Outskirts of Galaxy Clusters: Intense Life in the Suburbs
Proceedings IAU Colloquium No. 195, 2004
A. Diaferio, ed.

DOI: 10.1017/S174392130400033X

Non-thermal phenomena in galaxy clusters

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Abstract. The discovery of diffuse synchrotron radio emission and, more recently, of the hard X-ray (HXR) tails have triggered a growing interest about non-thermal phenomena in galaxy clusters. After a brief review of the most important evidences for non-thermal emission, I will focus on the origin of the emitting particles and of the hadronic component. In particular I will describe the particle-injection and -acceleration mechanisms at work in the intra-cluster medium (ICM) and, at the same time, discuss the possibility to test current modellings of these phenomena with future radio, HXR, and gamma ray observatories.

1. Introduction

There is now firm evidence that the ICM is a mixture of hot gas, magnetic fields and relativistic particles. While the hot gas results in thermal bremsstrahlung X-ray emission, relativistic electrons and positrons generate non-thermal radio (synchrotron) and hard X-ray radiation (inverse Compton). In principle, the amount of the energy budget of the intracluster medium in the form of high energy hadrons can be large, due to the confinement of cosmic rays over cosmological time scales (Völk et al. 1996; Berezinsky, Blasi & Ptuskin 1997). The collisions between thermal and relativistic hadrons in the ICM generate π^o and secondary $e^{\pm}$. Both these species radiate a relevant fraction of their energy into the gamma band via π^o decay and via $e^{\pm}$-inverse Compton scatter of the photons of the cosmic microwave background. However, such gamma radiation that would allow us to constrain the energetics of relativistic hadrons in clusters has not been detected as yet (Reimer et al. 2003).

2. Observations

The most important evidence for relativistic electrons in clusters of galaxies comes from the diffuse synchrotron radio emission observed in a growing number of massive clusters (e.g., Feretti 2003). The diffuse emissions are referred to as *radio halos* (Fig. 1a) and/or radio *mini–halos* when they appear confined to the center of the cluster, while they are called *radio relics* when they are found in the cluster periphery. Giovannini, Tordi and Feretti (1999) found that ∼5% of clusters in a complete X-ray flux limited sample have a diffuse radio source. The detection rate of diffuse radio sources shows a abrupt increase with the X-ray luminosity of the host clusters: about 30-35% of the galaxy clusters with X-ray luminosity larger than 10^{45} erg s^{-1} show diffuse radio emission (Feretti 2003). Interestingly, there is a correlation between the non–thermal diffuse radio emission and the presence of merger activity in the host clusters of galaxies (Buote 2001; Schuecker et al. 2001): this suggests a link between the process of formation of galaxy clusters and the origin of the non-thermal activity.

A second important evidence for relativistic electrons comes from the hard X-ray (HXR) excess emissions detected in a few galaxy clusters by the BeppoSAX and RXTE satellites (Fusco-Femiano et al. 2003a; Rephaeli et al. 2003). HXRs may be explained in

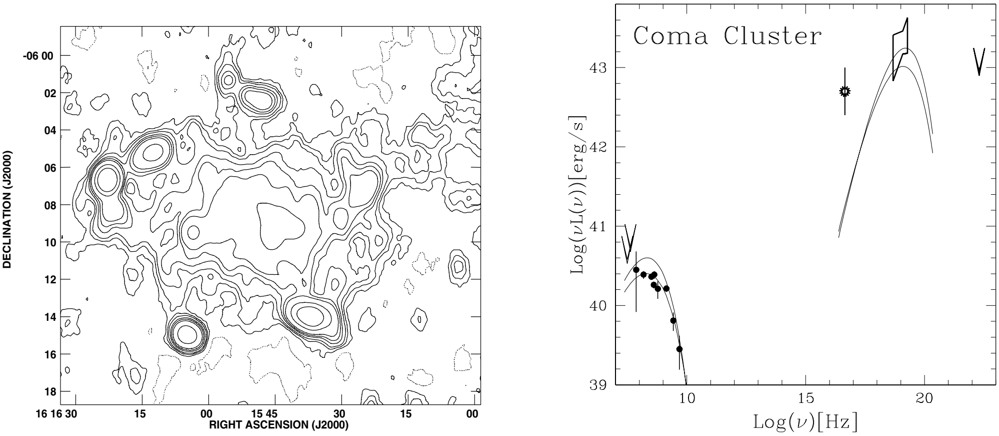

Figure 1. Left Panel: 327 MHz image of the giant radio halo in A 2163 (Feretti et al. 2004). Right Panel: Broad band non-thermal spectrum of the Coma radio halo: the fit to the radio and HXR data is provided by synchrotron and IC emission from a reaccelerated electron population.

