

PARTICLE ACCELERATION AND NON-THERMAL EMISSION FROM GALAXY CLUSTERS

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ABSTRACT

The existence and extent of non-thermal phenomena in galaxy clusters is now well established. A key question in our understanding of these phenomena is the origin of the relativistic electrons which may be constrained by the modelling of the fine radio properties of radio halos and of their statistics. In this paper we argue that present data favour a scenario in which the emitting electrons in the intracluster medium (ICM) are reaccelerated *in situ* on their way out. An overview of turbulent-particle acceleration models is given focussing on recent time-dependent calculations which include a full coupling between particles and MHD waves.

Key words : acceleration of particles – clusters of galaxies – radio continuum – radiation mechanism: non-thermal – turbulence – X-ray

I. INTRODUCTION

There is now firm evidence that the ICM is a mixture of hot gas, magnetic fields and relativistic particles. While the hot gas results in thermal bremsstrahlung X-ray emission, relativistic electrons and positrons generate non-thermal radio (synchrotron) and possibly hard X-ray radiation (inverse Compton, IC). In principle, relativistic hadrons can store a relevant fraction of the energy budget of the ICM since they are essentially no-loss particles and remain confined in the cluster volume (Völk et al. 1996; Berezhinsky, Blasi & Ptuskin 1997). However, the gamma radiation that would allow us to constrain the energetics of these particles has not been detected as yet (Reimer et al., 2003). Our understanding of the non-thermal activity in galaxy clusters is thus based on the synchrotron and IC emission from the relativistic leptons. The most spectacular example is given by the giant radio halos (e.g. Feretti 2003). The difficulty in explaining these sources arises from the combination of their \sim Mpc size, and the relatively short radiative lifetime of the radio emitting electrons (about 10^8 yrs): the diffusion time necessary to these electrons to cover such distances is much larger than their radiative lifetime. This is still an open problem and two main possibilities have been proposed so far. Relativistic electrons can be continuously reaccelerated *in situ* on their way out (e.g., Jaffe 1977), or these electrons can be continuously injected in the ICM by inelastic proton-proton collisions through production and decay of charged pions (secondary models; e.g. Dennison 1980).

After a discussion on the observations which seem to favour the first hypothesis, we focus on particle acceleration models; $H_0=50$ km/s/Mpc is assumed.

II. SECONDARY MODELS & OBSERVATIONS

A relatively straightforward possibility to have synchrotron emission on Mpc scale in galaxy clusters is provided by a continuous injection of fresh relativistic secondary electrons generated by hadronic collisions (Dennison 1980; Blasi & Colafrancesco 1999). It has been shown that secondary models may be able to account for the basic properties of the observed radio halos provided that the strength of the magnetic field averaged over the emitting volume is of the order of few μ G or greater (e.g., Dolag & Ensslin 2000; Miniati et al. 2001). On the other hand, it has been shown that the detailed properties are difficult to be explained through these models (Brunetti 2003; Feretti et al. 2004; Kuo et al. 2004; Reimer et al. 2004) suggesting that additional mechanisms of particle acceleration should be active in the ICM.

In this Section we discuss in detail some of these fine properties which thus become the tool to discriminate among different explanations for the origin of radio halos. We show that current observations, although may be still affected by biases and incompleteness which deserve future studies, provide evidence in favour of diffuse electron acceleration in galaxy clusters.

(a) Basic Formalism for Secondary Electrons

In order to derive general expectations to be compared with observations, in this Section we derive the basic properties of the synchrotron emission from secondary models.

Relativistic hadrons might be efficiently injected in the ICM by cosmological shocks (e.g., Miniati et al. 2001), Galactic Winds (e.g., Völk & Atoyan 1999), and AGNs. These particles do not suffer efficient energy losses so that their spectrum can be described by a

power law in momentum which extends up to very high energies (e.g., Blasi 2001; see also Drury, and Blasi, these proceedings) :

$$N_p(p) = K_p p^{-s} \quad (1)$$

and the energy density in the ICM is given by :

$$\mathcal{E}_p = m_p c^2 \int_{p_{\min}} dp_p N_p(p) \left[\left(1 + \left(\frac{p_p}{m_p c} \right)^2 \right)^{\frac{1}{2}} - 1 \right] \quad (2)$$

where p_{\min} is the minimum momentum of the protons which are accelerated. It is believed that shocks may play a leading role in the acceleration of cosmic ray protons in the ICM. In general, the injection of these particles at shocks is computed according to the thermal leakage model (Kang & Jones 1995) so that the momentum threshold for the injected protons is $p_{\min} = c_1 2(m_p k_B T_{\text{psh}})^{1/2}$ where k_B and T_{psh} are the Boltzmann's constant and the post shock temperature, respectively. The number of thermal protons passing through shocks which are accelerated at supra-thermal and relativistic energies is controlled by the value of the parameter c_1 . Numerical simulations aimed at the modelling of non-thermal phenomena in galaxy clusters adopt $c_1 = 2.6$ which is claimed to be consistent with observational and theoretical studies (e.g., Miniati et al. 2001 and ref. therein).

