



MULTIWAVELENGTH OBSERVATIONS OF CLUSTERS OF GALAXIES AND THE ROLE OF CLUSTER MERGERS

PASQUALE BLASI

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory, Box 500, Batavia, IL 60510-0500, USA

Abstract

Some clusters of galaxies have been identified as powerful sources of non-thermal radiation, from the radio to X-ray wavelengths. The classical models proposed for the explanation of this radiation usually require large energy densities in cosmic rays in the intracluster medium and magnetic fields much lower than those measured using the Faraday rotation. We study here the role that mergers of clusters of galaxies may play in the generation of the non-thermal radiation, and we seek for additional observable consequences of the model. We find that if hard X-rays and radio radiation are respectively interpreted as inverse Compton scattering (ICS) and synchrotron emission of relativistic electrons, large gamma ray fluxes are produced, and for the Coma cluster, where upper limits are available, these limits are exceeded. We also discuss an alternative and testable model that naturally solves the problems mentioned above.

1 Introduction

Non-thermal radiation is observed in several clusters of galaxies at frequencies varying from the radio [see (Ensslin 1999) for a recent review] to the UV to the soft and hard X-rays. These observations are hard to reconcile with our classical view that would interpret the radio radiation as synchrotron emission and the hard X-rays and UV radiation as ICS of the same electrons off the photons of the cosmic microwave

background. This interpretation in general requires a large rate of injection of cosmic rays at recent times and intracluster magnetic fields smaller than those obtained by Faraday rotation measurements (Eilek 1999; Clarke et al. 1999) by a factor $\sim 50 - 100$. These can be considered at least circumstantial evidence for some problems in the *conventional interpretation*, although additional observational tests are required in order to have more solid proofs.

The only events that seem to be able to provide the required energetics are mergers of clusters of galaxies. In this paper we study in detail all the channels that may contribute to the production of non-thermal radiation during a cluster merger, including the contribution of both primary and secondary electrons. Since in some of the clusters observed in radio and X-rays there does not seem to be evidence for an ongoing merger, we concentrate our attention on mergers occurred in the past. Although the calculations are carried out in the most general form, we apply them specifically to the case of the Coma cluster, for which a complete set of multiwavelength observations have been carried out. A more general discussion of our results and more technical details can be found in (Blasi 2000).

For the case of Coma, fitting the non-thermal multiwavelength observations has the following implications: 1) Magnetic fields ~ 50 times smaller than the ones measured by Eilek (1999) and Clarke et al. (1999) are necessary; 2) the gamma ray flux at ~ 100 MeV exceeds the EGRET upper limits; 3) the merger must have been just ended.

Since the main reason for these problems resides in the synchrotron plus ICS model, some attempts have been made to look for alternative interpretations of the hard X-ray excess, in particular invoking the bremsstrahlung emission from a non-thermal tail in the electron distribution, produced by stochastic acceleration (Blasi 2000a; Ensslin, Lieu and Biermann 1999; Dogiel 1999). The X-ray spectra can be fitted by this model without requiring small magnetic fields, although large injection rates of MHD waves are needed (compatible with the expectations in a merger of two clusters of galaxies).

The paper is structured as follows: in section 2 we describe mergers as particle accelerators; in section 3 we describe our calculations; in section 4 we discuss an alternative model of the non-thermal radiation produced during cluster mergers and its consequences. We conclude in section 5.

