flux density of 671 mJy at 610 MHz and a rather uniform spectral index of 0.8±0.1 between 610 and 1415 MHz[6]. A fainter extended emission permeates the cluster centre (diffuse emission around *D* in Bridle *et al.* [6]) with a steeper radio spectral index of ∼1.8 as estimated by Bridle *et al.* [6] and in agreement with the 327 MHz data from the Westerbork Northern Sky Survey[24]. The total flux density is 100 mJy at 610 MHz and no polarized emission has been detected from this region. The confidence contours of the parameters kT and photon spectral index, α_X, derived by the MECS & PDS data analysis of A2256, give an upper limit for the spectral index of 1.7 (90%) that is marginally consistent with that expected by the IC model. A value of ~ 0.05 μG 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* .

2.3 Alternative Interpretations to the IC Model

An alternative explanation for the HXR radiation detected in Coma is nonthermal bremsstrahlung (NTB) emission from suprathermal electrons currently accelerated at energies greater than ~10 keV by shocks or turbulence[10,31]. 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 $\geq 1\ \mu G$.

A quite different interpretation is given by Blasi & Colafrancesco[3] that proposed IC scattering of electrons generated as secondaries in cosmic rays interations in the ICM.

In the case of in-situ acceleration of particles from the thermal pool, the HXR emission can be generated by the bremsstrahlung radiation of the thermal particles with the Maxwellian spectrum distorted by the acceleration, as suggested by Blasi[2] and Dogiel[9]. This mimics the effect of a two-temperature thermal spectrum.

Brunetti *et al.* [7] proposed instead a model in which the relativistic particles injected in the Coma cluster by some processes (merger, accretion shocks, turbulence) are systematically reaccelerated for a relatively long time (~1 Gyr). Such scenario can account for the several radio properties of the Coma cluster as the steepening of the radio spectral index with increasing radius, the radio halo size at different frequencies and the integrated radio spectrum. Besides, with a suitable choice of the parameters the model can also account for the HXR emission observed in Coma.

Another proposed emission mechanism is given by IC scattering of a large population of cosmic rays by the CMB photons[21]. In this model the same relativistic component could be also responsible for the soft excess discovered in a few clusters. In particular, for the Coma cluster the extrapolation of the EUV and soft X-ray data (photon index ~1.75) to the PDS energy range gives a flux only a factor ~2 lower than the hard excess, suggesting a possible physical connection between the soft and hard excesses. However, as it has been pointed out by Sarazin[30], one would not expect a same power law spectrum that fit the HXR and radio emissions and that extends to the EUV emission because the lifetimes of the electrons are very different for HXR/radio and EUV emissions. This may happen only if a large fraction of cosmic ray electrons is generated in an ongoing or very recent strong merger and this should be the case of the Coma cluster where an ongoing merger between the two groups NGC4889 and NGC4874 is likely present in the core of the cluster.

Finally, a 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[23]. In the central region ($\sim 30'$ in radius), the MECS images[13,14] do not show evidence of this kind of sources in both the clusters where HXR radiation has been detected. In particular, the analysis of the two observations for A2256 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.

3 Conclusions and Future Observations

New perspectives to the study of the astrophysics of clusters of galaxies are given by the detection of soft and hard excesses whose interpretation appears to be not completely clear yet.

Various mechanisms have been proposed to explain the detected HXR excess. A good determination of the photon spectral index would be crucial to discriminate among the different emission mechanisms. At this scope the Coma cluster will be observed again for an exposure time of 300 ksec by *BeppoSAX* in the fourth Announcement of Opportunity (P.I.: L.Feretti). The search for hard X-ray emission in cluster of galaxies will provide insight into nonthermal phenomena in the intracluster space. Problems as the role of magnetic fields on the cluster dynamical history, origin and nature of intracluster magnetic fields, heating of the gas by cosmic ray particles, origin and propagation mode of cosmic ray electrons can be put on a more quantitative basis. Besides, an improved spectral description of cluster X-ray emission will also result in a more accurate determination of the gas thermal properties, such as the baryon fraction that has cosmological implications[32].

After the positive detection of nonthermal emission in two clusters showing extended radio regions attesting the presence of relativistic electrons, in the fourth AO (P.I.: R.Fusco-Femiano) *BeppoSAX* will observe two clusters of galaxies that do not show evidence of extended radio emission (A119) or where this is uncertain, and in any case only marginal (A754[16]). Both clusters are sites of merger processes. Major cluster mergers are the most energetic events in the Universe since the Big Bang. The subclusters collide at velocities of ~2000 km/s, and shocks are driven into the ICM giving a strong contribution to the gas heating. We also expect that particle acceleration by these shocks will produce nonthermal electrons and ions able to generate syncrotron radio, inverse Compton EUV, hard X-ray, and gamma-ray emission. The aim of this proposal is to verify whether clusters showing merger events can produce HXR radiation also in the absence of a clear evidence of diffuse radio emission. A positive detection would put constraints on the radio halo formation, while the opposite case would put constraints on the acceleration processes during merger events.

A considerable contribution to the detection of soft and hard excesses may be given by *XMM-Newton* operating in the 0.1-15 keV energy range. In particular, for the hard excess clusters with a low gas temperature must be considered, as A1367 ($T \sim 4keV$) that will be observed for 30 ksec (P.I.: R.Fusco-Femiano) [this cluster has been observed also by *BeppoSAX* in AO3 (P.I.: Y.Rephaeli) and the data analysis is in progress]. The observation of A2199 for 50 kec (P.I.: J.Kaastra) should clarify the presence of nonthermal emission in the external regions of the cluster as marginally indicated by the *BeppoSAX* observation[18].

Finally, *RXTE* will observe A2319 for 200 ksec and the Coma cluster for 300 ksec (P.I.: Y.Rephaeli).

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