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Non-Thermal Activity and Particle Acceleration in Clusters of Galaxies

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Abstract. Evidence for non-thermal activity in clusters of galaxies is well established from radio observations of synchrotron emission by relativistic electrons, and new windows (in EUV and Hard X-ray ranges) have provided more powerful tools for its investigation. The hard X-ray observations, notably from Coma, are summarized and results of a new RXTE observations of a high redshift cluster are presented. It is shown that the most likely emission mechanism for these radiations is the inverse Compton scattering of the cosmic microwave background photons by the same electrons responsible for the radio radiation. Various scenarios for acceleration of the electrons are considered and it is shown that the most likely model is episodic acceleration by shocks or turbulence, presumably induced by merger activity, of high energy electrons injected into the inter-cluster medium by galaxies or active galactic nuclei.

1. Introduction

The intra-cluster media (ICM) of several clusters of galaxies, in addition to the well studied thermal bremssstrahlung (TB) emission in the 2 to 10 keV soft X-ray (SXR) region, show growing evidence for non-thermal activity, first observed in the form of diffuse radio radiation (classified either as relic or halo sources) and more recently, at extreme ultraviolet (0.07–0.4 keV; EUV) and hard X-ray (20–80 keV; HXR) regions. In the next section I will give a brief review of the status of these observations and present new yet unpublished HXR observation of another cluster, and in §3 I will compare the merits of different emission mechanisms proposed for their production. Even though the presence of non-thermal electrons in the ICM was established decades ago, very little theoretical treatment of the acceleration mechanism was carried out (see e.g. Schlickeiser, Siervers & Thiemann 1987) until the discovery of the EUV and HXR radiations. Given the meager amount of data, detailed calculations of the energy sources and the exact mechanisms of the acceleration may be premature. Consequently, I will emphasize the general physical characteristics and not the numerical details of the problem. It turns out that one can put significant and meaningful constraints on the general aspects of the acceleration mechanism. I will describe these in §4.

2. Observations

The first cluster observed to have **diffuse radio emission** was the Coma cluster and recent systematic searches have identified more than 30 clusters with halo

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or relic sources. The rate of occurrence of these sources increases with cluster redshift z, SXR luminosity or temperature T (Giovannini & Feretti 2000). There is little doubt that this radiation is due to synchrotron emission in a magnetic field of strength $B \sim \mu$G by a population of relativistic electrons of Lorentz factor $\gamma \sim 10^4$. In the case of Coma the electron spectra may be represented by a broken power law (Rephaeli 1979) or a power law with an exponential cutoff (Schlickeiser et al. 1987).

Extreme UV (0.07–0.4 keV) radiation was detected by the *Extreme Ultraviolet Explorer* from Coma (Liu et al. 1966) and some other clusters. A cooler ($kT \sim 2$ keV) component and inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by relativistic ($\gamma \sim 10^3$) electrons are two possible ways of producing this excess radiation. Some of the observations and the emission process are still controversial (Bowyer & Hwang 2003). I will not discuss this emission any further here.

The third evidence for non-thermal activity comes from the observations of excess **HXR** emission in the 20 to 80 keV range by instruments on board the *Beppo*SAX and *RXTE* satellites. Each of these observatories has detected HXR excess from Abell 2256 once and Coma twice, although the second *Beppo*SAX observation shows a weaker signal (Fusco-Femiano et al. 1999 and Rephaeli et al. 1999, 2002). HXR detections have also been reported in Abell clusters 754, 2199, 2319 and 3667 all in the redshift range $0.023 < z < 0.056$. Most of these excesses can be best fitted with a fairly hard spectrum (photon power-law index $\alpha \sim 2$). Recently, detection of non-thermal X-rays (albeit at lower energies) have been reported from a poor cluster IC 1262 (Hudson et al. 2003). In Figure 1 I show the HXR spectrum and its characteristics for the cluster RXJ0658−5557 with a considerably higher redshift ($z = 0.296$) obtained by *RXTE*. These observations encompass a wide range of temperature, redshift and luminosity, indicating that HXR emission may be a common property of all clusters with significant diffuse radio emission.

