Modelling the non–thermal emission from galaxy clusters

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**Abstract.** We discuss the relevant processes for the relativistic electrons in the ICM and the possible mechanisms responsible for the production of these electrons. We focus on the origin of the radio halos giving some of the observational diagnostics which may help in discriminating among the different models proposed so far. Finally, we briefly discuss the discrepancy between the value of the magnetic field assuming an inverse Compton (IC) origin of the hard X–ray emission (HXR) and that obtained from Faraday Rotation Measurements (RM).

1. **Introduction**

The most important evidence for relativistic electrons in clusters of galaxies comes from the diffuse synchrotron radio emission observed in about 35 % of the clusters selected with X–ray luminosity \(>10^{45}\)erg s\(^{-1}\) (e.g., Giovannini, Tordi, Feretti, 1999; Giovannini & Feretti 2001). The diffuse emissions are referred to as radio halos and/or radio mini–halos when they appear projected on the center of the cluster, while they are called relics when they are found in the cluster periphery.

The difficulty in explaining the extended radio halos arises from the combination of their \(\sim\)Mpc size, and the short radiative lifetime of the radio emitting electrons. Indeed, the diffusion time necessary to the radio electrons to cover such distances is orders of magnitude greater than their radiative lifetime. To solve this problem Jaffe (1977) proposed continuous in situ reacceleration of the relativistic electrons. The in situ reacceleration scenario was quantitatively reconsidered by Schlickeiser et al.(1987) who successfully reproduce the integrated radio spectrum of the Coma halo. In the framework of the in situ reacceleration model, Harris et al.(1980) first suggested that cluster mergers may provide the energetics necessary to reaccelerate the relativistic particles. The role of mergers in particle acceleration and in the amplification of the magnetic fields was than investigated in more detail by De Young (1992) and Tribble (1993). Alternatively, to avoid the energy loss problem of the radio electrons, Dennison (1980) first suggested that the radio emission in radio halos may be emitted by a population of secondary electrons continuously injected by hadronic interactions. Primary and the secondary electron models still constitute the basis of the more recent theoretical works developed on the argument (see Sect.3). Additional evidence for the presence of non–thermal phenomena in clusters of galaxies comes from the detection in a number of cases of EUV excess emission (e.g., Bowyer
et al. 1996; Lieu et al., 1996; Berghöfer et al., 2000; Bonamente et al., 2001) and of HXR excess emission in the case of the Coma cluster and A2256 (Fusco–Femiano et al., 1999, 2000; Rephaeli et al., 1999; Rephaeli & Gruber, 2002; Fusco–Femiano, this meeting). While, with the exception of the Coma and of the Virgo clusters, the EUV detections are still controversial (e.g., Berghöfer et al., 2000; Berghöfer, Bowyer, Nevalainen, this meeting), the HXR detections are quite robust as they are independently obtained by different groups and with different X-ray observatories (BeppoSAX, RXTE). On the other hand, while there is agreement on the IC origin at least of the most significant cases of EUV excess emission (e.g., Hwang 1997; Bowyer & Bergöfer 1998; Ensslin & Biermann 1998; Sarazin & Lieu 1998; Atoyan & Völk 2000; Brunetti et al. 2001b, Petrosian 2001, Tsay et al., 2002), the origin of the XHR is still debated. The XHR excess may be generated by IC scattering of relativistic electrons off the CMB photons (Fusco–Femiano et al., 1999, 2000; Rephaeli et al., 1999; Völk & Atoyan 1999; Brunetti et al. 2001a; Petrosian 2001; Fujita & Sarazin 2001). Alternatively XHR might also result from bremsstrahlung emission from a population of supra–thermal electrons (e.g., Ensslin, Lieu, Biermann 1999; Blasi 2000; Dogiel 2000; Sarazin & Kempner 2000). Both the IC model and the bremsstrahlung interpretation have problems: the first one would require cluster magnetic field strengths smaller than that inferred from RM observations (e.g., Clarke, Kronberg, Böringer 2001), the second one would require a too large amount of energy to maintain a substantial fraction of the thermal electrons far from the thermal equilibrium for more than $10^8$ yrs (e.g., Petrosian, 2001). In this contribution we will describe the populations of relativistic electrons expected in clusters of galaxies and we will focus on the origin of radio halos and HXR emission from galaxy clusters. We refer to the contribution by Ensslin for the origin of radio relics and to the contributions by Bowyer for a review on the EUV excesses.