2 Cluster mergers as particle accelerators

During the merger between two clusters of galaxies, a typical gravitational energy of $E_{merger} \sim 1.4 \times 10^{64}$ erg is available (we assumed here a typical total mass of a cluster to be $\sim 5 \times 10^{14} M_{\odot}$ and a distance of ~ 1.5 Mpc between the two clusters). During the approach, this energy is mainly converted into kinetic energy of the dark matter component, which is weakly interacting. However, at some point a strong shock is formed in the baryonic component and energy is transferred from dark matter to baryons (and electrons). This process is thought to produce the heating of the intracluster gas. A small fraction of this energy however can be converted into kinetic energy of particles out of equilibrium (non-thermal) through first order Fermi acceleration at the shock. Both electrons and protons are expected to be accelerated although the process should be more efficient for protons. A detailed description of this problem can be found in (Levinson 1994; McClements et al. 1997), but a brief description can be useful here:

protons with low energy do interact with Alfvén waves, while electrons do not. Therefore protons can be more easily injected into the accelerator while electrons need to interact with some other kind of waves (for instance whistlers). Moreover, in order for a particle to be accelerated at the shock, its Larmor radius must be larger than the width of the shock, comparable with the Larmor radius of thermal protons. It is easy to see that this condition is realized only for electrons with energy larger than 5 – 10 MeV (much larger than the typical cluster temperature). Electrons need therefore a preacceleration, otherwise the fraction of electrons injected in the shock region remains insignificantly small. We introduce here the coefficient $\xi < 1$ as the ratio of the spectra of electrons and protons at injection at fixed energy. For the injection spectrum of electrons and protons we use here a power law in momentum with index $\gamma = 2.32$, needed to fit the radio spectrum of Coma (this value is compatible with the compression ratios at the merger’s shocks observed in the simulations of Takizawa and Naito (2000)). These spectra are changed by propagation and losses effects, which we calculate by solving the full transport equations for primary electrons, protons and secondary electrons, generated by the decay of the charged pions due to pp inelastic scattering in the intracluster medium [see (Sarazin 1999) for a detailed description of the energy losses and radiative properties of primary electrons].

The cosmic ray confinement of the proton component over cosmological scales (Berezinsky, Blasi and Ptuskin 1997; Volk, Aharonian and Breitschwerdt 1996; Colafrancesco and Blasi 1998) and the fast energy losses of electrons make the results very weakly dependent on the choice of the diffusion coefficient, with the exception of the maximum energies achievable in the acceleration. We use a diffusion coefficient derived by applying the quasi linear theory to a Kolmogorov spectrum of magnetic fluctuations (Blasi and Colafrancesco 1999) with the size of the largest eddy ~ 200 kpc (typical size between two galaxies). Higher maximum energies can be attained adopting a Bohm diffusion coefficient, but the fluxes far away from the tails do not change appreciably, as stressed above.

3 The calculations

Our calculations are fully time-dependent, therefore we can evaluate the non-thermal spectra at each time during or after the merger. Some general findings are the following: *i)* sufficiently high energy electrons, required to generate radio radiation and hard X-rays, exist in the cluster only if the merger has just ended or is currently ongoing. In particular the higher frequencies in the radio spectrum can be produced only if the merger was not over more than ~ 20 million years ago. *ii)* The secondary electron component is time independent: in fact the protons injected during the merger are confined in the intracluster medium and serve as a continuous source of new electrons, even if the proton injection ended long ago. *iii)* The gamma ray fluxes due to secondary electrons or due to pion decays are time independent. They cannot be washed out by the time evolution.

On this basis, we assume here that the merger just ended in Coma and calculate the fluxes of non-thermal radiation. The results for the radio emission of Coma are plotted in Fig. 1, where a magnetic field of $\sim 0.15\mu G$ was required. The thick curve that fits the observations (Feretti et al. 1995) refers to synchrotron emission of primary

