High Energy Phenomena in Clusters of Galaxies

P. Blasi [a] and S. Colafrancesco[b]

[a]Department of Astronomy & Astrophysics, and
E. Fermi Institute, The University of Chicago,
5640 S. Ellis Av., Chicago, IL 60637

[b]Osservatorio Astronomico di Roma,
Via dell'Osservatorio 2, I-00040, Monteporzio (ITALY)

Several phenomena in high energy astrophysics have been recently related to clusters of galaxies and to cosmic ray interactions occurring inside these structures. In many of these phenomena the observable effects depend on the energy density of cosmic rays confined in the Intra Cluster (IC) medium, which is a poorly known quantity. We propose here that useful indications about this quantity can be obtained from present and future observations of galaxy clusters in the radio and hard X-ray frequency ranges.

1. Introduction

Clusters of galaxies are the largest gravitationally bound structures in the universe. They are exceptionally useful laboratories for *cosmology* and *high energy astrophysics*.

From the cosmological side these structures probe:
i) the amplitude and shape of the primordial fluctuation spectrum, because the mass (or temperature) function of rich clusters is strongly sensitive to the value of the fluctuation power-spectrum, $\sigma(M,z)$. Thus it is possible to measure $\sigma(M,z)$ on the cluster scales fitting the mass or temperature function to the local data (see, e.g., [1] [2] and references therein);
ii) the evolution of baryons, both condensed in the form of galaxies and diffuse in the form of IC gas, which is abundantly present within the cluster potential wells. In fact, galaxies are responsible for the chemical enrichment of the IC gas at a level $Fe/H \gtrsim 0.3$ of the solar value, during their life-cycles. Thus, high-quality X-ray spectral observations of galaxy clusters allow to study in details the physical state of the IC gas and the feedbacks from galaxy evolution [3];
iii) the overall structure of the universe, using the possibility to measure directly H_0 and Ω_0 through X-ray and Sunyaev-Zel'dovich effect (in the radio and sub-mm bands) cluster observations [4].

Clusters of galaxies are also relevant for high energy phenomena in large scale structures because they can be regarded as the *largest particle accelerators in the sky*. In the following, we will discuss some aspects in which galaxy clusters can yield important insights for high energy astrophysical phenomena.

2. Clusters of galaxies as γ-ray sources

There are different types and sites of particle acceleration in galaxy clusters from which γ-rays and neutrinos can be produced through the following channels:

$$p + p \rightarrow \pi^0 + X, \qquad \pi^0 \rightarrow \gamma + \gamma$$
$$p + p \rightarrow \pi^\pm + X, \qquad \pi^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu),$$
$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) . \qquad (1)$$

The possible sites are [5] [6]: *i)* normal galaxies with low cosmic ray (CR) emitted powers, $L_{CR} \lesssim 10^{43}$ erg/s; *ii)* active galaxies (like radio-galaxies living in the cluster cores or AGNs) with moderate powers, $L_{CR} \sim 10^{44}$ erg/s; *iii)* accretion and/or merging shocks which are produced during the cluster collapse and virialization (see Fig.1) and can produce large powers, $L_{CR} \gtrsim 2 \cdot 10^{44}$ erg/s, through first order Fermi acceleration mechanism. In the *pp* collisions giving