2. Competing mechanisms at work

Before discussing the origin of the emitting electrons in galaxy clusters, it is convenient to briefly review the basic processes which modify the energy and spectrum of the relativistic electrons. It is important to underline that the efficiency of these processes is related to the energy of the electrons in a way that depends on the particular process so that the time evolution of electrons with different energies is dominated by different processes. More specifically relativistic electrons with energy $mc^2\gamma$ in the intracluster medium (ICM) lose energy via two main processes:

a) ionization losses and Coulomb collisions:

$$\left(\frac{d\gamma}{dt}\right)_{\text{ion}} = -1.2 \times 10^{-12} n_{\text{th}} \left[1 + \frac{\ln(\gamma/n_{\text{th}})}{75}\right]$$

(1)

where $n_{\text{th}}$ is the number density of the thermal plasma.

b) synchrotron and IC radiation:

$$\left(\frac{d\gamma}{dt}\right)_{\text{syn+ic}} = -1.3 \times 10^{-20} \gamma^2 \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2 \theta}{2/3} + (1 + z)^4\right]$$

(2)
where $B_{\mu G}$ is the magnetic field strength in $\mu G$, and $\theta$ is the pitch angle of the emitting electrons.

On the other hand, the electrons in the ICM can be re-accelerated by several mechanisms. Two relevant cases in clusters of galaxies are shock acceleration and acceleration via wave–particle interaction (e.g., MHD or HD turbulence). 

a) *Shock Acceleration* (e.g., Blandford & Eichler, 1987) yields an energy gain:

$$
\left( \frac{d\gamma}{dt} \right)^{+}_{sh} \approx \gamma \frac{U_-^2}{f} \left( \frac{f-1}{f+1} \right) \frac{1}{3K(\gamma)}
$$

$K(\gamma)$ is the spatial diffusion coefficient, $U_-$ is the velocity of the plasma in the region before the shock discontinuity (measured in the shock frame and in unit of $c$), and $f$ is the shock compression ratio.

b) *Acceleration via Turbulence*: if the resonance scattering condition is satisfied (e.g., Hamilton & Petrosian 1992), turbulent Alfven waves can accelerate electrons via resonant pitch angle scattering. A power law energy spectrum of the Alfven waves:

$$
P(k) = b \frac{B^2}{8\pi} \frac{s-1}{k_o} \left( \frac{k}{k_o} \right)^{-s}
$$

in the range $k_o < k < k_{\text{max}}$ is assumed, where $k$ is the wave number ($k_o << k_{\text{max}}$) and $b$ is a normalization factor indicating the fraction of the energy density of the magnetic field $B$ in energy of waves. Under this assumption it can be shown that the systematic energy gain is (e.g., Blasi 2000; Ohno et al. 2002):

$$
\left( \frac{d\gamma}{dt} \right)^{+}_{A-tur} \sim b \frac{\pi}{c} \left( 1 - \frac{1}{s} \right) \nu_A^2 \left( \frac{eB}{m_e c^2} \right)^2 k_o^{s-1} \times \gamma^{s-1}
$$

where $\nu_A$ is the Alfven velocity.

MHD turbulence can also accelerate relativistic particles in radio sources via Fermi–like processes (e.g., Lacombe 1977; Ferrari et al. 1979). Under the simple assumption of a quasi-monochromatic turbulent scale responsible for particle acceleration (e.g., Gitti, Brunetti, Setti 2002) the systematic energy gain is:

$$
\left( \frac{d\gamma}{dt} \right)^{+}_{F-tur} \sim 4 \times 10^{-11} \gamma \nu_A^2 \left( \frac{\delta B}{B} \right)^2
$$

where $l$ is the distance between two peaks of turbulence and $\delta B/B$ is the fluctuation in a peak of the field intensity with respect to the average field strength. Note that Eq.(6) and Eq.(5) have the same dependence on the relevant parameters for $P(k) \propto k^{-2}$.

A comparison between losses and gain (shocks, or turbulence with $s = 2$) processes is given in Fig.1a,b: radio emitting electrons ($\gamma \sim 10^4$) have radiative lifetimes of $\sim 10^8$ yrs, in addition the acceleration of electrons with $\gamma < 10$ and $\gamma > 10^5$ appears extremely difficult (see also Petrosian, this meeting).
3. Electron populations in galaxy clusters

It has been shown that a magnetic field with strength $\geq 0.1 \mu G$ can easily store the bulk of cosmic rays in the cluster volume for a time greater than the Hubble time (e.g., Berezinski, Blasi and Ptuskin 1997). If this holds in the case of protons, the confinement is much easily obtained for electrons. Indeed the diffusion length of the particles decreases with the energy, and thus it is much shorter in the case of relativistic electrons than in that of the relativistic protons.