The inelastic collisions of relativistic protons with the thermal protons may generate a population of secondary electrons due to the decay of charged pions. The process of pion production in pp scattering is a threshold reaction that requires protons with kinetic energy larger than ~ 300 MeV. The spectral distribution of the injection rate of secondary electrons is given by (e.g., Mannheim & Schlickeiser 1994) :

$$q_e(p) = C(s) n_{\text{th}} K_p p^{-\frac{2}{3}(2s-1)} \quad (3)$$

and the spectrum of secondary electrons in the ICM can be estimated under stationary conditions (e.g., Dolag & Ensslin 2000):

$$N_e(p) = \frac{1}{|\dot{p}|} \int_p^\infty q_e(p) dp \quad (4)$$

where

$$\dot{p} = C_{\text{rad}} p^2 (B^2 + B_{\text{IC}}^2(z)) \quad (5)$$

is the rate of energy losses (e.g., Sarazin 1999; Brunetti 2003) of the injected electrons (for $\gamma \geq 10^3$); $B_{\text{IC}} \simeq 3.2 \mu\text{G}(1+z)^2$ and C_{rad} is a constant. Combining Eqs.(3,4,5) one has the spectrum of the secondary electrons :

$$N_e(p) = \frac{C_{\text{rad}} C(s) n_{\text{th}} K_p}{\frac{4}{3}s - \frac{5}{3}} \frac{p^{-\left(\frac{4}{3}s + \frac{1}{3}\right)}}{B^2 + B_{\text{IC}}^2(z)} = m_e c K_e \gamma^{-\delta} \quad (6)$$

The value of the maximum energy of the injected electrons is driven by that of the maximum energy of the accelerated protons which depends on many unknown quantities. However this energy should be very high and thus the maximum energy of the injected secondary electrons is expected at energies well beyond those of the electrons emitting synchrotron radiation in the radio band (e.g., Blasi 2001).

(b) Synchrotron Spectra of Radio Halos

For a power law energy distribution which extends up to very high energies (Eq.6), the synchrotron spectrum is given by :

$$j_{\text{syn}} = C_{\text{syn}}(\delta) K_e B^{\alpha_{\text{syn}}+1} \nu^{-\alpha_{\text{syn}}} \quad (7)$$

where $\alpha_{\text{syn}} = (\delta - 1)/2$, and $C_{\text{syn}}(\delta)$ is given in classical books (e.g., Rybicki & Lightman, 1979). Assuming a strength of the magnetic field in the ICM, from Eqs.(2,6,7) it is possible to estimate the energy density of cosmic ray protons which is necessary to produce a fixed synchrotron emissivity (at ν) due to the secondary electrons :

$$\mathcal{E}_p = \frac{C_E C_{\text{rad}} C(s)}{C_{\text{syn}}(\delta)} I(s, p_{\min}) \frac{B^2 + B_{\text{IC}}^2(z)}{B^{1+\alpha_{\text{syn}}}} j_{\text{syn}}(\nu) \nu^{\alpha_{\text{syn}}} \quad (8)$$

where C_E is a constant and $I()$ is the integral in Eq. (2). In Fig. 1 we report the energy density of cosmic ray protons which is required for a fixed j_{syn} (at 1.4 GHz) as a function of α_{syn} . The hadrons' energy density is normalized to the case of a Coma-like spectral index, $\alpha_{\text{syn}} \simeq 1.14$. With increasing α_{syn} the fraction of secondary electrons with $\gamma \sim 10^4$ (which emit at $\nu = 1.4$ GHz) decreases and thus the total number (and energy) of these electrons and of the relativistic protons should increase to match the fixed synchrotron flux. This is dramatic for $\alpha_{\text{syn}} > 1.5$ since in this case the spectrum of protons is steep and most of the energy is associated to the non-relativistic part of the particle spectrum. From an energetical point of view, Fig. 1 basically indicates the existence of a forbidden region for secondary models for values of the synchrotron spectral index $\alpha_{\text{syn}} > 1.5$. For example, for a fixed emissivity at 1.4 GHz secondary models with $\alpha_{\text{syn}} = 1.5, 1.7$ and 1.8 should require an energy budget of relativistic hadrons $\sim 10, 50$ and 100 times larger than that of a $\alpha_{\text{syn}} = 1.14$ model, respectively. In Fig. 1 we report the observed spectral indices of a sample of well studied radio halos (Feretti et al. , these proceedings): half of the sample lies in the forbidden region. Since most of these halos are more powerful and extended than Coma C (for

which $\geq 10\%$ of the thermal energy should be required in the form of protons, see above), the explanations of these radio halos may represent a serious challenge for secondary models.