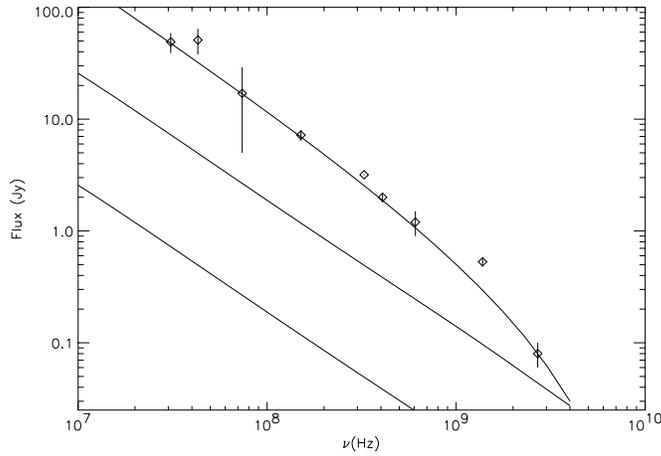


Figure 1: *Spectrum of radio radiation from Coma.*

electrons. The cutoff is due to the maximum energy of the electrons and therefore might be in a different place for different choices of the diffusion coefficient. The real presence of a cutoff at > 2 GHz was questioned anyway by Deiss et al. (1997). The two thin lines represent the synchrotron contribution of the secondary electrons for $\xi = 0.1$ (lower curve) and $\xi = 0.01$ (upper curve).

The results of our calculations for the hard X-rays and UV-soft X-ray radiation are plotted in Fig. 2, together with the expectation due to thermal bremsstrahlung of a gas of electrons at the temperature of Coma (thick solid curve). The data points are from BeppoSAX (Fusco-Femiano et al. 1999). The thick band is an estimate of the UV excess (Lieu et al. 1999). The thin solid line is the ICS contribution of primary electrons while the two dashed lines represent the ICS radiation of secondary electrons for $\xi = 0.1$ (lower curve) and $\xi = 0.01$ (upper curve).

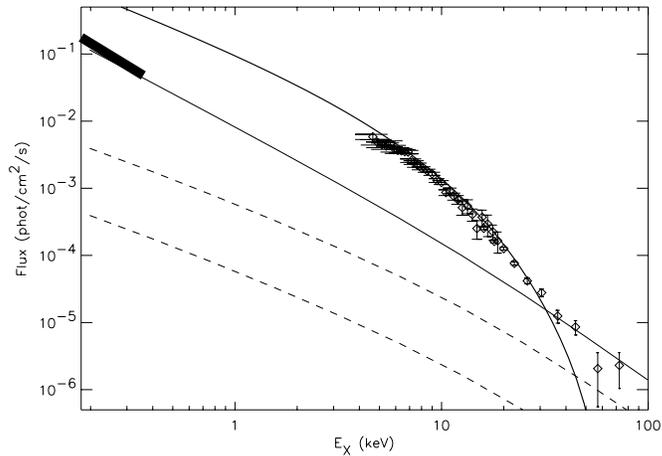


Figure 2: *Spectrum of ICS radiation from Coma.*

With the parameters used to fit the radio and X-ray fluxes, we also calculate the gamma ray emission, due to several channels. The results are plotted in Fig. 3. The thick solid curve is the bremsstrahlung contribution of primary electrons, the two solid thin lines represent the fluxes of gamma rays from pion decay, the dashed lines are ICS fluxes from secondary electrons and the dashed dotted lines are the bremsstrahlung fluxes from secondary electrons. The fluxes produced by secondaries are always plotted for $\xi = 0.1$ (lower curves) and $\xi = 0.01$ (upper curves). The EGRET upper limit (Sreekumar et al. 1996 - arrow in the figure) is exceeded by a factor 3-4 . If a Bohm diffusion coefficient is used, then the maximum energy of primary electrons becomes large enough to generate an appreciable flux of gamma rays due to ICS. In this case the excess is a factor ~ 15 .