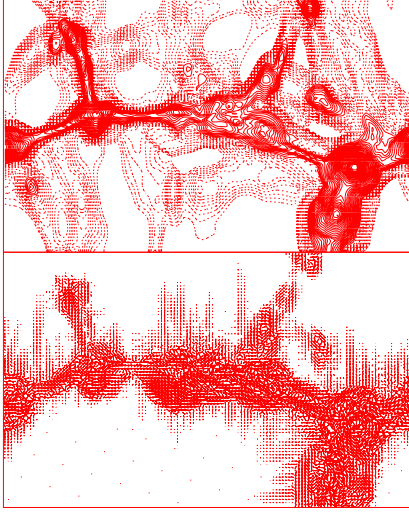Figure 1. *Shocks in large scale structures from N-body simulations [7] (courtesy of D.Ryu) in which are shown the distribution of the baryonic matter (upper panel) and of the magnetic field (lower panel). Clusters of galaxies are found as the knots of the large scale matter condensations.*
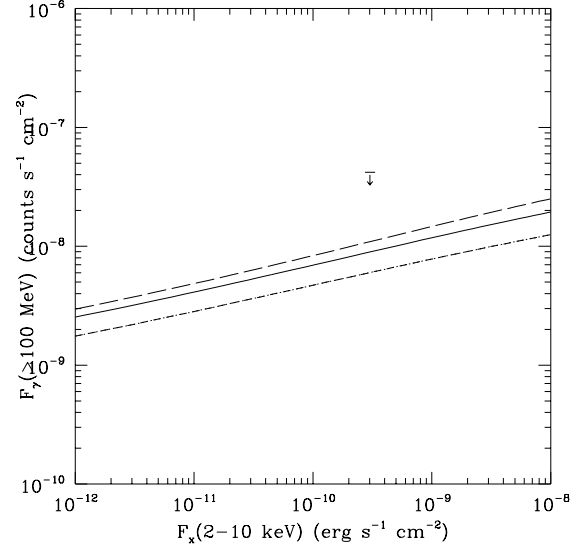

Figure 2. *Gamma ray fluxes for clusters at $z = 0.023$ in different cosmological scenarios: CDM ($\Omega_0 = 1$; dashed curve), CDM+Λ ($\Omega_0 = 0.4$; continuous curve), open CDM ($\Omega_0 = 0.3$; long-dashes curve) and mixed DM ($\Omega_0 = 1$, $\Omega_\nu = 0.3$; dotted curve). The arrow indicates the EGRET upper limit for A1656 (Coma).*

rise to γ-ray production, bullet protons are supplied by the previous particle accelerators found within galaxy clusters, while the target protons are those of the hot ($T \sim 10^7 \div 10^8$ K), diffuse ($n_e \sim 10^{-3}$ cm^{-3}) and metal enriched IC gas (see [8] for a review) which is responsible for the cluster X-ray thermal emission. Thus, a correlation is expected between the X-ray (thermal) power:

$$L_X \propto n_0^2 T^{1/2} r_c^3 \; , \tag{2}$$

and the γ-ray (non-thermal) power:

$$Q_i(E) \propto Y_i \sigma_{pp} c n_0 Q_p(E) r_c^2 \; , \tag{3}$$

where n_0 is the central density of the IC gas, T its temperature and r_c the core radius of a cluster with density profile $n(r) = n_0(1 + x^2)^{-3\beta/2}$, with $x \equiv r/r_c$ and $\beta \sim 0.6 \div 0.8$ (see [6] for details). The correlation among the X-ray and γ-ray fluxes (see Fig.2) reads:

$$F_\gamma \propto F_X \left(n_0 r_c T^{1/2} \right)^{-1} \; . \tag{4}$$

In the previous formulae, $Q_p(E)$ is the CR spectrum which determines L_{CR} and consequently the cluster γ-ray emissivity, but it is a poorly known quantity in clusters of galaxies and in large scale structures in general. Assuming $L_{CR} \approx 10^{44}$ erg/s (as produced by accretion shocks and/or active galaxies) we predicted that the contribution of galaxy clusters to the diffuse gamma ray background is $\lesssim 3\%$, quite independently of the assumed cosmological scenario and on cluster evolution (see Fig.3). This result (apparently not relevant for the discussion on the origin of the DGRB) is indeed relevant because it shows that galaxy clusters cannot overcome the fraction of the DGRB left available from other (resolved or truly diffuse) sources summing up to
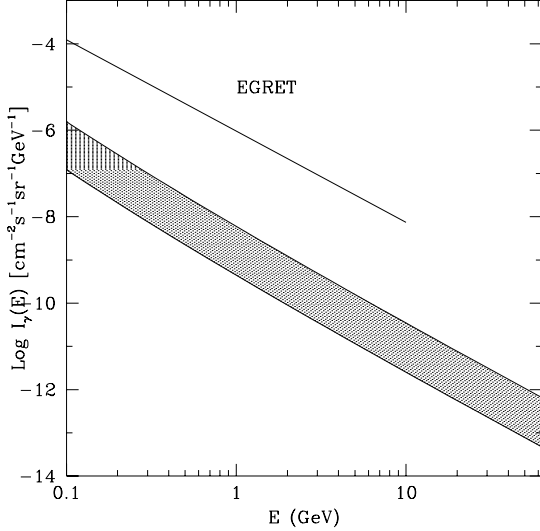
Figure 3. *The expected DGRB from clusters, considering various sources of theoretical uncertainties in the cluster modelling. A flat CDM ($\Omega_0 = 1; h = 0.5; n = 1$) model is considered here. The thick solid line show the best fit to the EGRET data [9].*