Here we focus our attention on the case of the populations of relativistic electrons. Electrons can be injected in the ICM by different processes:

i) **Acceleration by shocks (Pop.A)**: Radio observations of supernovae indicate that strong shocks convert at least a few percent of their energy into the acceleration of relativistic particles. Thus, merger shocks may represent a natural acceleration mechanism for the relativistic electrons in galaxy clusters (e.g., Sarazin, 1999). Particle acceleration by merger shocks has been studied in detail (e.g., Takizawa & Naito, 2000; Miniati et al., 2001; Fujita & Sarazin, 2001), and it might explain the apparent correlation between the non-thermal phenomena and the presence of merger activity in clusters of galaxies (e.g., Buote, 2001 and ref. therein).

ii) **Reaccelerated electrons (Pop.B)**: There is a number of sources of relativistic electrons in galaxy clusters. In particular active galaxies (e.g., radio galaxies), merger shocks, supernova and galactic winds can efficiently in-
ject relativistic protons and electrons in the cluster volume over cosmological time (e.g., Sarazin, 2002 and ref. therein). High relativistic electrons have very short radiative lifetimes, however, when they reach energies of $\gamma \sim 100 - 300$ they survive for some billion years (Fig.1b) and thus can be accumulated in the cluster volume. Cluster mergers may produce a significant level of turbulence in the ICM, in this case Alfvén waves and/or some other Fermi–like processes diffuse in the cluster volume could reaccelerate $\gamma \sim 100 - 300$ relativistic electrons to the higher energies required to explain radio halos (e.g., Brunetti et al., 2001a). Electron reacceleration has been also invoked for the origin of radio mini–halos in cooling flow clusters. In this case the energy for the reacceleration may be provided by the cooling flow itself (Gitti et al.2002).

iii) **Secondary electrons (Pop.C):** Dennison (1980) first pointed out that a possible source of the relativistic electrons in radio halos is the continuous injection due to the decay of charged mesons generated in cosmic ray ion collisions. This idea has been reconsidered in detail in the model by Blasi & Colafrancesco (1999), and then by Dolag & Ensslin (2000) assuming a radial profile of the cluster magnetic field taken from numerical simulations. In order to explain the connection between cluster mergers and radio halos, Ensslin (1999) proposed that relativistic protons are released from radio ghosts into the ICM during a cluster merger event. More recently, Miniati et al. (2001) have developed numerical simulations of cluster formation and calculated the injection of primary relativistic protons by strong shocks. These authors find that, under some assumptions, the resulting secondary electrons might produce diffuse synchrotron emission in agreement with some of the observed properties of radio halos.

From a theoretical point of view the above electron populations are very reasonable, thus it may very well be that all of them contribute to the injection of the relativistic electrons in the ICM. In addition it should be noticed that the final electron population may be due to a complicated mix of all the above reported processes. For example, shocks may accelerate relic electrons contributing to the Pop.B, but they can also (re)accelerate relativistic protons increasing the rate of injection of secondary electrons (Pop.C). In addition to the acceleration of relic electrons (Pop.B), cluster turbulence would (re)accelerate protons increasing the rate of injection of secondary electrons (Pop.C). Finally, secondary electrons can be (re)accelerated by shocks and/or cluster turbulence powered by a merger event (Pop.A,B).

4. **Possible diagnostics**

A possibility to break the degeneracy on the origin of the emitting electrons might be provided by some observational diagnostics.

4.1. **Diffusion lengths**

The $\sim$ Mpc size of most radio halos suggests that a population of electrons accelerated by shocks in the clusters (Pop. A) cannot significantly contribute
to the observed diffuse radio emission. This is because, after being accelerated by a shock, the synchrotron emitting electrons have a short ($\sim 10^8$ yrs) radiative lifetime and cannot diffuse over the cluster volume.

In order to better quantify the typical diffusion length $R_d$ of the radio electrons, we should derive the diffusion time $\tau_{\text{diff}} \sim R_d^2/(4\mathcal{K}(\gamma))$, where $\mathcal{K}(\gamma)$ is the spatial diffusion coefficient. We assume a Kolmogorov spectrum of the magnetic field (e.g., Blasi & Colafrancesco, 1999) and obtain:

$$\mathcal{K}(\gamma) \simeq 1.8 \times 10^{28} L_{20\text{ kpc}}^{2/3} \left( \frac{\gamma}{B_{\mu G}} \right)^{1/3}$$

(7)

where $L_{20\text{ kpc}}$ is the largest coherence scale of the field and $B_{\mu G}$ is the magnetic field strength in $\mu G$. The diffusion length $R_d$ is obtained when the diffusion time equals the radiative lifetime, $\tau_{\text{loss}} = \gamma (d\gamma/dt)^{-1}$ (Sect.2). In the most interesting regime, when IC losses dominate (i.e., for $\gamma >> 10^3$ and $B_{\mu G} < 3$), we obtain:

$$R_d(\text{kpc}) \sim 36(1 + z)^{-2} \left( \frac{\gamma}{10^4} \right)^{-1/3} \left( \frac{L_{\text{kpc}}}{B_{\mu G}^{1/2}} \right)^{1/3}$$

(8)

A more general result is reported in Fig.2: the maximum diffusion length is obtained for electrons with $\gamma \sim 100 - 1000$, while radio emitting electrons cannot diffuse for more than about 50 kpc.