terms of IC scattering of relativistic electrons off the photons of the cosmic microwave background (e.g., Fusco–Femiano et al. 2003a) and thus they represents a unique tool to unambiguously disentangle the energy of the relativistic electrons from that of the magnetic field in the ICM. Unfortunately the poor sensitivity of the present and past HXR-facilities does not allow to obtain an iron-clad detection of HXR excesses and thus future observatories (e.g. ASTRO-E2, NEXT) are necessary to definitely confirm these excesses (see Rossetti & Molendi 2004; Fusco-Femiano et al. 2004).

Additional evidence for non-thermal emission may also come from the extreme ultraviolet (EUV) excesses discovered in a number of galaxy clusters (e.g., Bowyer 2003). EUV excesses, and their origin, are however still matter of debate (see however Bonamente and Kaastra, these proceedings).

In Fig. 1b a compilation of the non-thermal spectrum of the Coma cluster is reported.

3. Modelling the origin of the emitting leptons

So far relativistic leptons are the unique non-thermal component detected in the ICM and thus our present understanding of the non-thermal activity is mostly based on the modelling of this component. The most spectacular example of non-thermal emission in galaxy clusters is given by the giant *radio halos* (Fig.1a). The difficulty in explaining these sources arises from the combination of their ∼Mpc size, and the relatively short radiative lifetime of the radio emitting electrons (about 10^8yrs): the diffusion time necessary to these electrons to cover such distances is orders of magnitude larger than their radiative lifetime. Thus the emitting electrons cannot be injected by clusters' Galaxies and/or AGN and then simply diffuse into the ICM.

i) primary models: as proposed first by Jaffe (1977), a solution to this puzzle would be provided by continuous *in situ* reacceleration of the relativistic electrons on their way out; this possibility was then studied more quantitatively by Schlickeiser et al. (1987).

ii) secondary models: an alternative to the *in situ* reacceleration scenario was put forward by Dennison (1980), who suggested that relativistic electrons may be continuously injected in the ICM by inelastic proton-proton collisions through production and decay of charged pions.

3.1. *Broad band spectrum*

A first possibility to constrain the spectrum and origin of relativistic leptons is given by the study of the broad band spectrum of the non-thermal emission (e.g., Fig. 1b).

i) HXRs and γ-rays: If the HXR excess in the Coma cluster is of IC origin, then the number of relativistic electrons in the ICM should be large and this can be combined with the EGRET upper limit to reject the hypothesis of a secondary origin of the emitting particles. Indeed in this case a large number of relativistic hadrons is required and the gamma ray flux produced via π^o decay should overproduce the EGRET upper limit (e.g., Blasi & Colafrancesco 1999). Thus *secondary models* should admit a different origin for the HXRs. One possibility is given by supra-thermal bremsstrahlung emission (Blasi 2000; Dogiel 2000) which however would require a too large energy budget to maintain the HXR excess for more than 10^8 yr (Petrosian 2001).

ii) EUV and HXR excesses: A second possibility is given by the combination of the EUV and HXR excesses. If HXRs are due to IC scattering by the same electrons which emit the synchrotron radiation, then a low frequency (e.g., < 10 keV) flattening of the photon spectrum is required. The presence of this flattening indicates a corresponding flattening of the spectrum of the electrons at the energies responsible for IC emission below the HXR band; this flattening can result from Coulomb losses if the emitting electrons are in the cluster core, or it would be also naturally obtained if particles are accelerated by stochastic processes (e.g., via turbulent acceleration, Fig. 1b).

It is clear that the HXR fluxes are pivot points in the modelling of the non-thermal spectra of galaxy clusters and thus that the advent of the future observatories (ASTRO-E2, NEXT) will be crucial to confirm the above issues.