A second point is given by the integrated synchrotron spectra. In a number of well studied radio halos the spectrum steepens at ≥ 1 GHz frequencies (e.g., Coma C: Thierbach et al. 2003; Abell 754: Fusco-Femiano et al. 2003; Abell 1914: Komissarov & Goubanov 1994; Abell 2319: Feretti et al. 1997). Ensslin (2002) claimed that the steepening observed in the Coma halo, where the 2.7 and 5 GHz points fall a factor of ~ 1.8 and ~ 3.3 below the extrapolation from the lower frequency data, may be significantly mitigated if the SZ decrement by the thermal electrons of the cluster is taken into account (a cluster radius $R=5h_{50}^{-1}\text{Mpc}$ was assumed). The radio halo however covers only a small fraction of the cluster area (e.g., Thierbach et al. 2003). In the Rayleigh-Jeans part of the CMB spectrum, the SZ distortion of the CMB integrated over the area of the radio halo is a negative flux; we obtain (Brunetti et al. in prep.):

$$F_{sz}^-(\nu) \simeq \frac{16\pi}{D^2} \frac{k_B^2 T_{\text{cmb}} T_{\text{th}} \sigma_T}{m_e c^2} \left(\frac{\nu}{c}\right)^2 \int_0^{R_H} dx x \int_x^{R_V} \frac{dr r n_{\text{th}}(r)}{\sqrt{r^2 - x^2}} \quad (9)$$

where D is the distance of the cluster, and R_H and R_V are the radius of the halo and the virial radius of the cluster, respectively. This gives a correction of only $\sim 20\%$ of the flux measured at 5 GHz (and negligible at 2.7 GHz) when applied to the case of Coma C (this correction is within the errorbars reported in Thierbach et al., 2003). A similar result is obtained by adopting the value of the Compton parameter measured for the Coma cluster (Reimer et al. 2004, Figs.1-2). Thus provided that the radio data are correct, the observed high frequency spectral steepenings are most likely related to the presence of a cut-off at $\gamma \sim 10^4$ in the spectrum of the emitting electrons. This represents a serious challenge for secondary models.

A third point is given by the spatial distribution of the synchrotron spectral indices of radio halos. It is well known that the 0.3–1.4 GHz spectral index map of the Coma radio halo indicates a progressive steepening of the spectrum from the center to the periphery (with $\alpha_{\text{syn}} \sim 0.8$ to ~ 2 ; Giovannini et al. 1993). More recently Feretti et al. (2004) have found a similar trend in the case of the giant radio halos in Abell 665 and 2163 along undisturbed cluster regions and complex spectral patches in coincidence with dynamically disturbed regions (see also Feretti et al. these proceedings). These observations suggest that the shape of the spectrum of the emitting electrons is relatively complex even on 100–200 kpc scales. On the other hand, the continuous injection of secondary electrons in the ICM is expected to produce power law spectra rather independent from the spatial location in the cluster (at least on $\ll \text{Mpc}$ scales) and thus these observations represent a chal-

lenge for the hypothesis of a secondary origin of that the emitting electrons.

(c) Synchrotron Brightness Profiles of Radio Halos

Giant radio halos are very extended sources (up to 2–2.5 Mpc). In some cases the radial profiles of the synchrotron emission are broader than those of the X-rays emitted from the hot gas (e.g., Govoni et al. 2001). This basically suggests that the decrease of the synchrotron emissivity at a given distance is smaller than that of the bremsstrahlung emissivity, $j_{\text{th}} \propto n_{\text{th}}^2$, and thus that the relativistic electrons are much broadly distributed than the thermal particles (e.g., Brunetti 2003). In case these electrons are secondaries, this should imply a very broad distribution of the cosmic ray protons and may cause an energetic problem. The energetic problem may be alleviated by assuming stronger magnetic fields combined with a more gentle radial decay of the field strength, or by searching for minimum energy configurations of the particles and field distributions (Pfrommer & Ensslin 2004).

To test the hypothesis of a secondary origin of the emitting electrons with the observed radial profiles it is necessary to focus on the case of the most extended and powerful radio halos. The radial dependence of the projected synchrotron brightness from secondary electrons is given by :

$$b_{\text{syn}}(\nu, y) = \frac{3}{2} \nu^{-\alpha_{\text{syn}}} \frac{C_{\text{syn}}(\delta) C_{\text{rad}} C(s)}{\frac{4}{3} - \frac{s}{3}} \frac{k_B T_{\text{th}} K_p(0)}{\mathcal{E}_p(0)} \times \int_y \frac{dR R X_{\text{th}}^p(R)}{\sqrt{R^2 - y^2}} n_{\text{th}}^2(R) \frac{B^{1+\alpha_{\text{syn}}}(R)}{B^2(R) + B_{\text{IC}}^2(z)} \quad (10)$$

