Gamma ray emission and stochastic particle acceleration in galaxy clusters

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Abstract. FERMI (formerly GLAST) will shortly provide crucial information on relativistic particles in galaxy clusters. We discuss non-thermal emission in the context of general calculations in which relativistic particles (protons and secondary electrons due to proton-proton collisions) interact with MHD turbulence generated in the cluster volume during cluster mergers. Diffuse cluster-scale radio emission (Radio Halos) and hard X-rays are produced during massive mergers while gamma ray emission, at some level, is expected to be common in galaxy clusters.

Keywords: Particle acceleration, Turbulence, Galaxy clusters, Gamma rays.

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INTRODUCTION

Clusters of galaxies contain \( \approx 10^{15} \text{ M}_\odot \) of hot (10\(^8\) K) gas, galaxies, dark matter and non-thermal components.

The origin of non-thermal components is likely connected with the cluster formation process: a fraction of the energy dissipated during cluster mergers is expected to be channelled into the acceleration of particles via shocks and turbulence that lead to a complex population of primary electrons and protons in the IGM (e.g., [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]). Theoretically relativistic protons are expected to be the dominant non-thermal particle components since they have long life-times and remain confined within galaxy clusters for an Hubble time (e.g., [11] and ref. therein). Confinement enhances the probability to have proton-proton (p-p) collisions that in turns give gamma ray emission via decay of the neutral pions produced during these collisions [12, 13]. p-p collisions also inject secondary electrons that give synchrotron and inverse Compton (IC) emission whose relevance depends on the proton content in the IGM [14]. The inter-galactic medium (IGM) is expected to be turbulent at some level and MHD turbulence can re-accelerate both primary and secondary particles via second order Fermi mechanisms. Turbulence is naturally generated in cluster mergers (e.g., [15, 16, 17, 18]) and the resulting particle re-acceleration process should enhance the synchrotron radio emission and the IC hard X–ray emission by orders of magnitude.

The energy content in the form of relativistic protons in the IGM is still poorly constrained since present gamma ray observations can provide only upper limits to the gamma ray emission from galaxy clusters [19]; also Reimer and Perkins, this conference). On the other hand radio observations of Mpc-sized diffuse synchrotron emission from galaxy clusters provide crucial information on the relativistic electron component (e.g. [20, 21]).

The FERMI gamma-ray space telescope will shortly allow to measure (constrain) the energy content of relativistic protons in the IGM. For this reason, starting from present understanding of non thermal components in galaxy clusters, we discuss expectations for gamma ray emission.

CLUSTER-SCALE RADIO EMISSION

In this Section we outline our starting point to model non thermal (including gamma ray) cluster emission.

The most prominent examples of diffuse cluster emission are giant Radio Halos: Mpc-scale diffuse synchrotron sources at the centre of a fraction of massive and merging galaxy clusters [20, 21]. This Mpc-scale radiation may originate from secondary electrons injected by collisions between relativistic and thermal protons in the IGM (e.g. [22, 14]), alternatively extended radio emission may originate from relativistic electrons re-accelerated in situ by various mechanisms associated with the turbulence in massive merger events (e.g. [4, 6, 23]). These two processes likely happen at the same time and a unified scenario that models both the injection and re-acceleration of secondary electrons and primary particles due to MHD turbulence has been investigated by [24].

Radio Halos are not common: although a fairly large
number of clusters has adequate radio follow up, they are presently detected only in a fraction of massive and merging clusters \[25, 26, 27, 28\]. Studies based on the analysis of present X-ray selected cluster samples with radio follow up allow to conclude that the fraction of clusters with Radio Halos depends on cluster X-ray luminosity \[1\] and that clusters have a bimodal behaviour in the 1.4 GHz radio luminosity \(P_{1.4} \) – soft X–ray luminosity \(L_x\) plane with Radio Halo clusters being one order of magnitude more radio luminous than upper limits for clusters with no Radio Halos \((29);\) Fig. 1).

These facts suggest that Radio Halos are transient phenomena connected with cluster mergers and that some threshold in the mechanism for the generation of these sources should come into play. Unless we admit the possibility of strong dissipation of the magnetic field in clusters, these properties cannot be easily understood in the case that the continuous injection of secondary electrons in the IGM plays the major role in the origin of these sources. In this case - indeed - Radio Halos should be long living phenomena and common, and some general \(P_{1.4} - L_x\) trend would be predicted for all clusters \((e.g. 7, 30, 10)\). In particular, the bimodality in Fig. 1 and the substantial lack of clusters between the Radio Halo and radio quiet regions implies that the bulk of the magnetic energy in clusters should be dissipated in a time-scale of only \(\approx 0.1 - 0.2\) Gyr which is challenging to reconcile with present understanding of cluster magnetic fields \((e.g. 31)\).