3.2. *Detailed properties of the radio emission*

Additional possibilities to constrain the origin of the emitting particles derive from the study of the detailed radio properties of a few well studied *radio halos*:

i) Broad synchrotron radio profiles: Giant *radio halos* are very extended sources with an extension up to 2-2.5 Mpc. The radial synchrotron profiles of these giant *radio halos* are found to be broader than that of the X-rays emitted by the hot gas (e.g., Govoni et al. 2001). This basically means that the synchrotron emissivity ($j \propto K_e B^{1+\alpha}$ for a spectrum of electrons $N(\gamma) = K_e \gamma^{-(1+2\alpha)}$) decreases with distance from the cluster center less rapidly than the bremsstrahlung emissivity $j \propto n_{th}^2$ (n_{th} is the density of the thermal plasma), and thus that the spatial distribution of the relativistic electrons is broader than that of the thermal particles. If radio electrons are of *secondary origin* then a very large number of relativistic hadrons is required in the clusters outskirts (since the production rate of secondary particles depends on n_{th}) and this causes a serious energetic problem at least if μG central fields and a relatively steep decrease of the field strength from the cluster center (as theoretically expected, e.g. Dolag et al. 2002) are assumed (Brunetti 2003). Obviously the energetic problem may be alleviated in some cases (e.g. Coma) by assuming stronger central fields and a slower radial decrease of the field strength (Pfrommer & Ensslin 2004).

ii) Observed synchrotron spectra: The integrated synchrotron spectrum of a few *radio halos* steepens at high frequencies (e.g., Giovannini et al. 1993; Fusco-Femiano et al. 2003b). Although, in some cases, the observed steepening may be mitigated by taking into account the SZ effect (Ensslin 2002), these observations point out to the presence of a high energy break or a cut-off in the spectrum of the emitting electrons. A second point is that the 0.3-1.4 GHz spectral index maps of an increasing number of *radio halos* indicate a progressive steepening of the radio spectrum from the center to the periphery of the clusters (Fig. 2a); the radial steepening in the Coma cluster, originally discovered with interferometric observations, is also required by single dish observations (Deiss et al. 1997). Radial spectral steepenings are theoretically explained in terms of the presence of a high energy break or cut-off in the electron spectrum combined with a radial decrease of the ICM-field strength (Brunetti et al. 2001; Kuo et al. 2003). Such high energy cut-offs should be at energy $\gamma \sim 10^3 - 10^5$ and are naturally expected if the electrons are re-accelerated by some kind of mechanism (e.g., Brunetti et al. 2001; Petrosian 2001).

iii) Synchrotron spectral and brightness variations: A more recent observational hint is that most *radio halos* show synchrotron brightness increments and complex spectral features in the spectral-index maps in coincidence with dynamically disturbed regions of the clusters and with temperature patches (Markevitch et al. 2002; Feretti et al. 2004). These observations suggest a close link between the dynamical status of the ICM and the spectrum of the particles (and/or the magnetic field) on 100-200 kpc scales.

Although future observations are obviously required to confirm all the above findings, it is clear that when the broad radial profiles of *radio halos* are *consistently* combined with the observed radial spectral steepenings, then *secondary models* have inescapable problems.

4. Cluster mergers and particle acceleration: a general view

In this Section we release the “historical” dichotomy between *primary* and *secondary* origin of the emitting particles and give a more general (but brief) theoretical overview of the mechanisms which are believed to drive non-thermal processes; a simple scheme is given in Fig.2b.

4.1. *Injection processes*

The first step in our understanding of non-thermal activity is given by the modelling of the injection and of the spatial diffusion of relativistic particles in the ICM (Fig.2b, bottom-left), and of the energy released by cluster mergers into shock waves and turbulence which will be responsible for particle acceleration (Fig.2b, top-center).

i) Injection of relativistic particles in the ICM: clusters contains galaxies and AGN which would inject relativistic leptons and hadrons which will remain confined in the cluster volume (Völk et al. 1996; Berezinsky et al. 1997). We don’t know what is the fraction of energy channeled by these sources into relativistic leptons and hadrons; relativistic leptons, however, radiate their energy on a time-scale much shorter than a Hubble time, and thus it is very likely that the non-thermal energy stored in galaxy clusters is dominated by the hadronic component. Relativistic hadrons in the ICM continuously generate secondary leptons due to collisions with thermal protons and these particles contribute to the population of relativistic leptons in the ICM.

