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Giant Radio Halos in Galaxy Clusters as Probes of Particle Acceleration in Turbulent Regions

G. Brunetti

INAF- Istituto di Radioastronomia, via P. Gobetti 101, I-40129, Bologna, Italy.
e-mail: brunetti@ira.inaf.it

Abstract. Giant radio halos in galaxy clusters probe mechanisms of particle acceleration connected with cluster merger events. Shocks and turbulence are driven in the inter-galactic medium (IGM) during clusters mergers and may have a deep impact on the non-thermal properties of galaxy clusters. Models of turbulent (re)acceleration of relativistic particles allow good correspondence with present observations, from radio halos to γ-ray upper limits, although several aspects of this complex scenario still remain poorly understood.

After providing basic motivations for turbulent acceleration in galaxy clusters, we discuss relevant aspects of the physics of particle acceleration by MHD turbulence and the expected broad-band non-thermal emission from galaxy clusters. We discuss (in brief) the most important results of turbulent (re)acceleration models, the open problems, and the possibilities to test models with future observations. In this respect, further constraints on the origin of giant nearby radio halos can also be obtained by combining their (spectral and morphological) properties with the constraints from γ-ray observations of their parent clusters.

Key words. Galaxies: clusters: general—cosmic rays—turbulence.

1. Introduction

Radio observations show the presence of diffuse (on Mpc scale) radio emission in a fraction of massive galaxy clusters, *radio halos* from cluster X-ray emitting regions, and *relics*, typically in the clusters peripheral regions (e.g., see Ferrari *et al.* 2008; Venturi 2011 for recent reviews). Giant radio halos are the most spectacular and best studied cluster-scale non-thermal sources. They probe the existence of complex mechanisms, responsible for their origin, that are still poorly understood.

Several sources of relativistic particles exist in galaxy clusters: ordinary and active galaxies (AGN), and cosmological shock waves (e.g. Blasi *et al.* 2007 for a review). However the time necessary for GeV electrons[1] to diffuse on Mpc (halo) scales from these sources is much longer than their radiative life-time ($\sim 10^8$ yrs). Thus

[1]Those responsible for the synchrotron radiation in the radio band.

radio halos prove processes of acceleration/injection of GeV electrons that must be 'distributed' on cluster scales (Jaffe 1977).

Giant radio halos are not common in galaxy clusters and observed only in about 1/3 of the most massive systems (e.g. Giovannini *et al.* 1999; Kempner & Sarazin 2001; Cassano *et al.* 2008). Radio-observations and their follow up in the X-rays suggested that radio halos are found only in dynamically disturbed systems (e.g. Buote 2001; Govoni *et al.* 2004). More recently, the sensitivity of the Radio Halo Survey at the GMRT (Venturi *et al.* 2007, 2008) allows for starting a solid statistical exploration of clusters radio properties. It allows the discovery of the clusters radio bimodality that pin-points the *transient* nature of radio halos that are generated in connection with clusters mergers and fade away when clusters become more relaxed systems (e.g. Brunetti *et al.* 2009; Cassano *et al.* 2010a).

These observations suggest that a fraction of the gravitational energy that is dissipated during merger events is channelled into the generation of non-thermal components. A popular scenario for the origin of radio halos assumes that relativistic particles are (re)accelerated in Mpc regions by MHD turbulence generated during cluster mergers (e.g., Brunetti *et al.* 2001; Petrosian 2001), this may naturally explain the tight connection between halos and mergers. Alternative possibilities that have been proposed so far for the origin of the emitting electrons include the generation of secondary electrons due to proton–proton collisions in the IGM (e.g. Blasi & Colafrancesco 1999; Pfrommer & Enßlin 2004; Keshet & Loeb 2010), and dark-matter annihilation in the cluster volume (e.g. Colafrancesco *et al.* 2006). Here we discuss the case of the turbulent (re)acceleration scenario.