where the parameter $X_{\text{th}}^p(R) = \mathcal{E}_p(R)/\mathcal{E}_{\text{th}}(R)$ gives the radial dependence of the ratio between the energy densities of the relativistic protons and of the thermal particles. A toy model which assumes a constant value of X_{th}^p and a strength of the magnetic field, $B \propto n_{\text{th}}^{2/3}(R)$ (magnetic-flux freezing), gives brightness profiles which are much steeper than the observed ones (Fig. 2). In order to reproduce the profiles the parameter X_{th}^p should increase with radius. The result (with X_{th}^p increasing with radius and adopting a more gentle $B(R) \propto n_{\text{th}}^{1/2}$), is reported in Fig. 2. However, the large number of relativistic protons necessary to match the brightness in the external regions of the clusters inflates the energy budget associated to these particles: for example ~ 7 times the energy of the thermal pool is required in the case of Abell 2163. This is clearly unacceptable, in addition, the energy density of the relativistic protons should increase by a factor ~ 20 going from the core to the external regions of the cluster. Obviously, the energetics of the relativistic protons may be reduced by assuming a flatter profile of the magnetic field strength. However sub-equipartition conditions

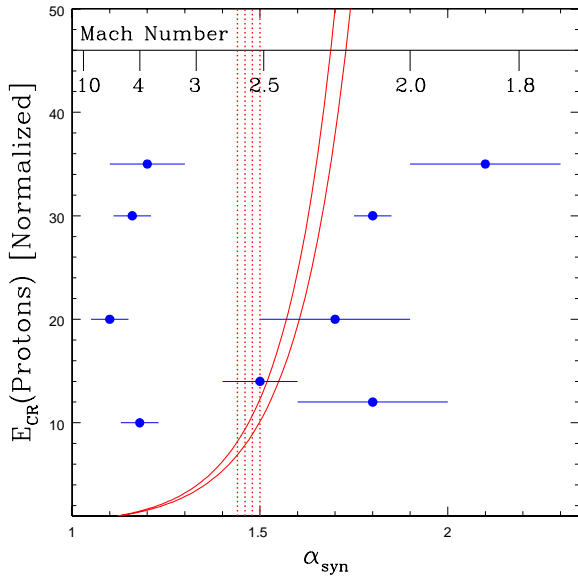


Fig. 1.— Energy density (normalized) of cosmic ray protons necessary to produce a fixed synchrotron flux at 1.4 GHz as a function of α_{syn} . The two curves are calculated for $B = 1.0$ (upper) and 1.5 (lower) μG ; $c_1 = 2.6$ is assumed. Data are taken from Feretti et al. (these proc.). The upper bar gives the Mach number of the shocks (if protons are accelerated at shocks) necessary to give α_{syn} .

(relativistic/thermal) in Abell 2163 and similar radio halos can be reached only by adopting an almost flat profile of the field strength on Mpc scales (Brunetti et al., in prep.), which however contrasts with the current scenario in which the magnetic fields are strongly amplified in the ICM during cluster formation (e.g., Dolag et al. 2004 and ref. therein). Thus the explanation of the $> \text{Mpc}$ extension of powerful radio halos (Abell 2163 class) is difficult if the emitting electrons are simply injected by hadronic collisions.

(d) Connection with Cluster Mergers and Occurrence of Radio Halos

Interestingly, there is a correlation between the non-thermal diffuse radio emission and the presence of merger activity in the host clusters of galaxies (Buote, 2001; Schuecker et al. 2001): this suggests a link between the process of formation of galaxy clusters and the origin of the non-thermal activity. If this evidence is confirmed by future measurements the secondary electron models have an additional problem. In this case the radio emission would be dominated at any time by the electrons continuously produced by the cosmic ray protons accumulated during the cluster history, rather than by the more recent merger events. No significant correlation should therefore be expected unless the decay time-scale of the magnetic fields amplified during a cluster merger on Mpc scale is much shorter than a Hubble time. This however seems to be in contrast with the current scenario of a gradual amplification of mag-