Figure 2 (left panel) shows the photon flux at all wavelengths from Coma, where in addition to the above mentioned radiations, we show the gamma-ray upper limit from EGRET on board *CGRO* (Sreekumar et al. 1996), and the equivalent flux for the CMB and optical radiation density present in the cluster. (To these should be added the contribution from Far IR background radiation.) Similarly, an equivalent flux has been indicated for the static magnetic field of $\sim 1\mu$G, which is the size of the field strength deduced in several clusters (Eilek 1999, Clarke et al. 2001). The observed Faraday rotation of the Coma cluster can be interpreted as indicating a uniform magnetic field along the line of sight of $\sim 0.3\mu$G. However, the field lines are most likely chaotic. Kim et al (1990) and Clarke et al. (2003) estimate a mean magnetic field of $\sim 2-3\mu$G. It should be noted, however, that the interpretation of these observations is controversial (see Rudnick & Blundell 2003).

3. Radiation Mechanisms

The HXR emission could be produced via IC scattering of CMB photons by the same population of relativistic electrons responsible for the radio emission (see e.g. Sarazin & Lieu 1998) shown by the solid lines in Figure 2 (right panel).

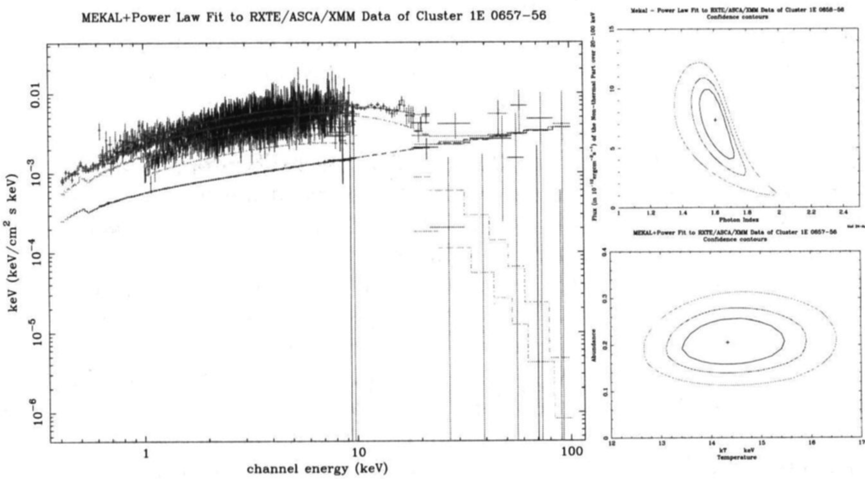

Figure 1. **Left panel:** Thermal plus a power law fit to 300ks RXTE and ASCA+SMM observations of the cluster RXJ0658−5557, and the 68, 90 and 99% confidence levels of the photon power-law index vs. 20–100 keV flux and temperature vs hydrogen column density. From Petrosian, Madejski and Luli, in preparation.

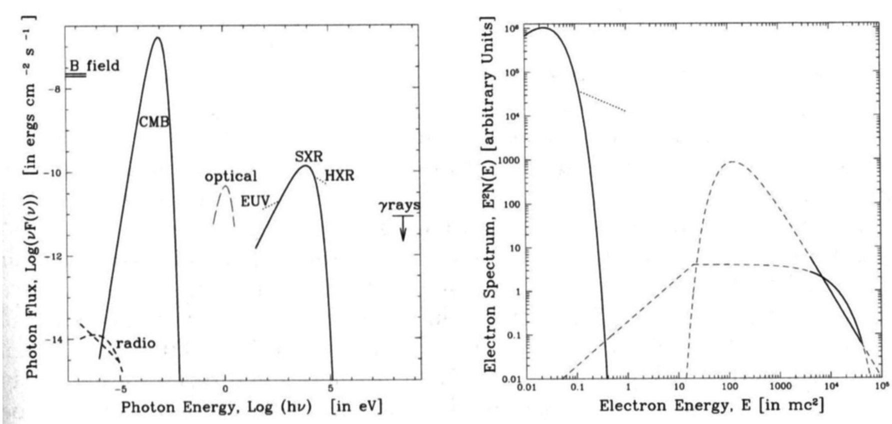

Figure 2. **Left Panel:** Schematic presentation of the $\nu f(\nu)$ flux of the electromagnetic fields in the ICM of Coma cluster including the B field. The two short dashed lines show two different fits to the radio data. **Right Panel:** Schematic spectra of the thermal ($T = 10^8$ K) and two non-thermal electrons responsible for the radio emission (solid lines). The dashed lines show maximal extrapolations of spectra so that one avoids unacceptably high rate of heating of the ICM plasma. The dotted line is the electron spectrum for the NTB model. This clearly exceeds the heating limit.