Another possibility is given by a scenario in which a fast shock crosses the cluster center and accelerates the relativistic electrons across the cluster volume. In this case the diffusion time of the electrons is replaced by the crossing time.
of the shock that should be shorter than the radiative lifetime of the radio emitting electrons, i.e.:

$$\tau_{\text{cross}}(\text{yrs}) \sim \frac{10^9 D(\text{Mpc})}{U_{\text{sh}}/10^3} < \tau_{\text{loss}}(\gamma \sim 10^4)$$

which for a typical total extension of $\sim 2$ Mpc would require an unreasonably high Mach number of the shock $M_{\text{sh}} > 5$. A detailed calculation of the electron population accelerated by merger shocks has been recently developed by Miniati et al. (2001). These authors calculate the resulting synchrotron radiation and they find indeed that the morphology of the resulting emission is similar to that of radio relics rather than to radio halos. Furthermore, due to the field compression in the shock, the emitted synchrotron radiation is highly polarized (as in the case of radio relic) in contrast with the very low polarization found in the radio halos. Additional evidence against a direct link between merger shock acceleration and non–thermal emission has been obtained by Gabici & Blasi (2002) who have shown that the low Mach number expected in the merger shocks would accelerate a very steep spectrum of protons and electrons which cannot account for the observed synchrotron spectrum of radio halos (also in the case of secondary models).
4.2. Radio brightness profiles

The timescale of the p–p collision, which is the process responsible for the injection of secondary electrons (Pop C), is \( \propto n_{\text{th}}^{-1} \). Consequently, for a given number density of the relativistic protons, secondary electrons are expected to be injected in the denser regions and the radio emission would be stronger in the cluster core. So far, a quantitative comparison of the observed radio and thermal bremsstrahlung X–ray profiles (\( b_{\text{r}} \) and \( b_{\text{x}} \), respectively) was obtained for 5 extended radio halos (Govoni et al. 2001; Feretti et al. 2001). In two cases a linear correlation exists between the radio and X–ray brightness (i.e., \( b_{\text{r}} \propto b_{\text{x}} \), with \( b \sim 1 \)) whereas in the remaining three cases a sub–linear trend is found (Coma: \( b=0.64 \), A2319: \( b=0.82 \), A2163: \( b=0.64 \)). On the other hand, simple - but viable - secondary models would predict \( b > 1 \) trend (Dolag & Ensslin 2000). In this Section we explore if this discrepancy can be accommodated. We assume a power low energy distribution of the injected relativistic protons:

\[
N_p(\epsilon, R) = N_p(R)\epsilon^{-s}
\]  

where \( N_p(R) \) gives the spatial distribution of the protons. In this case, following standard recipes for the calculation of proton proton decay (e.g., Mannheim & Schlickeiser, 1994) and assuming time independent conditions (e.g., Dolag & Enslin 2000), it can be shown that the energy distribution of the relativistic electrons is also a power law :

\[
N_e(\epsilon, R) = C_e n_{\text{th}}(R)N_p(R)\epsilon^{-\delta}
\]

where \( C_e \) is a constant, and the slope of the electron spectrum is \( \delta = \frac{4}{3}s + \frac{1}{3} \). In order to calculate the number density of the secondary electrons we parameterize the number density of the relativistic protons with that of the thermal plasma:

\[
N_p(R) = C_p n_{\text{th}}(R)\mathcal{F}(R)kT
\]

where \( C_p \) is a constant, and \( \mathcal{F}(R) \) gives the ratio between relativistic and thermal protons energy densities. The synchrotron brightness profile is thus given by:

\[
b_{\text{syn}}(y) = C_e C_p C_{\text{syn}}\epsilon^{-\alpha}kT \times \int_y dR R \frac{R^2 - y^2}{\sqrt{R^2 - y^2}} n_{\text{th}}(R)\mathcal{F}(R) \frac{B(R)^{1+\alpha}}{B^2(R) + B_{\text{cmb}}^2}
\]

We remind that the thermal brightness emission from a cluster is given by:

\[
b_{\text{th}}(y) \propto \int_y dR R \frac{R^2 - y^2}{\sqrt{R^2 - y^2}} n_{\text{th}}^2(R)\Lambda(T)
\]

and thus the ratio between thermal and synchrotron brightness depends on the quantity \( \Phi = \mathcal{F}(R)B(R)^{1+\alpha}/(B^2(R) + B_{\text{cmb}}^2) \) in Eq.(14), which is \( \propto \mathcal{F}(R)B(R)^{1+\alpha} \) for a magnetic field strength < 3\( \mu \)G. More specifically, if \( \Phi(R) \) is a decreasing function of \( R \) the synchrotron profile will be narrower than the X–ray thermal profile. In Fig.3a we report the comparison between the synchrotron brightness profile from secondary models and the observed one. The theoretical profiles
are considerably steeper than observed. This happens in the case of both flux freezing approximation \( B \propto n_{th}^{2/3} \) and of a radial dependence of the field as that from numerical MHD simulations (Dolag, Bartelmann and Lesch 2002). These simulations suggest a rapid decrease of the field in the regions out of the cluster core \( B \propto n_{th} \). In order to reproduce the observed brightness profile with secondary models, \( \mathcal{F}(R) \) is then forced to rapidly increase with \( R \) (Fig. 3b). As a net result, we find that secondary models can reproduce the profile of the Coma halo only by forcing the energy density of the relativistic protons to be considerably larger than that of the thermal ICM out of the cluster radius; this is quite unreasonable. On the other hand, Miniati et al. (2001) have shown that secondary models can account for the radio extension of a Coma like halo. We stress that our calculations are not in contradiction with Miniati et al. (2001) as we have assumed a physical model for the magnetic field strength profile, whereas those authors assumed a value of the magnetic field \( \sim 3 \mu \text{G} \) roughly constant up to several core radii from the cluster center. In this case the resulting synchrotron emissivity at \( > r_c \) would obviously be increased considerably with respect to our calculations.

