RELATIVISTIC ELECTRONS & MAGNETIC FIELDS IN CLUSTERS OF GALAXIES

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RXTE and BeppoSAX observations have yielded evidence for the presence of a secondary power-law spectral component in the spectra of several clusters of galaxies. This emission in clusters with extended regions of radio emission is likely to be by relativistic electrons that are Compton scattered by the CMB. The radio and non-thermal (NT) X-ray measurements yield the values of the volume-averaged magnetic field and electron energy density in the cluster extragalactic environment. These directly deduced quantities provide a tangible basis for the study of NT phenomena in clusters.

1. Radio & X-ray Measurements

Extended radio emission has been detected in some 40 clusters.1 2 The emission typically extends over a region \( \sim 1 \) Mpc in size, with spectral indices in the range \( 1.2 - 1.7 \), luminosities \( 10^{41} - 10^{42} \) erg/s, and \( \sim 1 \) \( \mu \)G equipartition magnetic fields. From Faraday Rotation measurements of radio sources seen through 16 clusters, a mean field value of \( \sim 5 - 10 (\ell/10 \text{ kpc})^{-1/2} \) \( \mu \)G, where \( \ell \) is a characteristic field spatial coherence length, was deduced.3

A direct prediction from the presence of relativistic electrons in the IC space is NT X-ray emission from Compton scattering of the electrons by the CMB. This emission is expected in the energy range of (at least) \( \sim 1 \) keV – 10 MeV, with a spectral index that is roughly similar to the radio index. Calculations of the predicted properties of this emission were carried out long ago.4 5 Searches for NT IC emission began with archivel analysis of HEAO-1 data,6 7 and continued with CGRO8 and ASCA9 observations, yielding only upper limits on spectral power-law components. The improved sensitivity and wide spectral band of the RXTE and BeppoSAX allowed a more detailed spectral analysis of long exposure measurements that resulted in significant evidence for NT emission in five clusters: Coma, A2256, A2319, A119 & A754 (references 10–15).

The level of NT flux deduced from the RXTE measurements is roughly \( \sim 5 - 8\% \)

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Figure 1. RXTE spectrum of the Coma cluster and folded Raymond-Smith ($kT \simeq 7.67$), and power-law (index = 2.3) models (from Rephaeli & Gruber 2002). HEXTE data points are marked with circles and 68% error bars. The total fitted spectrum is shown with a histogram, while the lower histogram shows the power-law portion of the best fit. The quality of the fit is demonstrated in the lower panel, which displays the observed difference normalized to the standard error of the data point.

of the total emission (which is dominated by thermal emission). As an example, the RXTE spectrum of the Coma cluster is shown in Figure 1; the cluster was observed for $\sim 260$ ks in 1996 and 2000. Note the spectral overlap between the PCA and the higher energy HEXTE experiments, which also have the same FOV, thereby allowing simultaneous determination of the thermal parameters, as well as those of a possible secondary NT component. (This is a clear advantage over BeppoSAX, whose MECS and PDS do not overlap, neither spectrally nor spatially.)

2. Field Strength & Electron Energy Density

Radio and NT X-ray measurements yield volume-averaged values of the magnetic field in the central $\sim 1$ Mpc region of clusters $B_{rx} \sim 0.1 - 0.4 \mu$G, somewhat lower than values deduced from Faraday rotation measurements, $B_{fr}$. The mean strength of IC fields has direct implications on the feasibility of detecting cluster NT X-ray emission, on the electron (Compton-synchrotron) loss times, and therefore on the viability of relativistic electron models (e.g., references [16,17]). Reliable estimates of the field are thus quite essential.

Differences between $B_{rx}$ and $B_{fr}$ could, however, be due to the fact that the former is a volume-weighted measure of the field, whereas the latter is an average along the line of sight, weighted by the electron density. In addition, the field and relativistic electron density would generally be expected to have different spatial
profiles that could lead to different spatial averages. More generally, IC field values derived from Faraday rotation measurements suffer from various statistical and physical uncertainties. In particular, the inclusion in the sample of cluster radio sources, whose large contributions to the rotation measures could be due to their intrinsic fields, may have led to systematic over-estimation of IC fields, a possibility that was recently ruled unlikely.

When it is assumed (as has been customary in joint radio and X-ray analyses) that IC relativistic electrons and fields are co-spatial, the deduced value of $B_{rx}$ is independent of the volume of the emitting region. The electron energy density, $\rho_e$, does depend on the source radius ($R$); integration of the electron energy distribution over energies inferred from the observed radio (and X-ray) band yields $\rho_e \sim 10^{-13\pm0.5}(R/1\text{ Mpc})^{-3} \text{erg cm}^{-3}$. If protons are the main cosmic ray component in clusters (as in galaxies), the total particle energy density could be much higher. If so, energetic protons can give rise to $\gamma$-ray emission via neutral pion decay, may account for a substantial fraction of the relativistic electron density through charged pion decays, and could possibly provide appreciable (Coulomb) heating of IC gas within the cluster core where the gas (bremsstrahlung) cooling rate can be relatively high.

References