On the other hand, the emerging observational picture supports the idea that turbulent re-acceleration of relativistic electrons may play a role in the formation of Radio Halos in connection with cluster mergers. In particular, it is interesting to note that in the context of this scenario radio-quiet clusters are expected to evolve into Radio Halo clusters (and vice versa) in a time-scale of the order of the electron acceleration time-scale, \(\approx 0.1 - 0.2\) Gyr. Spectral studies are also important: the discovery of Radio Halos with steep spectrum \(\approx L_x\) and the synchrotron cut off that is found in the spectrum of the Coma Radio Halo \(33, 34\) imply a maximum energy in the spectrum of the emitting electrons at energies \(\approx\)GeV suggesting that the mechanism responsible for the acceleration of electrons in the IGM is poorly efficient, consistent with turbulent acceleration.

**EMISSION FROM GALAXY CLUSTERS**

In this Section we calculate non-thermal (multifrequency) emission from galaxy clusters under the assumptions that MHD turbulence plays a role in the particle acceleration process during cluster mergers. We do not include the contribution to the non thermal emission from fast electrons accelerated at shock waves that develop during cluster mergers and accretion of matter (see Pfrommer, this conference).

As already mentioned, it is believed that clusters are reservoir of relativistic protons that accumulate in the IGM during cluster life-time \((e.g. 11)\). Thus we model the re-acceleration of relativistic particles by MHD turbulence in the most simple situation in which only relativistic protons are initially present in a turbulent IGM. These protons generate secondary electrons via p-p collisions and in turns secondaries (as well as protons) are re-accelerated by MHD turbulence. Following \(24\) we restrict to the case of Alfvén wave \(4\) and calculate the spectrum of particles and MHD waves and their evolution with time by solving a set of coupled equations that

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1. The fraction is \(\approx 30\%\) for \(L_x > 8 \cdot 10^{44}\) erg s\(^{-1}\) clusters and \(\leq 10\%\) for clusters with \(L_x \approx 3 \cdot 10^{44} - 8 \cdot 10^{44}\) erg s\(^{-1}\); Montecarlo approaches show that the two fractions differ at \(\approx 4\sigma\) level \(27\).

2. This means that assuming that all massive clusters may host Radio Halos during their life, the life-time of Radio Halos must be much shorter, \(< 1\) Gyr, than the cluster life-time.

3. Even in the (worst) case of simply decaying MHD turbulence, the energy density of the rms field decreases with time only (about) linearly and \(\geq 5\) eddy turnover times \((\approx\) Gyr) are required to allow dissipation of the bulk of the magnetic field \((\text{Fig.2 in 31})\).

4. An additional possibility is given by magnetosonic waves \(35, 36\).
FIGURE 2. Broad band spectrum produced within $R < 1$ Mpc from a Coma-like cluster. **Upper panels:** Synchrotron (left, SZ decrement at high frequencies is not taken into account), and IC and $\pi^0$-o emission (right) calculated at $t=0.5$ Gyr from the injection of MHD turbulence in the IGM (the energy injected in Alfven modes between $t=0-0.5$ Gyr is $\approx 3\%$ of the thermal energy). **Lower panels:** Synchrotron (left) and IC and $\pi^0$-o emission (right) calculated at $t=1$ Gyr after dissipation of turbulence in the IGM. In all panels calculations are shown assuming a ratio between the energy density of relativistic and thermal protons $= 1\%$ (dashed lines), $0.5\%$ (dotted lines) and $0.3\%$ (solid lines) at $t=0$ (with proton spectrum $\delta_e=2.2$) and a central cluster-magnetic field $B_0 = 2\mu$G. For the sake of completeness we show radio data, BeppoSAX data and EGRET upper limit for the Coma cluster ([24] and ref. therein) the recent VERITAS upper limit (Perkins, this meeting) and the approximate sensitivity after 1 yr of FERMI (dashed).

\[
\frac{\partial N^\pm_e(p,t)}{\partial t} = \frac{\partial}{\partial p} \left[ N^\pm_e(p,t) \left( \left| \frac{dp}{dt} \right| - \frac{1}{p^2} \frac{\partial}{\partial p} (p^2 D_{pp}^\pm) + \frac{dp}{dt} \right) \right] + \frac{\partial^2}{\partial p^2} \left[ D_{pp}^\pm N^\pm_e(p,t) \right] + Q^\pm_e[p,t;N^\pm_e(p,t)],
\]