$\sim 80 \div 95\%$ (see discussion in [6]). Larger fractions of the DGRB contributed by galaxy clusters would give sensitive constraints to the current scenarios for structure formation.

Note, however, that these results rely on the (reasonable and motivated) value assumed for the CR power in clusters, $L_{CR} \approx 10^{44}$ erg/s, which depends on the CR spectrum $Q_p(E)$. So far, there are only heuristic derivations of such a crucial quantity. Nonetheless, in the following we will propose an operative procedure to obtain quantitative indications on the CR spectrum in galaxy clusters.

3. Non-thermal emission from secondary electrons in galaxy clusters

Most of the cosmic rays produced in galaxy clusters are confined in the IC medium for times larger than the age of the universe [5] [6]. However, the maximum energy for which this confinement is still efficient depends strongly on the adopted diffusion model, so that for very extreme choices of the parameters, confinement can be limited to low energies. Here we shall consider the two limiting cases of complete confinement and no confinement in order to outline the general picture of the CR diffusion in clusters. During the lifetime of the CR in the IC medium, they interact with the hot IC protons and produce secondary particles through pp collisions (see eq.1). In such collisions charged pions are also produced and they produce a flux of neutrinos (see [5] [6]) and electrons (here we will refer to both electrons and positrons as 'electrons', being this distinction irrelevant for our purposes).

The global normalization of the gamma or neutrino spectra obtained in previous works depends on a poorly known quantity, namely the energy density of CRs in clusters. Here we propose that useful indications on the CR energy density in clusters can be obtained by the radio measurements already existing and by X-ray measurements in the hard part of the spectrum, that will be available in the next future. In our model, radio and non-thermal X-ray emissions are produced by relativistic electrons through synchrotron and inverse compton scattering (ICS) off the microwave background photons, respectively.

We assume here a CR spectrum of the form:

$$Q_p(E) = \frac{L_p}{E_0^2}(\gamma_g - 1)(\gamma_g - 2)\left(\frac{E}{E_0}\right)^{-\gamma_g}, \qquad (5)$$

where $E_0 \sim 1 \, GeV$ and L_p is the cluster total CR luminosity. The rate of production of secondary electrons from pp collisions is [10]:

$$Q_e(E_e) = 36\frac{I(\gamma_g)(\gamma_g - 1)(\gamma_g - 2)}{\gamma_g(\gamma_g + 2)(\gamma_g + 3)}L_p n_H c \sigma_0 t_0$$

$$\frac{m_\pi^2}{m_\pi^2 - m_\mu^2}E_e^{-\gamma_g}, \qquad (6)$$

in the case of complete CR confinement. For the case of no confinement we obtain:

$$Q_e(E_e) = 36 \frac{I(\gamma_g,\eta)(\gamma_g-1)(\gamma_g-2)}{(\gamma_g+\eta)(\gamma_g+\eta+2)(\gamma_g+\eta+3)}$$

$$L_p n_H c \sigma_0 \frac{R_{cl}^2}{6D_0} \frac{m_\pi^2}{m_\pi^2 - m_\mu^2} E_e^{-\gamma_g-\eta} \quad (7)$$

Here n_H is the average gas density in clusters, $\sigma_0 = 3.2 \times 10^{-26} cm^2$, $t_0 = 2.06 \times 10^{17} h^{-1}$ s is the age of universe and m_π and m_μ are the pion and muon masses. The diffusion coefficient can been written as $D(E) = D_0 E^\eta$. The functions $I(\gamma_g)$ and $I(\gamma_g,\eta)$ are defined as $I(\gamma_g) = \int_0^1 dx f_\pi(x) x^{\gamma_g-2}$ and $I(\gamma_g,\eta) = \int_0^1 dx f_\pi(x) x^{\gamma_g+\eta-2}$, where $f_\pi(x) = 1.34(1 - x)^{3.5} + e^{-18x}$, is a scaling function entering the calculation of the secondary electrons from the decay of charged pions (see [10]). In the following we use $\gamma_g = 2.4$, checking at the end how the results change for $\gamma_g = 2.1$.