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However, simple arguments show that this scenario requires a field strength $B_\perp < 0.2\mu$G, which is much smaller than values of several μG deduced from Faraday rotation mentioned above and equipartition arguments. Consequently, several workers have proposed non-thermal bremsstrahlung (NTB) for the HXR emissions (Enßlin et al. 1999, Sarazin & Kempner 2000, Blasi 2000). The dotted line in Figure 2 (right panel) shows the spectrum of the required electrons. However, as shown by Petrosian (2001, **P01**), the NTB process faces a serious difficulty, which is hard to circumvent. This is because compared to Coulomb losses the bremsstrahlung yield is very small: $Y_{\rm br} \sim 3 \times 10^{-6}(E/25{\rm keV})^{3/2}$ (see Petrosian 1973). Thus, for a HXR luminosity of 4×10^{43} erg s^{-1} (for Coma), a power of $L_{\rm HXR}/Y_{\rm br} \sim 10^{49}$ erg s^{-1} is fed into the ICM, increasing its temperature to $T \sim 10^8$ K after 3×10^7 yr or to 10^{10} K in a Hubble time! Therefore, *the NTB emission phase, if any, must be very short lived.*

This inefficiency of the NTB appears more serious than the inefficiency of the IC relative to the synchrotron process. There are several arguments which indicate that a higher B field can be tolerated in the IC model (see **P01**). Briefly, this discrepancy can be alleviated by i) a more realistic electron spectral distribution (e.g. Exponential spectral break beyond $\gamma \sim 10^4$); ii) a non-isotropic pitch angle distribution (Epstein 1973); and iii) spatial inhomogeneities (Goldschmidt & Rephaeli 1993, Govoni et al. 2003). Finally, the Faraday rotation measures may give a somewhat biased view of the B field by selecting clusters with the highest values of B while the EUV or HXR observations favor clusters with low values of B. The cluster RXJ 0658−5557 was chosen for observations because it was estimated that it should have relatively high IC flux of $\sim 7 \times 10^{-12}$ erg cm^{-2} s^{-1} which is what is observed. This increases our confidence in the validity of the IC model.

4. Acceleration Mechanism

It turns out that the acceleration mechanism of electrons can also be constrained significantly, even though we have very limited data. This mechanism should produce the relativistic electron spectra shown in Figure 2 (right panel). The lifetimes of these electrons are longer than their crossing time, $T_{\rm tr} \sim 3 \times 10^6$ yr. Therefore, these electrons will escape the cluster and radiate most of their energy outside it unless there exists some scattering agent with a mean free path $\lambda_{\rm scat} \sim 1$ kpc to trap the electrons in the ICM for at least a time scale of $T_{\rm esc} = (R/\lambda_{\rm scat})T_{\rm tr} \sim 3 \times 10^9$ yr, for cluster size $R \sim 1$Mpc. **Turbulence** can be this agent and can play a role in stochastic acceleration directly, or indirectly in acceleration by **shocks**. Both shocks and turbulence can presumably be produced during merger events. Several lines of argument point to an ICM which is highly turbulent. The possible scenarios of acceleration by turbulence and/or shocks are explored in **P01** leading to the following conclusions: i) The seed electrons cannot be the ICM thermal electrons for the same reason that the NTB fails as a source of HXRs, namely because it will lead to excessive heating of the ICM. Therefore, we require injection of high energy (> 50 MeV) electrons into the ICM, presumably from galaxies or AGNs. ii) The short lifetimes of the relevant electrons with respect to $T_{\rm esc}$ and the small $\lambda_{\rm scat}$ imply a continuous and *in situ* acceleration process. iii) A *steady state* model seems natural but it leads to a flatter spectrum than required unless the turbulence has an unreasonably steep spectrum. iv) *Time Dependent Models* can produced the desired spectra but only for a short period ($\sim 3\times10^8$ to 10^9 yr) implying an *episodic acceleration process* induced by merger activity.

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