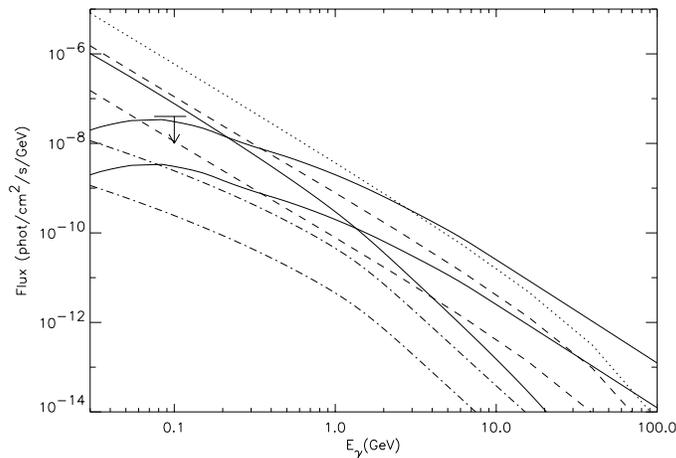


Figure 3: *Spectrum of gamma radiation from Coma.*

Adopting magnetic fields even slightly larger than $0.15\mu G$ causes the radio radiation to exceed observations if the X-ray flux (e.g. the cosmic ray normalization) is fixed. Viceversa, if the magnetic field is increased and we fit the radio observations, the X-ray fluxes become too small.

4 Cluster mergers: alternative views

In the previous section we emphasized that the *conventional interpretation* of the non-thermal phenomena observed in clusters of galaxies leads to implications that seem to be in contrast with observations: a) small magnetic fields compared with Faraday Rotation measurements; b) large gamma ray fluxes.

There is an alternative way of explaining observations (Blasi 2000a; Dogiel 1999) without these problems: the idea consists of the following key points (Blasi, 2000a): 1) magnetic fields in the intracluster medium are at μG level, as indicated by Faraday rotation measurements; 2) radio radiation is generated by synchrotron emission of relativistic electrons, with a very small energy content; 3) during the merger the electron thermal distribution is changed due to resonant interactions with perturbations

in the magnetic field and acquire a non-Maxwellian tail; 4) hard X-rays are the result of bremsstrahlung of this modified electron distribution.

Detailed calculations of the development of this tail were carried out by Blasi (2000a): all processes responsible for the thermalization, resonant interaction with waves, and energy losses were included in the form of terms in a time-dependent non-linear Fokker-Planck (FP) equation, which was then solved numerically. This is equivalent to study the process of thermalization of a plasma in the presence of a perturbed magnetic field. We find that the electron distribution is not a Maxwell-Boltzmann distribution, which is a rather general result. There are two aspects to keep in mind: first, the thermalization time of electrons at low energies is extremely short, therefore the only region where possible distortions from a thermal distribution can occur is on its tail; second, the FP equation is such that even if the energy transfer from the waves to electrons occurs only on the tail (lower energy electrons do not resonate), also the rest of the distribution is affected.

As a consequences of the points just stressed, the resonant interaction of electrons with waves in the intracluster medium mainly results into two effects: 1) the bulk of the electrons is heated up (the effective temperature increases); 2) a non-Maxwellian tail develops.

The results of Blasi (2000a) are plotted in Fig. 4a for the electron spectra and 4b for the X-ray spectra obtained as bremsstrahlung emission of the modified electron distribution. The data points are from BeppoSAX while the upper limits are from OSSE (Rephaeli et al. 1994). The different curves refer to different times.