### 4.3. Integrated and radial spectral steepenings

Radio observations of the best studied radio halo, Coma C, have discovered a cut-off around 1 GHz in the integrated synchrotron spectrum (e.g., Deiss et al. 1997) and a strong steepening of the spectrum with increasing the distance from the center (Giovannini et al. 1993; Fig. 4a). The presence of a similar radial spectral steepening has been also found in the well studied radio mini–halo of the Perseus cluster (Sijbring, 1993; Fig. 4b). So far, the lack of similar multifrequency radio data for other radio halos (or mini–halos) does not allow to understand if the synchrotron spectral properties of Coma and Perseus are common among radio halos and mini–halos.

Brunetti et al. (1999, 2001a) pointed out that synchrotron radial spectral steepenings are expected in the case of extended radio halos if the synchrotron radiation is emitted by reaccelerated electrons (Pop B). In these models, the maximum energy of the reaccelerated electrons is expected at \( \gamma_c \sim 2.5 \times 10^4 / (\tau_{\text{acc}}/10^7 \text{yrs}) \), where \( \tau_{\text{acc}} \) is the reacceleration time. Since the Fermi II–like processes in the ICM give typical acceleration time scales \( \tau_{\text{acc}} > 10^7 \text{yrs} \) (e.g., Eilek & Weatherall 1999), it is \( \gamma_c < 10^5 \). Consequently, a cut–off in the synchrotron spectrum might be present in the radio band. Another consequence of these models is that, if the field strength in clusters decreases with distance from the center (e.g. Dolag et al. 2002), the corresponding frequency of the cut–off in the synchrotron spectrum should decrease with the distance from the center yielding a possible radial steepening of the spectrum between two fixed frequencies (see also Kuo et al., this proceedings). On the other hand, as already discussed, if the spectrum of the primary protons is a power law, the secondary electron-positron pairs (Pop C) from \( \pi^\pm \) decay have also a power low spectrum. This is still true (\( \gamma > 1000 \)), if the complete proton–proton cross section is taken into account in the calculations (e.g., Blasi 2001) and the spectrum \( (\nu > 10 \text{ MHz}) \) of the synchrotron emission predicted by secondary models should be a straight power law without a cut–off. One possibility to obtain a cut–off in the spectrum of the secondary electrons, and thus in the emitted synchrotron spectrum, is to assume a cut–off
in the energy distribution of the primary relativistic protons. This should be at $E_p \leq 50$ GeV to have the cut–off of the spectrum from the secondary electrons at the $\sim$GHz. Although, at present, such a cut–off cannot be ruled out by direct observations, we stress that it is very unlikely as it is in contrast with the observations of the spectrum of (Galactic) cosmic rays and with the theoretical expectations from the most accepted acceleration mechanisms. Cosmic ray protons in the Galaxy are detected up to $E_p \geq 10^{20}$ GeV and independently on their origin, no cut–off is observed at least up to $E_p \sim 4 \times 10^6$ GeV. So far, all the mechanisms invoked to inject the primary population of relativistic protons in galaxy clusters do not predict a cut–off in the spectrum of the protons at low energies. In particular, merger shocks are expected to accelerate protons up to $E_p \sim 10^7 - 10^9$ GeV (e.g., Blasi, 2001), AGNs might accelerate relativistic protons in jets and hot spots at $E_p \geq 10^8$ GeV (e.g., Biermann, 1995) and SNRs, which - indeed - are likely to produce at least the Galactic cosmic rays up to the observed knee at $E_p \sim 4 \times 10^6$ GeV, can accelerate protons at $E_p \sim 10^3 - 10^8$ GeV (e.g., Bhattacharjee & Sigl, 2000). Studies aimed at constraining the spectrum of secondary electrons in clusters and their contribution to the radio halos are important (Blasi, Brunetti, Gabici, 2002, in prep.).