ii) Cluster mergers: injection of shocks and turbulence: accretion of matter at the virial radius is likely to form strong shocks, while cluster mergers should drive shock waves in the internal regions of the clusters (e.g., Miniati et al. 2000 and references therein). There is still some debate on the typical Mach number of the shocks developed during mergers. Some numerical simulations suggest that a relatively large fraction of these shocks have a high Mach number (Miniati et al. 2000, 2001). On the other hand semi–analytical calculations (Gabici & Blasi 2003; Berrington & Dermer 2003) find Mach numbers of order unity as also observed by *Chandra* (e.g., Markevitch et al. 2003). More recent numerical simulations (Ryu et al. 2003) seem to find weaker shocks than in Miniati et al.; however, the comparison with analytical calculations appears difficult because of a different classification of the shocks in the two approaches. Fluid turbulence is expected to be injected in galaxy clusters during cluster mergers. Numerical simulations find that an energy budget of 10-30% of the thermal energy of the ICM can be associated to

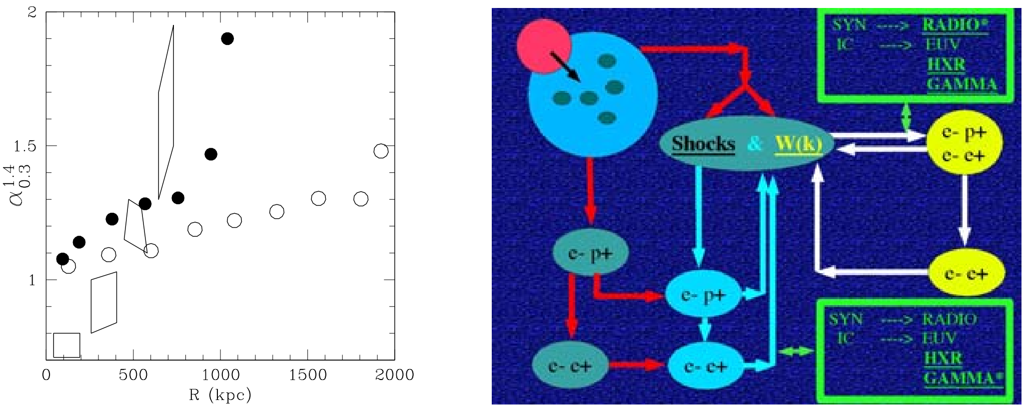

Figure 2. Left Panel: Spectral index (327 – 1400 MHz) vs. distance from the cluster center of Coma (boxes, Giovannini et al. 1993), A665 (filled circles) and A2163 (open circles, Feretti et al. 2004). Right Panel: Scheme of the processes in galaxy clusters (see text).

cluster turbulence (Sunyaev et al. 2003); this may be tested directly with future X-ray observatories (ASTRO-E2). In addition, first evidence for cluster turbulence has been found by the analysis of a very recent Newton-XMM observation of the Coma cluster (Schuecker et al. 2004).

4.2. *Particle acceleration*

The second point related to the generation of non-thermal phenomena is the interplay between particles and acceleration mechanisms. The idea is that this interplay is particularly efficient during cluster merger events. Two mechanism of interplay are reported in Fig.2b: shock-particle coupling (*shock loop*, Fig.2b bottom-center) and turbulence-particle coupling (*turbulence loop*, Fig.2b center-right).

i) Shock loop: Collisionless shocks are generally recognized as efficient particle accelerators through the so-called “diffusive shock acceleration” (DSA) process (Blandford & Eichler 1987). This mechanism has been invoked several times as acceleration process in clusters of galaxies (Takizawa & Naito 2000; Blasi 2001; Miniati et al. 2001; Fujita & Sarazin 2001). Although the scale and morphology of the synchrotron emission of *radio halos* are not naturally accounted for by shock-accelerated particles, evidence for shock acceleration in galaxy clusters may come from the so called *radio relics* which indeed can be produced through the combination of shock acceleration and adiabatic compression of *ghost radio plasma* by shock waves propagating into the ICM (e.g., Ensslin 2003). Shocks in the ICM may accelerate particles from the thermal pool and/or reaccelerate seed relativistic particles in the ICM with a power law in momentum with a slope $= 2(\mathcal{M}^2+1)/(\mathcal{M}^2-1)[+1]$ ($\mathcal{M}$ is the Mach number and “[+1]” should be added to calculate the spectrum of particles in the ICM under the assumption of a stationary continuous particle-injection by shock waves). If shocks related to major mergers are weak as suggested by semi-analytical calculations (Sect. 4.1), they accelerate very steep particle-spectra and thus they are not the dominant process for the injection of relativistic particles in the ICM. However, the maximum energy of particles accelerated at a shock wave is very high:

$$E^e_{max}(GeV) \sim 2.5\times 10^4 B_{\mu G}^{1/2} v_8 \qquad \text{and} \qquad E^p_{max}(GeV) \sim 4.5\times 10^8 B_{\mu G} v_8^2 \qquad (4.1)$$

for leptons and hadrons, respectively (v_8 is the speed of the shock in units of 10^8km/s,

$B_{\mu G}$ is the field in units of μG and Bohm diffusion coefficient is assumed). The decay of π^o generated in hadronic collisions together with the IC emission from *secondary* leptons injected by the same collisions and from *primary* electrons accelerated at shock waves will produce gamma ray radiation above 100 MeV (e.g., Blasi 2001). The amount of radiation depends on the energy budget of relativistic hadrons and on their spectrum. Gamma rays emitted from the outskirts of galaxy clusters are expected to be dominated by IC emission from primary electrons accelerated at accretion shocks, these shocks are indeed expected to be very strong and thus the spectrum of the accelerated electrons should be flat ($\propto E^{-2}$). On the other hand, given the different results on the Mach number of merger shocks obtained by different approaches (Sect.4.1), there is no general agreement on the gamma ray flux and spectrum expected from the central regions of galaxy clusters where the contributions from the products of hadronic collisions should be important (e.g., Miniati 2002). Hopefully, future gamma ray observations will unambiguously clarify this issue and will allow us to constrain the energetics and spectrum of relativistic hadrons in galaxy clusters (Gabici & Blasi 2004).

ii) Turbulence loop: The origin of the giant *radio halos* and possibly of the HXR tails is most likely associated with the turbulence loop. Indeed, it has been shown that re–acceleration of a population of relic electrons by turbulence powered by major mergers is suitable to explain the very large scale of the observed radio emission and is also a promising possibility to account for the complex spectral behaviour observed in the diffuse radio sources and for the HXR tails (Brunetti et al. 2001a,b; Petrosian 2001; Ohno, Takizawa and Shibata 2002; Fujita, Takizawa and Sarazin 2003).

iii) Self-consistent modellings: Very recently, the problem of particle-Alfvén wave interactions has been investigated in the most general situation in which relativistic electrons, thermal protons and relativistic protons exist within the cluster volume (Brunetti et al. 2004). In this modelling the interaction of all these components with the waves, as well as the turbulent cascading and damping processes of Alfvén waves, have been treated in a fully time-dependent way in order to calculate the spectra of electrons, protons and waves at any fixed time. This work has provided a first investigation of the importance of the presence of the relativistic protons in the ICM for the electron acceleration. The most important result of this work is that Alfvénic electron acceleration can produce the observed phenomena provided that relativistic protons are not dynamically important in the ICM (less than few percents of the thermal energy). Of course additional MHD waves which do not interact with particles via resonant-acceleration (e.g., magnetosonic waves) may increase the efficiency of the electron acceleration without being very sensitive to the presence of relativistic hadrons. In addition, if reaccelerated, the spectrum of the hadronic component becomes harder and this may increase the efficiency in producing secondary particles in the ICM. These particles can be reaccelerated interacting with the MHD waves as in the case of the primary seed electrons, so that the leptonic acceleration can efficiently generate non-thermal phenomena also in the case in which the number of primary leptons in the ICM is negligible (Brunetti & Blasi, in preparation).

Acknowledgements

We acknowledge partial financial support from INAF (Istituto Nazionale di Astrofisica) through grant D4/03/IS. It is a pleasure to thank my collaborators and colleagues P. Blasi, R. Cassano, L. Feretti, S. Gabici and G. Setti for useful discussions.

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