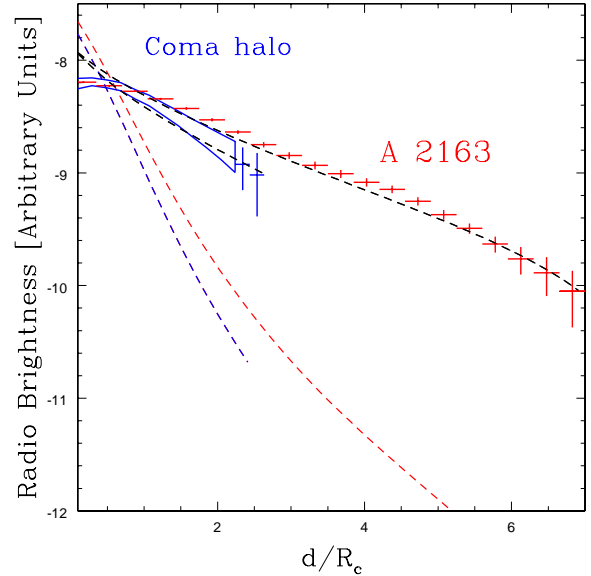


Fig. 2.— Radial SYN profiles for Coma C (blue data) and for A 2163 (red data) as a function of the distance from the center in units of the cluster core radius. Secondary models are calculated to match the observed radio luminosities. All the models adopt a central field $B_o = 3\mu\text{G}$. Results are obtained assuming $B(r) \propto n_{\text{th}}^{2/3}$ and $X_{\text{th}}^{\text{P}} = \text{const}$ (red and blue dashed curves), and $B(r) \propto n_{\text{th}}^{1/2}$ and X_{th}^{P} increasing with distance (black curves). The energy of relativistic protons is $\sim 4.5\%$ and $\sim 17\%$ of the thermal pool in the case of the Coma cluster (blue and black curves, respectively) and $\sim 60\%$ and $\sim 700\%$ for A 2263 (red and black curves, respectively).

netic fields in the ICM during cluster formation (e.g., Dolag et al. 2004).

A very important point is the statistics of radio halos. These sources are very rare if extraceted by a flux limited sample of galaxy clusters (Giovannini, Tordi, Feretti 1999). However, the detection rate of these diffuse radio sources shows an abrupt increase with the X-ray luminosity of the host clusters: about 30-35% of the galaxy clusters with X-ray luminosity larger than $10^{45} \text{ erg s}^{-1}$ show diffuse radio emission (Feretti, 2003). Kuo et al. (2004) have used this point as a tool to investigate the origin of the emitting electrons and concluded that, given the observed statistics, the typical life-time of radio halos should be of the order of 1 Gyr, in contrast with a secondary origin of the emitting electrons which would produce very long living radio halos (see also Kuo et al., these proceedings). On the other hand, very recently it has been shown that an abrupt increase of the occurrence of radio halos with the mass of the parent clusters can be understood in the framework of particle acceleration models (Cassano et al., these proceedings).

The importance of these points deserve additional observations to test the radio halos– cluster merger connection and to better describe their statistics.

III. PARTICLE ACCELERATION MODELS

Given the difficulties which have secondary models in explaining the fine radio properties and the statistics of radio halos, one possibility is to admit the presence of particle acceleration processes active in the ICM.

Although the physics of particle acceleration models is difficult to be tested, it should be stressed that these models predict very clear and general properties of radio halos which are almost independent from the details of the adopted physics:

- i)* in these models, the accelerated electrons have a maximum energy at $\gamma < 10^5$ which produces a high frequency cut-off in the resulting synchrotron spectrum (e.g., Schlickeiser et al. 1987; Brunetti et al. 2001; Petrosian 2001). This may naturally produce the observed steepenings of the synchrotron spectrum and the complex spatial distributions of the synchrotron spectral index between two frequencies (Feretti et al. 2004);
- ii)* a relatively tight connection of radio halos with cluster mergers is a very natural expectation of these models (e.g., Tribble 1993; Roettiger et al. 1997). In the framework of these models it can also be shown that an abrupt increase of the possibility to host giant radio halos with increasing mass of the parent cluster is expected (Cassano et al., these proceedings).

Obviously massive observations are necessary to confirm the spectral and statistical properties of radio halos, and thus to test the hypothesis of particle acceleration in the ICM. In addition expectations from particle acceleration models in the still unexplored observational bands (e.g., $< 300\text{MHz}$ and gamma rays) are required to efficiently test these models.

(a) Cluster Mergers: Turbulence and Particle Acceleration

It is well known that mergers and accretion of matter at the virial radius are likely to form shocks and to inject turbulent motions in the ICM (e.g., Roettiger et al. 1997; Ricker & Sarazin 2001).

There is still some debate on the typical Mach number of the shocks developed during cluster mergers (e.g., Miniati et al. 2001; Gabici & Blasi 2003; Ryu et al. 2003) and on the resulting efficiency of particle acceleration in the cluster volume (e.g., Ryu et al. these meeting). However, at least in the framework of *in situ* particle acceleration models, this is not relevant since the radiative life-time of the emitting electrons is much shorter than the crossing time of sub-halos through the main clusters, and thus shock-acceleration cannot explain the scale and morphology of radio halos (e.g., Brunetti 2003).