5. Hard X–ray emission and the $B$–field discrepancy

In this Section we focus on the IC model, in particular the aim of this Section is to critically review the discrepancy between the magnetic field strength as requested by the IC interpretation and that from RM observations (e.g., Carilli & Taylor, 2001 and ref. therein). The measure of the magnetic field strengths with the IC method and via RM observations clearly involves different spatial
averages of the magnetic field itself: the first measure provides a volume average of the field on scales \( \geq \) Mpc, while the second one provides a weighted average of the field vector and thermal gas density along the line of sight. In addition, the IC method is very sensitive to the spectrum of the relativistic electrons especially in the case of \( B < 1 \mu G \). Taking into account the radial dependence of the thermal gas and magnetic field strength, Goldshmidt & Rephaeli (1993) first showed that the field strength estimated with the IC method is expected to be smaller than that ‘measured’ with the RM observations. In addition, as shown in Fig.5a, the presence of a high energy cut–off in the spectrum of the emitting electrons (e.g., Brunetti et al. 2001a; Fujita & Sarazin 2001) might further increase the discrepancy of the field strengths obtained making use of the two methods. Indeed, the ratio between the typical Lorentz factor of the radio emitting electrons and of those emitting IC radiation in the HXR band is \( \gamma_{\text{syn}} / \gamma_{\text{HXR}} \sim 3.5 \times B_{\mu G}^{-1/2} \), thus, in the case \( B < 1 \mu G \), a cut–off close to \( \gamma_{\text{syn}} \) would reduce the synchrotron emission without affecting the IC in the HXR band. As a net result, the ratio between radio synchrotron and IC HXR flux is reduced. Since the IC magnetic field is derived by such a ratio, the argument can be reversed so that given an observed ratio between radio and HXR flux, the assumption of a cut–off in the electron spectrum (close to the energy of the radio electrons) allows us to obtain a value of the magnetic field strength higher than that calculated with the standard power law assumption. This effect, combined with possible anisotropies in the pitch angle distribution of the emitting electrons and with observative biases (Petrosian, 2001), may alleviate the discrepancy between the magnetic field values as obtained assuming an IC origin of the HXR and those as estimated by RM observations.

We stress, however, that the result shown in Fig.5a might be misleading as the energy of the cut–off in the electron spectrum and the value of the \( B \) field are constrained by the shape of the radio spectrum. A possibility to check how much the field discrepancy can be alleviated is given by detailed calculations based on models of radio halos whose parameters are forced to reproduce the overall radio synchrotron properties of the Coma halo (i.e., brightness profiles, integrated radio spectrum, and radial spectral steepening). Given a model for particle acceleration, the comparison between the overall radio properties and the model expectations provides a set of possible radial profiles of the cluster magnetic field. In Fig.5b we report two representative profiles obtained by fitting the radio properties with the two–phase model (Brunetti et al. 2001a) compared with two profiles obtained by independent numerical simulations (Dolag et al., 2002). The IC calculations in the case of the low field model in Fig.5b provide a HXR flux from the Coma cluster compatible with the observations, whereas IC scattering would account for \( \sim 30\% \) of the observed HXR in the case of medium field profile. It is important to notice that, while the volume averaged magnetic field strength in both the cases in Fig.5b is \( \sim 0.3 – 0.4 \mu G \), the magnetic field strength in the cluster core region (\( \leq 12 \) arcmin), i.e. the region in which RM observations are effective, is between 0.8 and 2 \( \mu G \). This value is compatible within a factor of \( \sim 2 \) with the values of the magnetic fields inferred by RM observations in a number of clusters (e.g., Clarke et al., 2001; Carilli & Taylor, 2001). In addition, when a power spectrum of the field is assumed, the magnetic field strengths inferred from RM data is lower than that inferred with standard
recipes (e.g., Dolag et al., 2002; Newman, Newman, Rephaeli, 2002; Govoni et al., this meeting). If so, the discrepancy between IC and RM field may be considerably alleviated. The improvement in sensitivity provided by the future X-ray observatories (e.g., ASTRO–E2, NEXT) is impressive and it will probably allow us to test the IC hypothesis.

6. Conclusions

Highly relativistic electrons (i.e., $\gamma > 10^3$) can be injected in clusters of galaxies by several processes: they can be accelerated by merger shocks (Pop A), they can be relic relativistic electrons (i.e., $\gamma \sim 10 - 100$) reaccelerated by cluster turbulence (Pop B), and they can be secondary electrons injected by hadronic collisions (Pop C). We examine three diagnostic which can help us to better understand the origin of the relativistic electrons producing the observed radio synchrotron emission:

i) Electrons accelerated by strong merger shocks (Pop. A) cannot produce synchrotron emission diffuse on $\geq$Mpc scale as that of classical radio halos. This is due to the short radiative lifetime of the electrons after being accelerated in the shock region. A possibility to accommodate the Mpc sizes within the Pop. A is given by very fast $(M > 5)$ - but unlikely - shocks crossing the cluster center or by the presence of cluster turbulence in addition to the merger shocks.