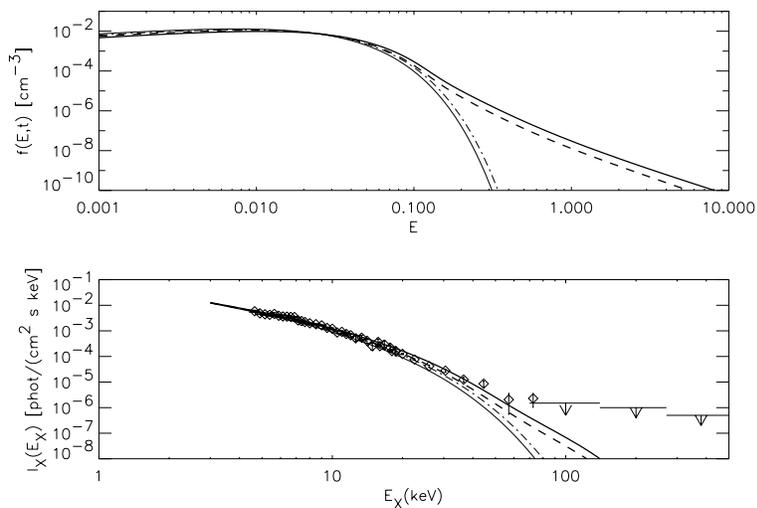


Figure 4: *a. Spectrum of electrons. b) X-ray spectra. The thin solid lines are for $t = 0$, the dashed lines refer to 500 million years and the thick solid lines refer to 1 billion years. The dash-dotted lines refer to the thermal case at the temperature of Coma. The initial temperature of the gas is 7.5 keV.*

This alternative model can be tested: since the electron spectrum is changed, the spectrum of the upscattered photons of the microwave background radiation (the so-called Sunyaev-Zeldovich effect) is also affected. Blasi, Olinto and Stebbins (2000)

calculated in detail this modified SZ effect and found that: *i)* accurate measurements of the SZ spectrum should show distortions distinguishable from the ordinary SZ effect; *ii)* these changes in the SZ spectra would affect the estimate of the Hubble constant and other cosmological parameters by $\sim 20\%$; *iii)* the masses estimated from X-rays should be a factor ~ 2 smaller than those derived from gravitational lensing, sensitive to the total energy (mass plus thermal energy plus non-thermal energy) in the cluster.

5 Conclusions

Radio radiation, hard and soft X-ray excesses and UV radiation have been observed from several clusters of galaxies, as a clear demonstration of the presence of cosmic rays and magnetic fields in the intracluster medium. The energetics involved, in terms of rate of injection of cosmic rays in clusters, seems to be compatible with the ones expected during mergers of clusters of galaxies. For this reason, in this paper we investigated the propagation and the radiative processes of both primary and secondary electrons and of protons, and we calculated the expected fluxes of radio, X and gamma radiation, applying our results to the specific case of Coma, for which a complete set of multiwavelength observations is available.

The general conclusion is that primary electrons can provide a good fit to the observations, provided the merger just ended (or is still ongoing). The rate of injection of primary electrons needed to fit the X-ray data is $\sim 2 - 3\%$ of the total energy available during the merger, and a magnetic field of $0.15\mu G$ is required to fit the radio data. The flux of UV radiation is automatically obtained in the right order of magnitude. All these fluxes are rapidly fading away with time, due to energy losses of high energy electrons. The contribution of the secondary electrons is slightly smaller but time independent, due to the confinement of cosmic ray protons on cosmological time scales.

The main consequence of the model is that the gamma ray fluxes above ~ 100 MeV exceed the EGRET upper limit by a factor between 3-4 to ~ 15 depending on the diffusion coefficient, which determines the maximum energy of the primary electrons. Besides this, the use of a magnetic field of $\sim 0.15\mu G$ seems to be inconsistent with the results of recent Faraday rotation measurements (Eilek 1999; Clarke et al. 1999).

There are two things to do in order to clarify the situation: 1) carry out a new measurement of the gamma ray fluxes in the GeV range, in order to check that EGRET did not just miss the detection; 2) carry out gamma ray measurements in the range > 100 GeV, as proposed by Blasi (1999). These measurements can give precious information about the non-thermal content of clusters and they can be carried out even with current detectors like STACEE (Ong 1998).

A more theoretical approach consists in looking for alternative interpretations of the non-thermal radiation. We discussed this possibility in section 3, where we illustrated the calculations of Blasi (2000a), relative to the spectrum of a population of electrons that thermalize in the presence of a perturbed magnetic field. By solving the FP equation, Blasi (2000a) found that the electron spectrum presents an high energy tail, and that the bremsstrahlung emission from these electrons can explain the whole spectrum of X-rays, from the thermal region to the hard X-ray region. Magnetic fields compatible with the ones obtained by Faraday rotation measurements and low gamma

ray fluxes can be accommodated naturally within this approach.