2. Turbulence and turbulent acceleration in galaxy clusters

2.1 *Why turbulent acceleration? – A simple motivation*

Observations constrain models of giant radio halos, in several cases putting some tension on a 'pure' secondary origin of the emitting electrons (e.g. Ferrari *et al.* 2008 for review; Brunetti *et al.* 2008, 2009; Donnert *et al.* 2010a, b; Jeltema & Profumo 2011; Brown & Rudnick 2011; Bonafede *et al.* 2011 for recent results).

In this section we focus on the observed spectral properties of giant radio halos that provide part of the motivation for turbulent acceleration of the emitting electrons. Potentially the synchrotron spectrum gives information on the efficiency of the acceleration of the emitting electrons. The maximum energy of electrons is given by the competition between acceleration efficieny and (radiative) losses, $E_{\rm max} \approx \chi(E)/\beta_{\rm rad}$ ($\chi(E) = \chi$ for FERMI mechanisms, and $\beta_{\rm rad} = c_2(B^2 + B^2_{\rm IC})$). Consequently the maximum frequency of the synchrotron radiation from the accelerated electrons (at higher frequencies the spectrum steepens), $\nu_{\rm max} = c_1 B E^2_{\rm max}$, is:

$$\nu_{\rm max} \sim \frac{c_1}{c_2^2} \frac{B\chi^2}{(B^2 + B^2_{\rm IC})^2}. \tag{1}$$

Assuming that inverse Compton (IC) and synchrotron losses are of the same order of magnitude, i.e. $B \approx$ a few μG as suggested by the analysis of Rotation Measures (RM) of cluster radio sources (e.g., Bonafede *et al.* 2011 and references therein), the measure of $\nu_{\rm max}$ allows for estimating χ and the acceleration time-scale $\tau_{\rm acc} \sim 1/\chi$.

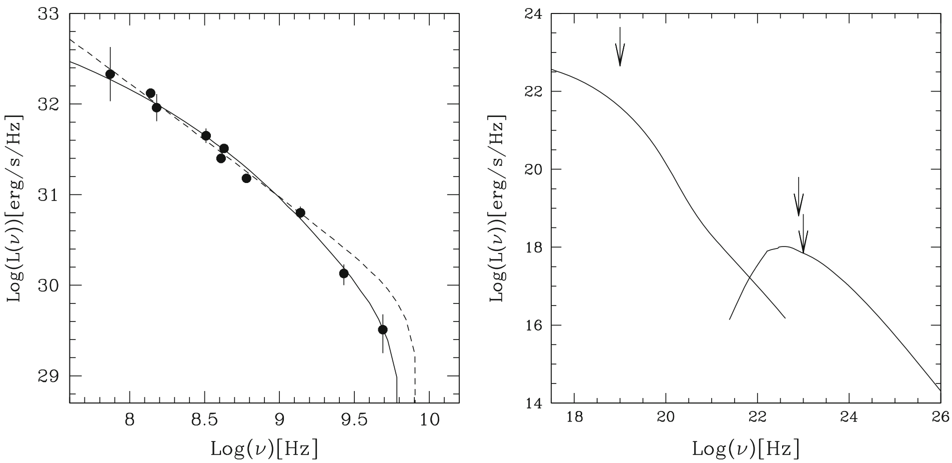

Figure 1. Radio (*left*) and high-energy (*right*) spectrum of Coma. Models, power-law spectrum (dashed) and reacceleration (solid), are shown including the effect (cut-off) due to SZ-decrement at high radio frequencies. Model details are in Brunetti & Lazarian (2011b), relevant data are in Ackermann *et al.* (2010); Deiss *et al.* (1997) and Pizzo (2010).

The 'historical' motivation for turbulent acceleration for the origin of radio halos comes from the spectrum of the Coma halo, the prototype of these sources (e.g., Willson 1970; Giovannini *et al.* 1993). Coma is the unique halo with a spectrum measured over a wide frequency range (Fig. 1). The spectrum significantly steepens at higher frequencies: a power-law that fits the data at lower frequencies overestimates the flux measured at 2.7 and 5 GHz by a factor 2 and 3, respectively (e.g. Thierbach *et al.* 2003)[2]. The observed steepening of Coma implies (from eq. (1)) $\tau_{acc} \approx 10^8$ yrs, i.e. that 'gentle' (poorly efficient) and spatially-distributed (on Mpc scales) mechanisms must be responsible for the acceleration of the emitting electrons; the most natural candidate is acceleration by turbulence, that is indeed poorly efficient (e.g. Schlickeiser *et al.* 1987).