Figure 5. **Panel a)**: The ratio between the HXR/SYN calculated assuming a high energy cut–off in the electron spectrum (given in the panel) and the HXR/SYN calculated with an infinite power law is given as a function of $B$. The SYN emission is calculated at 1.4 GHz. **Panel b)**: The comparison between the radial profiles of $B$ in Coma derived from the two phase model (solid lines) and from numerical simulations (dashed lines) are reported in the case of medium (upper) and low (lower) field. For display purposes, the profiles in the case of medium fields are shifted by 1.0$\mu$G.
\( ii) \) The comparison between the radio and the soft X-ray brightness of a number of radio halos indicates that the profile of the radio emission is broader than that of the X-ray thermal emission. This appears to be difficult to be accommodated within secondary models (Pop. C) which would yield narrower radio profiles. A possibility to skip this problem is to admit an \textit{ad hoc} increasing fraction of energy density of the relativistic protons with radius. However, at least in some cases, this would imply an energetics of the relativistic protons higher than that of the thermal pool.

\( iii) \) The spectral cut–off and radial spectral steepenings observed in the case of Coma (and in the mini–halo in the Perseus cluster) strongly point to the presence of a cut–off in the spectrum of the emitting electrons. This cut–off may be naturally accounted for if the synchrotron emission is produced by reaccelerated (Pop.B) electrons, whereas it is not expected in the case of secondary electrons (Pop.C). Future studies will clarify how much synchrotron spectral cut–offs and radial steepenings are common in radio halos.

Points i)–iii) would suggest that radio halos are powered by the synchrotron emission from electrons reaccelerated (Pop.B) in the cluster volume during merger events. This conclusion is, however, based on detailed studies of only few radio halos. As a consequence, detailed observations are still required to better understand the origin of radio halos.

The origin of the HXR emission detected in few clusters of galaxies is still matter of debate. It could be IC emission from relativistic electrons belonging to the same population of electrons responsible for the large scale radio emission. Alternatively HXR emission might result from bremsstrahlung emission from a supra–thermal tail of electrons. Both these hypothesis have problems: the IC emission would require a magnetic field value in apparent disagreement with that inferred from RM observations, while the supra–thermal bremsstrahlung requires a too large amount of energy if emitted for \( > 10^8 \) yrs. We have shown that the discrepancy between the field value obtained from the IC assumption and that from the RM observations can be significantly reduced. It is now clear that the combination of spatial trends and inhomogeneities in the thermal gas and magnetic field distribution with the presence of a cut–off in the electron spectrum at the energies of the radio emitting electrons would allow the IC magnetic field to be in better agreement with that from the RM observations. Although these assumptions are \textit{a posteriori} and might seem a sort of \textit{conjuring tricks}, it should be noticed that the presence of a high energy cut–off at \( \gamma_c \sim 10^4 \) would really results from models of radio halos invoking the reacceleration of relic relativistic electrons. In addition a decreasing radial profile of the magnetic field strength is naturally expected. In the framework of Pop.B models, we have shown that assuming the same model parameters necessary to reproduce the general radio properties of the Coma halo (brightness profile, integrated radio spectrum, and radial spectral steepening), the resulting IC HXR would easily be about \( \sim 30 - 100\% \) of that observed. In this case, the resulting magnetic field strength in the cluster core is of the order of \( \sim 1 \mu G \) which is in rough agreement with the RM observations especially when the field strength from the RM data is calculated assuming a power spectrum of the field itself.
Acknowledgments. I would like to thank S.Bowyer, C.-Y. Hwang and the local organizing committee for organizing such an enjoyable and interesting conference. I am grateful to L.Feretti and P.Blasi for useful discussions and to K.Dolag for providing the magnetic field profiles reported in Fig.5b.