The diffusion coefficient enters effectively in the calculation of the case in which no confinement is realized. For the case of a Kolmogorov spectrum of fluctuations, it can be easily written in terms of the average magnetic field B, the coherence scale l_c and the CR energy E (see [10]):

$$D(E) \simeq$$

$$3 \times 10^{31} E^{1/3} B_\mu^{-1/3} \left(\frac{l_c}{430 \ kpc}\right)^{2/3} \ cm^2 \ s^{-1}, \quad (8)$$

where E is the CR energy in GeV and B_μ is the magnetic field in μG. The coherence scale, l_c, of the magnetic field is a quite uncertain parameter: we assumed for it an upper value, 430 kpc, corresponding to the case in which the magnetic field lines are stretched by the bulk motion of the galaxies in the clusters on a typical scale equal to the average galaxy separation.

At the electron energies we are interested in, the time for energy losses is smaller than the typical diffusion time, so that the equilibrium electron spectrum is $n_e(E_e) \propto Q_e(E_e)\tau_e(E_e)$, where $\tau_e(E_e) = E_e/(dE_e/dt)$ is the time scale for losses. The details of the calculation of the radio and X-ray emission from synchrotron and ICS are given

in [10]; here we shall limit ourselves to outline the results obtained in different cases.

In the case of complete CR confinement, the radio power spectrum reads:

$$P_r(\nu) =$$

$$1.7 \times 10^{42} L_{44} n_3 h_{75}^{-1} \nu(Hz)^{-1.2} \ erg \ s^{-1} \ Hz^{-1}, \quad (9)$$

with $B = 1 \ \mu G$ and $\gamma_g = 2.4$. Here L_{44} is the cluster CR luminosity in units of $10^{44} \ erg/s$, n_3 is the gas density in units of $10^{-3} cm^{-3}$ and h_{75} is the Hubble constant in units of 75 $km/(s \ Mpc)$. With the same parameter choice, the X-ray spectrum reads:

$$I_X(E_X) =$$

$$5.3 \times 10^{50} L_{44} n_3 h_{75}^{-1} E_X(keV)^{-2.2} s^{-1} \ keV^{-1}. \quad (10)$$

While the X-ray flux is very weakly dependent on the magnetic field, the radio flux changes strongly with B. If we take $B \approx 0.1 \ \mu G$ eq.(9) yields;

$$P_r(\nu) =$$

$$1.2 \times 10^{40} L_{44} n_3 h_{75}^{-1} \nu(Hz)^{-1.2} \ erg \ s^{-1} \ Hz^{-1}. \quad (11)$$

This fact has a relevant implication: an accurate measurement of the flux in the hard X-ray region of the cluster spectra can fix the product $L_{44} n_3$ so that, in turn, a measure of $P_r(\nu)$ can give informations on the value of B.

In the case of *no confinement* we obtain for the radio power spectrum:

$$P_r(\nu) =$$

$$5.6 \times 10^{42} L_{44} n_3 h_{75}^{-1} \nu(Hz)^{-1.365} \ erg \ s^{-1} \ Hz^{-1}, \quad (12)$$

and for the X-ray spectrum:

$$I_X(E_X) =$$

$$1.4 \times 10^{50} L_{44} n_3 h_{75}^{-1} E_X(keV)^{-2.365} s^{-1} \ keV^{-1}. \quad (13)$$

Again $I_X(E_X)$ does not change appreciably with the magnetic field, while $P_r(\nu)$ does. For $B = 0.1 \ \mu G$ we obtain:

$$P_r(\nu) =$$

$$1.3 \times 10^{40} L_{44} n_3 h_{75}^{-1} \nu(Hz)^{-1.365} \ erg \ s^{-1} \ Hz^{-1}. \quad (14)$$

4. A future outlook

At present, there are only a few observations of cluster radio halo spectra, the most detailed one referring to the Coma cluster [12]. Based on the available observations, we can only put weak constraints to the cluster CR energy density, $\omega_{CR}^{cl} \lesssim 10^{-2} \ eV/cm^3$ (confinement with $B = 1\mu G$) or $\omega_{CR}^{cl} \lesssim 1 \ eV/cm^3$ (confinement with $B = 0.1\mu G$). Moreover, note that the EGRET upper limit on the γ-ray emission from Coma (see Fig.2) yields $\omega_{CR}^{cl} \lesssim 0.1 \ eV/cm^3$.