Cluster mergers induce large-scale bulk flows with velocities $\sim 1000 \text{ km s}^{-1}$ or larger. The Kelvin-Helmoltz instabilities generated during the passage of

the sub-clusters inject eddies which redistribute the energy of the mergers through the cluster volume and decay into turbulent velocity fields. The numerical simulations find that an energy budget of 10-30% of the thermal energy of the ICM can be channelled in the form of cluster turbulence (e.g., Sunyaev et al. 2003); also very recent semi-analytical calculations seem to be in rough agreement with these estimates (Cassano & Brunetti 2004; Cassano & Brunetti, these proceedings). Spatially-resolved *pseudo-pressure* maps of the Coma cluster obtained from a mosaic of XMM-Newton observations have revealed the signature of mildly supersonic turbulence (Schuecker et al. 2004). The calorimeters onboard of ASTRO-E2 should be able to detect the turbulent broadening of the lines of heavy ions in excess to the thermal broadening (Inogamov & Sunyaev 2003), thus directly probing cluster turbulence. There are a number of mechanisms to channel the energy flux of the turbulence in the acceleration of fast particles. Commonly used are acceleration via Magneto-Sonic (MS) waves (e.g., Kulsrud & Ferrari 1971), and Alfvén waves (e.g., Miller & Roberts 1995).

It has been shown that re-acceleration of a population of relic electrons by turbulence powered by major mergers is suitable to explain the very large scale of the observed radio emission and may also account for the complex spectral behaviour observed in some diffuse radio sources (Brunetti et al., 2001; Petrosian 2001; Ohno, Takizawa and Shibata 2002; Fujita, Takizawa and Sarazin 2003). These first calculations, however, did not take into account the full coupling between particles and MHD waves (Alfvén and MS) and consider only relativistic electrons neglecting the presence of the relativistic hadrons in the ICM. In the following we focus on the results from recent calculations of fully coupled and time-dependent Alfvénic acceleration in the ICM. A first application to the case of MS waves in the ICM including the relevant coupling and damping processes can be found in Cassano & Brunetti (2004) (see also Cassano & Brunetti, these proceedings).

(b) Acceleration of Protons and Primary Electrons

Very recently, the problem of particle-Alfvén wave interactions has been investigated in the most general situation in which relativistic electrons (primary), thermal protons and relativistic protons exist within the cluster volume (Brunetti et al., 2004). In this modelling the interaction of all these components with the waves, as well as the turbulent cascading and damping processes of Alfvén waves, have been treated in a fully time-dependent way in order to calculate the spectra of electrons, protons and waves at any fixed time.

The injection process of Alfvén waves in the ICM is the major hidden ingredient in these calculations since it depends on a number of unknown quantities and is not a well established mechanism. These waves couple with relativistic electrons (and protons) at very small

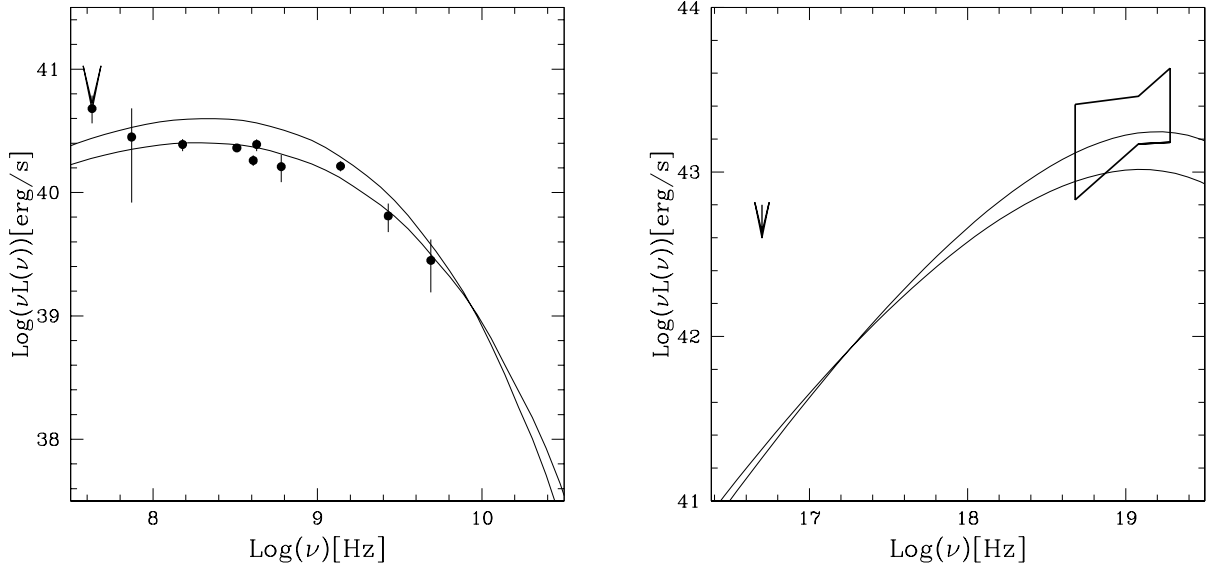


Fig. 3.— SYN and IC spectra calculated for a Coma-like cluster and compared with the radio, EUV (considered as an upper limit, see Brunetti et al. 2004) and HXR data. Calculations are obtained for a central field $B_o = 1.5\mu\text{G}$, $B(r) \propto n_{\text{th}}^{2/3}$, an injection power of Alfvén waves $P_A \propto n_{\text{th}}^{5/6}$ (e.g., Brunetti et al. 2004), $X_{\text{th}}^p = \text{const}$, and an initial electron and proton energy density $= 5 \times 10^{-5}$ and 10^{-2} that of the thermal pool. For the reported models the energy of the fluid turbulence is in the range 15–30% of the thermal pool.