References

Atoyan, A. M., Völk, H. J., 2000, ApJ, 535, 45
Berezinsky, V. S., Blasi, P., Ptuskin, V. S., 1997, ApJ, 487, 529
Berghöfer, T. W., Bowyer, S., Korpela, E., 2000, ApJ, 535, 615
Bhattacharjee, P., Sigl, G., 2000, Phys. Rep., 327, 109
Biermann, P., 1995, Nucl. Phys. B, 43, 221
Blandford, R. D., Eichler, D., 1987, Phys. Rep., 154, 1
Blasi, P., Colafrancesco, S., 1999, Astropart. Phys., 12, 169
Blasi, P., 2000, ApJ, 532, L9
Blasi, P., 2001, Astroparticle Physics, 15, 275
Bonamente, M., Lieu, R, Mittaz, J, 2001, ApJ, 547, L7
Bowyer, S., Lampton, M., Lieu, R., 1996, Science, 274, 1338
Bowyer, S., Berghöfer, T. W., 1998, ApJ, 506, 502
Brunetti, G., Feretti, L., Giovannini, G., Setti, G., 1999, in Diffuse thermal and relativistic plasma in galaxy clusters, Eds. H.Böhringer, L.Feretti, P.Schuecker, MPE Report, 271, 263
Brunetti, G., Setti, G., Feretti, L., Giovannini, G., 2001a, MNRAS, 320, 365
Brunetti, G., Setti, G., Feretti, L., Giovannini, G. 2001b, New A, 6, 1
Buote, D. A., 2001, ApJ, 553, 15
Carilli, C. L., Taylor, G. B., 2002, ARA&A, in press; astro-ph/0110655
Clarke, T. E., Kronberg, P. P., Böhringer, H., 2001, ApJ, 547, L111
Deiss, B. M., Reich, W., Lesch, H., Wielebinski, R., 1997, A&A, 321, 55
Dennison, B., 1980, ApJ, 239, 93
De Young, D. S., 1992, ApJ, 386, 464
Dolag, K., Ensslin, T. A., 2000, A&A, 362, 151
Dolag, K., Bartelmann, M., Lesch, H., A&A, 387, 383
Eilek, J., Weatherall, J. C., 1999, in Diffuse thermal and relativistic plasma in galaxy clusters, Eds. H.Böhringer, L.Feretti, P.Schuecker, MPE Report 271, 249
Ensslin, T. A., 1999, in Diffuse thermal and relativistic plasma in galaxy clusters, Eds. H.Böhringer, L.Feretti, P.Schuecker, MPE Report, 271, 275
Ensslin, T. A., Biermann, P. L., 1998, A&A, 330, 90
Ensslin, T. A., Lieu, R., Biermann, P. L., 1999, A&A, 344, 409
Feretti, L., Fusco-Femiano, R., Giovannini, G., Govoni, F., 2001, A&A, 373, 106
Ferrari, A., Trussoni, E., Zaninetti, L., 1979, A&A, 79, 190
Fujita, Y., Sarazin, C. L., 2001, ApJ, 563, 660
Fusco–Femiano, R., Dal Fiume, D., Feretti L., et al., 1999, ApJ, 513, L197
Fusco-Femiano, R., Dal Fiume, D., De Grandi, S., 2000, ApJ, 534, L7
Gabici, S., Blasi, P., 2002, ApJ, submitted; astro-ph/0207523
Giovannini, G., Feretti, L., Venturi, T., Kim, K. T., Kronberg, P. P., 1993, ApJ, 406, 399
Giovannini, G., Tordi, M., Feretti, L., 1999, New Astr., 4 141
Giovannini, G., Feretti, L., 2001, in Cluster Mergers and their Connection to Radio Sources, 24th meeting of the IAU, JD 10, Manchester, Highlights of Astronomy, Vol 12
Gitti, M., Brunetti, G., Setti, G. 2002, A&A, 386, 456
Goldshmidt, O., Rephaeli, Y., 1993, ApJ, 411, 518
Govoni, F., Ensslin, T. A., Feretti, L., Giovannini G., 2001, A&A, 369, 441
Jaffe, W. J., 1977, ApJ, 216, 212
Hamilton, R. J., Petrosian, V., 1992, ApJ, 398, 350
Harris, D. E., Kapahi, V. K., Ekers, R. D., 1980, ApJS, 39, 215
Hwang, C.-Y., 1997, Science, 278, 1917
Lacombe, C., 1977, A&A, 54, 1
Lieu, R., Mittaz, J. P. D., Bowyer, S., et al., 1996, Science, 274, 1335
Mannheim K., Schlickeiser, R., 1994, A&A, 286, 983
Miniati, F., Jones, T. W., Kang, H., Ryu, D., 2001, ApJ, 562, 233
Newman, W. I., Newman, A. I., Rephaeli, Y., 2002, ApJ, in press; astro-ph/0204451
Ohno, H., Takizawa, M., Shibata, S., 2002, ApJ, in press; astro-ph/0206269
Petrosian, V., 2001, ApJ, 557, 560
Rephaeli, Y., Gruber, D., Blanco, P., 1999, ApJ, 511, L21
Rephaeli, Y., Gruber, D., 2002, ApJ, in press; astro-ph/0207448
Sarazin, C. L., 1999, ApJ, 520, 529
Sarazin, C. L., 2002, in Merging Porcesses of Galaxy Clusters, Eds. L.Feretti, I.M.Gioia, G.Giovannini, ASSL, Kluwer Ac. Publish., p. 1
Sarazin, C. L., Lieu, R., 1998, ApJ, 494, L177
Sarazin, C. L., Kempner, J., 2000, ApJ, 553, 73
Schlickeiser, R., Sievers, A., Thiemann, H., 1987, A&A, 182, 21
Sijbring, L. G., 1993, PhD Thesis, Groeningen University
Takizawa, M., Naito, T., 2000, ApJ, 535, 586
Tribble, P. C., 1993, MNRAS, 263, 31
Tsay, M. Y., Hwang, C.-Y., Bowyer, S., 2002, ApJ, 566, 794
Völk, H. J., Atoyan, A. M., 1999, Astroparticle Phys., 11, 73