(1)

\[
\frac{\partial N_p(p,t)}{\partial t} = \frac{\partial}{\partial p} \left[ N_p(p,t) \left( \left| \frac{dp}{dt} \right| - \frac{1}{p^2} \frac{\partial}{\partial p} (p^2 D_{pp}) \right) \right] + \frac{\partial^2}{\partial p^2} \left[ D_{pp} N_p(p,t) \right],
\]

(2)

and

\[
\frac{\partial W_k(t)}{\partial t} = \frac{\partial}{\partial k} \left( k^2 D_{kk} \frac{\partial}{\partial k} \left[ \frac{W_k(t)}{k^2} \right] - \Gamma(k) W_k(t) \right) + I_k(t),
\]

(3)

give the spectrum of electrons, $N_e^-$, positrons, $N_e^+$, protons, $N_p$, and waves, $W_k$:

where $|dp/dt|$ marks radiative (r) and Coulomb (i) losses, $D_{pp}$ is the particle diffusion coefficient in the momentum space (and depends on the wave spectrum $W_k$), $Q^\pm_e$ is the injection term of secondary leptons due to p-p collisions (and depends on $N_p$), $D_{kk}$ is the diffusion coefficient in the wavenumber space, $I_k$ is the injection rate-spectrum of Alfven waves at resonant scales, and $\Gamma$ is the damping rate of waves due to non-linear resonance with thermal and relativistic particles ($N_p$ and $N_e$); details can be found in [24].

In the following we consider a simple model of galaxy cluster assuming that the energy densities of relativistic protons at the beginning of reacceleration, $\varepsilon_p$, and of the magnetic field, $B$, and the injection rate of Alfven waves during mergers, $I_k$, scale with thermal energy density, $\varepsilon_{th}$ ($\varepsilon_p \propto \varepsilon_{th}$, $B \propto \varepsilon_{th}$ and $\int I_k dk \propto \varepsilon_{th}$). An example of the expected broad band emission (synchrotron, IC, $\pi^0$ decay) is reported in Fig. 2 by adopting the spatial distribution and physical parameters of the thermal IGM of the Coma cluster. In the context of this model the non-thermal emission is a mixture of two main spectral components: a long-living one that is emitted by sec-
ondary particles (and by $\pi^0$ decay) continuously generated during p-p collisions, and a transient component that is due to the re-acceleration of relativistic particles by MHD turbulence generated (and then dissipated) in cluster mergers. In order to highlight these components we calculate the non-thermal emission during a cluster merger, i.e. assuming a turbulent IGM, (Fig. 2, upper panels) and 1 Gyr after turbulence is dissipated (Fig. 2, lower panels). Lower panels show the long-living component of the non-thermal cluster emission, because relativistic protons, that in turns generate secondaries, lose energy on a long time-scale. This long-living emission does not strongly depend on the dynamics of clusters but only on the energy content (and spectrum) of relativistic protons in the IGM (and on the magnetic field in the case of the synchrotron radio emission). On the other hand, the comparison between upper and lower panels of Fig. 2 highlights the transient emission that is generated by short-living electrons reaccelerated by turbulence during cluster mergers.

We note that the results in Fig. 2 have the potential to reproduce the radio bimodality observed in galaxy clusters (Fig. 1): Radio Halos develop in connection with particle re-acceleration due to MHD turbulence in cluster mergers where the cluster-synchrotron emission is considerably boosted up (upper panel), while a fainter long-living radio emission from secondary electrons is expected to be common in clusters (lower panel); the level of this latter component must be consistent with the radio upper limits from radio observations of clusters with no Radio Halos. IC hard X-rays are also produced in connection with Radio Halos, although the IC signal from re-accelerated secondary electrons is not expected to be very luminous (see discussion in [24] for a comparison with the case of re-acceleration of primary relic electrons).

An important point is that gamma ray emission is expected (at some level, depending on the content and spatial distribution of relativistic protons) to be common in galaxy clusters and not directly correlated with the presence of giant Radio Halos. Cerenkov arrays already constrain the level of gamma rays from Coma and few other nearby clusters (Fig. 2, Perkins et al., this meeting). After ≈1 yr of operations FERMI will reach adequate sensitivity in the energy range 0.1-100 GeV to start obtaining crucial constraints on nearby clusters and hopefully to measure the energy content of relativistic protons in these clusters.

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