From this first comparison of our results with the available data, it is evident the extreme importance of a definite detection of non thermal X-ray tail in the spectra of galaxy clusters. In fact, such X-ray spectra are very weakly dependent on the value of the magnetic field, so that X-rays can in principle fix the value of $L_{44}n_3$, provided that the radio halos observed in the same clusters are due to the same secondary electrons. Then, in turn, radio observations can be used to give reliable indications concerning both the amplitude and the power spectrum of the magnetic field in clusters.

The available observations at $E \geq 20$ keV from Coma can only provide upper limits to the hard, non-thermal X-ray tails [13]. In our model, these limits yield $L_{44}n_3 \lesssim 60 \div 600$ where the two values refer to the extreme cases of confinement and no confinement, respectively. These give $L_{44} \lesssim 1.4 \cdot 10^2 \div 1.4 \cdot 10^3$ for an average IC gas density in Coma of $n_3 \approx 0.43$. The previous limits are very weak and do not allow, at the moment, neither to distinguish between the two regimes nor to strongly constrain the CR energy density in Coma. The results obtained for the case of an electron production spectrum with index $\gamma_g = 2.4$, do not change appreciably if we use $\gamma_g = 2.1$, which is somewhat close to a lower limit for this slope if the parent CRs are assumed to be produced by acceleration at supernovae shocks.

Beyond the details of the calculations we presented here, the possible detection of hard X-ray tails in the spectra of galaxy clusters will provide new insights for the role of high-E phenomena in large scale structures. This is at hand in the hard X-ray region with the data on galaxy clusters achievable with the SAX satellite, which is now operating. In fact, the PDS instrument on board SAX has a limiting flux $\gtrsim 10^{-11}erg/cm^2s$, with $\Delta E \sim 15\%$ (at 60 keV) and a broad band, $\Delta E \sim 15 \div 300$ keV, response which makes it possible to detect hard X-ray tails in the spectra of several nearby clusters like Coma, A2163 and A2199.

Besides the analysis of the two extreme cases of CR confinement we presented here, the detection of a possible steepening in the X-ray tail spectra can suggest (see sect.3) that CR begin to be unconfined above some threshold energy, while no effect should be present in the radio spectrum. A more detailed discussion of this effect will be reported in a forthcoming paper [11].

Thus, in the light of the present results, better constraints on the CR energy density in the IC medium are expected to become available in the next future, together with a better insight on the structure of the IC magnetic fields.

REFERENCES

1. S. Colafrancesco, P. Mazzotta & N. Vittorio 1997, ApJ, 488, 566
2. N. Bahcall 1997, preprint astro-ph/9711062
3. S. Colafrancesco 1998, preprint
4. Y. Rephaeli 1995, ARA&A, 33, 541
5. V.S. Berezinsky, P. Blasi & V.S. Ptuskin 1997, ApJ, 487, 529
6. S. Colafrancesco & P. Blasi, Astroparticle Physics in press, preprint astro-ph/9804262
7. D.Ryu & H. Kang 1997, preprint astro/ph-9702055
8. C. Sarazin 1988, *X-Ray Emission from Clusters of Galaxies*, Cambridge Univ. Press
9. J.L. Osborne et al. 1994, J. Phys. G., 20, 1089
10. P. Blasi & S. Colafrancesco 1998, submitted to Astroparticle Physics
11. P. Blasi & S. Colafrancesco 1998, in preparation
12. K.T. Kim et al. 1990, ApJ, 355, 29
13. Y. Rephaeli, M. Ulmer & D. Gruber 1994, ApJ, 429, 554