Moreover it is possible to prove (or disprove) this alternative model by looking at precision measurements of the Sunyaev-Zeldovich (SZ) effect: the electron distribution, modified by the resonant interactions with waves in the intracluster magnetic field produces a modified SZ effect that can be distinguished by the ordinary one, as discussed by Blasi, Olinto and Stebbins (2000).

Acknowledgments This work was supported by the DOE and the NASA grant NAG 5-7092 at Fermilab.

6 References

- Berezinsky, V.S., Blasi, P., Ptuskin, V.S.: 1997 *Astrophys. J.* **487**, p. 529.
- Blasi, P.: 2000 submitted to *Astropart. Phys.*
- Blasi, P.: 2000a *Astrophys. J. Lett.* **532**, p. L9.
- Blasi, P.: 1999 *Astrophys. J.* **525**, p. 603.
- Blasi, P., Colafrancesco, S.: 1999 *Astropart. Phys.* **12**, p. 169.
- Blasi, P., Olinto, A.V., Stebbins, A.: 2000 *Astrophys. J. Lett.* in press.
- Clarke, T.E., Kronberg, P.P., Böringer, H.: 1999 in Ringberg Workshop on “Diffuse Thermal and Relativistic Plasma in Galaxy Clusters”, Eds: H. Böringer, L. Feretti, P. Schuecker, MPE Report No. 271.
- Colafrancesco, S., Blasi, P.: 1998 *Astropart. Phys.* **9**, p. 227.
- Deiss, R.M., Reich, W., Lesch, H., Wielebinski, R.: 1997 *A&A* **321**, p. 55.
- Dogiel, V.A.: 1999 in Ringberg Workshop on “Diffuse Thermal and Relativistic Plasma in Galaxy Clusters”, Eds: H. Böringer, L. Feretti, P. Schuecker, MPE Report No. 271, 1999.
- Eilek, J.A.: 1999 preprint astro-ph/9906485, to appear in ‘Diffuse Thermal and Relativistic Plasma in Galaxy Clusters’, 1999, Ringberg Workshop, Germany, MPE-Report.
- Ensslin, T.A.: 1999 Proceedings of *The Universe at Low Radio Frequencies*, ASP Conference Series, (preprint astro-ph/0001433).
- Ensslin, T.A., Lieu, R., Biermann, P.: 1999 *A&A* **344**, p. 409.
- Feretti, L., Dallacasa, D., Giovannini, G., Tagliani, A.: 1995 *A&A* **302**, p. 680.
- Fusco-Femiano, R., Dal Fiume, D., Feretti, L., Giovannini, G., Grandi, P., Matt, G., Molendi, S., Santangelo, A.: 1999 *Astrophys. J. Lett.* **513**, p. L21.
- Levinson, A.: 1994 *Astrophys. J.* **426**, p. 327.
- Lieu, R., Ip, W.-H., Axford, W.I., Bonamente, M.: 1999 *Astrophys. J.* **510**, p. 25.
- McClements, K.G., Dendy, R.O., Bingham, R., Kirk, J.G., Drury, L. O’C.: 1997 *MNRAS* **291**, p. 241.
- Rephaeli, Y., Ulmer, M., Gruber, D.: 1994 *Astrophys. J.* **429**, p. 554.
- Sarazin, C.L.: 1999 *Astrophys. J.* **520**, p. 529.
- Ong, R.A.: 1998 *Phys. Rep.* **305**, p. 93.
- Sreekumar, P. et al.: 1996 *Astrophys. J.* /bf 464, p. 628.
- Takizawa, M., Naito, T.: 2000 preprint astro-ph/0001046 (accepted for publication in *Astrophys. J.*).
- Volk, H.J., Aharonian, F.A., Breitschwerdt, D.: 1996 *Space Sci. Rev.* **75**, p 279.