scales $\lambda \sim 2\pi p/(\Omega m)$ and thus the cascading process should be very efficient if these waves are injected at large scales. However, it has been shown that the cascading process of Alfvén waves ends up with a highly anisotropic wave-spectrum which strongly reduce the efficiency of particle acceleration (Yan & Lazarian 2004 and ref. therein). One possibility to obtain an efficient coupling of Alfvén waves with relativistic particles is thus to inject these waves directly at relatively small scales in order to avoid strong anisotropy during the cascading process. This may be achieved via the *Lighthill* mechanism (e.g., Kato 1968; Eilek & Henriksen 1984) which essentially can be adopted to convert a fraction of the energy flux of the cascade of the large scale fluid turbulence into radiation of Alfvén waves at smaller scales (Fujita et al., 2003; Brunetti et al., 2004).

Provided that this mechanism is at work in the ICM, Brunetti et al. (2004) have shown that an efficient particle acceleration is obtained in the ICM if cluster mergers inject a fraction of large scale turbulence with energy $\sim 10 - 30\%$ of that of the thermal pool. On the other hand, since the major damping of the Alfvén waves is due to relativistic hadrons in the ICM, these authors have shown that efficient electron acceleration can be powered only by assuming that the energy budget of relativistic protons is less than a few percent of the thermal pool. Under these conditions these calculations have proved that the observations described in Sect. 2 (including the fine radio properties and HXR tails) can be successfully reproduced. In Fig. 3 we report an example of results obtained for of a Coma-like

cluster.

(c) Hybrid Models

In the most general situation, relativistic hadrons in the ICM may store an appreciable fraction of the thermal energy, and they should inject a non negligible component of secondary electrons in the cluster volume. The bulk of this component is associated to $\gamma \sim 100 - 300$ electrons. These electrons cannot be responsible for the observed synchrotron radio spectra, but they may be efficiently re-accelerated at higher energies giving a novel population of radio emitting particles.

Very recently, we have developed Hybrid Model calculations, which include, in a self-consistent way, this component together with the MHD waves and the primary electrons and protons. We find that the re-acceleration of secondary electrons is a very efficient mechanism since these electrons are re-accelerated and continuously injected at the same time; the efficiency increases toward the central regions of the clusters where the number density of the target-thermal protons is larger.

Fig. 4 shows an example of the results obtained from our calculations in the case of a Coma-like cluster. The following items should be outlined :

- i)* with increasing the energy budget of relativistic protons the efficiency of electron acceleration decreases. This effect is not compensated by the increase of the number of injected secondary elec-

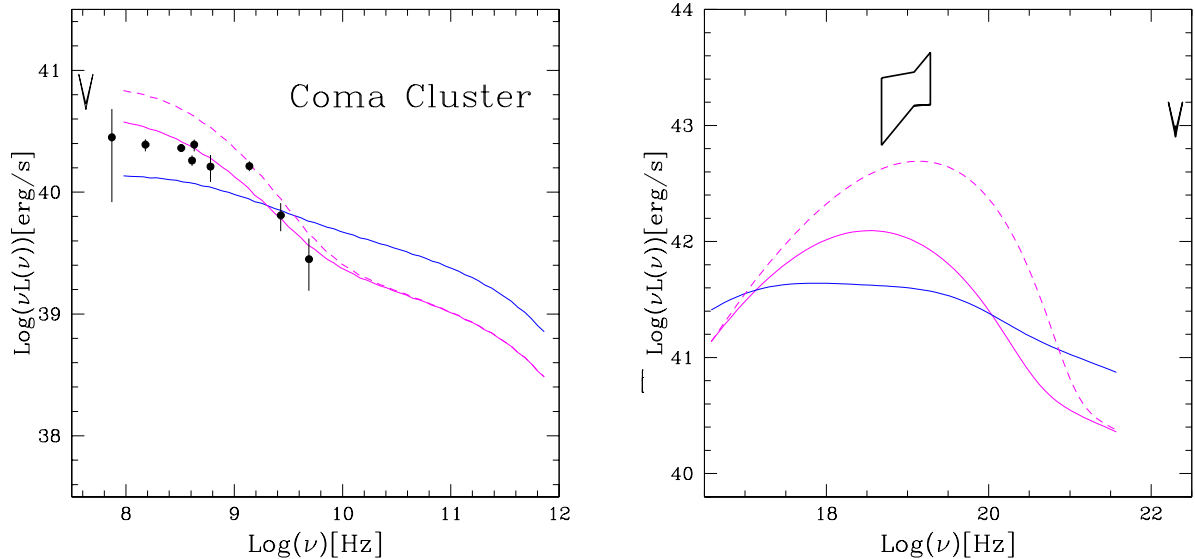


Fig. 4.— SYN and IC spectra calculated for a Coma-like cluster and compared with the radio, HXR and gamma-ray data. Calculations are obtained for a central field $B_o = 1.5\mu\text{G}$, $B(r) \propto n_{\text{th}}^{2/3}$, $X_{\text{th}}^{\text{p}} = \text{const}$, and an injection power of Alfvén waves $P_A \propto n_{\text{th}}^{5/6}$ (solid lines) and $P_A \propto n_{\text{th}}^{5/6}$ (dashed lines). The initial proton energy is 3×10^{-2} (magenta lines) and 10^{-1} (blue lines) that of the thermal pool. No *relic*-primary electrons are considered in the calculations. For the reported models the energy of the fluid turbulence is in the range 20–70% of the thermal pool (70% for dashed models). Calculations are stopped at $\sim 3 \times 10^{21}$ Hz in the right panel.

trons and consequently the synchrotron spectrum at \sim GHz frequencies drops down. On the other hand, the high frequency synchrotron tail expected at high frequencies (≥ 10 GHz), which is essentially produced by the injected fresh electrons, scales with the energy of the relativistic protons;

- ii) an energy budget of relativistic protons $< 10\%$ of the thermal pool is required to reproduce a clear steepening of the synchrotron spectrum at higher frequencies;
- iii) the IC spectrum produced without introducing a population of *relic*-primary electrons is below the HXR tail detected by BeppoSAX. This is simply because the number of secondary electrons in the cluster volume is limited by the decrease of the number density of thermal protons in the external regions. At least in the external regions, a population of *relic*-primary electrons (to be re-accelerated) is thus required to match the HXR;
- iv) similarly to the case of secondary models, gamma ray emission is expected by Hybrid Models. In Fig. 4 we report only the contribution from IC, while an additional contribution is expected by the decay of the π^0 produced during the hadronic collisions. However, at variance with secondary models, the amount of synchrotron GHz emission (and HXRs) is basically anti-correlated with the strength of the gamma ray emission.

A more detailed discussion will be presented in a forthcoming paper (Brunetti & Blasi, in prep.).

IV. CONCLUSIONS

The fine radio properties of radio halos and their statistics are a powerful tool to understand the origin of the emitting electrons. The study of the spectrum of radio halos and their very broad extension are crucial tests for the proposed models. In particular, the spectral steepenings observed in a few radio halos indicate the presence of a high energy cut-off in the spectrum of the emitting electrons at about $\gamma \sim 10^4$; we have shown that these steepenings are not appreciably affected by the SZ correction. The broad synchrotron profiles of some giant and luminous radio halos (e.g., Abell 2163) are also a challenge for secondary models: in order to maintain the energy budget of the relativistic hadrons significantly below that of the thermal pool, the strength of the magnetic field in the ICM should remain almost constant on scales comparable to the cluster size, which contrasts with the scenario of the amplification of the magnetic fields in clusters. A similar energetic problem is also found by looking at the spectral indices of a sample of luminous radio halos (Sect. 2b, Fig. 1).

All the above considerations suggest that the process of injection of secondary electrons in the ICM may not be the leading mechanism in producing the observed non-thermal activity. Thus we have focussed on *in situ* particle acceleration models and discussed a class of

self-consistent and time-dependent models which follow the interaction between MHD waves, protons (relativistic and thermal) and electrons (relativistic). The major hidden ingredient in these models is the injection of turbulence in the ICM and the generation of Alfvén and Fast MS waves. In this paper we have focussed on Alfvén waves which damps most of their energy flux on the relativistic protons in the ICM. In this case the electron acceleration is thus limited by the presence of the relativistic hadrons: efficient electron acceleration is obtained only provided that hadrons store a few percent of the thermal energy. Under these conditions, we have shown that if a fraction of $\sim 10 - 30\%$ of the energy of the thermal cluster is in the form of turbulence, then particle acceleration is found to be sufficiently efficient to generate giant radio halos (and possibly HXR tails). A novel approach is provided by Hybrid Models in which both primary and secondary electrons are considered. Although the reacceleration of only secondary electrons may reproduce the observed radio properties, it is found that a population of *relic*-primary electrons in the external regions (at least) is necessary to explain the HXR tails.

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