Also the spectrum of other radio halos favours turbulent acceleration. Although the spectrum of giant radio halos is still poorly known, and less than 10–12 halos are observed at 2 frequencies, the observed values of the spectral indices span a broad range, $\alpha \sim 1$–2[3] ($F(\nu) \propto \nu^{-\alpha}$, e.g. Venturi 2011). This readily implies that the synchrotron spectrum of radio halos is far from being a 'universal' power-law and *poses crucial constraints to the nature of the mechanisms that generate these sources*. In particular, halos with extreme spectral properties, $\alpha \sim 1.5$–2 (e.g., Brunetti *et al.* 2008; Brentjens 2008; Giovannini *et al.* 2009; Macario *et al.* 2010) are important. Energy arguments rule out the possibility that they have a (very steep) power-law spectrum extending to lower frequencies and also allow to disfavour a 'pure' secondary origin of the emitting electrons (Brunetti *et al.* 2008; Dallacasa *et al.* 2009).

[2]Even by considering the effect of the SZ-decrement (see also Donnert *et al.* 2010a).
[3]The upper bound of the range is probably limited by the fact that steeper halos would be difficult to observe with present radio telescopes.

Giant radio halos with $\alpha > 1.5$ are explained by assuming that their spectrum starts steepening at lower frequencies. It implies that present observations 'just' sample the range of frequencies where the steepening becomes severe. According to turbulent acceleration models, these very steep-spectrum sources are the halos generated with the smaller acceleration efficiency ($\tau_{acc} \approx 2$–3×10^8 yrs) among the presently observed radio halos.

2.2 *Turbulence in galaxy clusters*

Cosmological numerical simulations show that large-scale turbulent motions are generated during the process of cluster formation (e.g., Dolag *et al.* 2005; Iapichino & Niemeyer 2008; Vazza *et al.* 2011). These motions, with typical velocities $V_L \sim$ 500–700 km/s, are injected at large scales, $L_o \sim$ 300–500 kpc, during merging events and may provide the driver for turbulence at smaller scales.

Theoretically the viscosity in a turbulent and magnetized IGM is strongly suppressed due to the effect of the bending of magnetic field lines and of the perturbations of the magnetic field induced by plasma instabilities (Schekochihin *et al.* 2005; Lazarian 2006). Consequently an inertial range in the IGM may be established down to collisionless scales where a fraction of the turbulent energy is channelled into acceleration/heating of cosmic rays and thermal plasma. At this point we may think of several processes that can channel (at least a fraction of) the turbulent-energy into the (re)acceleration of particles. They include resonant and non-resonant couplings and their efficiency depends on the properties of turbulence and of the background magnetized plasma (e.g. see Cho & Lazarian 2006 for review).

2.3 *Turbulent acceleration models for the origin of giant radio halos and consequences for high energy emission from galaxy clusters*

Acceleration of electrons from the thermal pool to relativistic energies by MHD turbulence in the IGM faces serious problems due to energy arguments (e.g. Petrosian & East 2008). Consequently, turbulent acceleration models must assume a pre-existing population of relativistic particles that provides the seeds to 'reaccelerate' during cluster mergers (e.g. Brunetti 2003; Petrosian & Bykov 2008 for reviews).

To account for the turbulence–particles interaction properly, one must know both the scaling of turbulence, the changes with time of turbulence spectrum due to the most relevant damping processes, and the interactions of turbulence with various waves produced by cosmic rays. For this reason the fraction of the turbulent energy that gets into (re)acceleration of cosmic rays in the IGM is uncertain and reflects our ignorance of the details of the properties of turbulence and of the (connected) micro-physics of the IGM.

Cases where a large fraction of the turbulent energy is dissipated into the (re)acceleration of cosmic rays in galaxy clusters include the gyro-resonant interaction with Alfvén modes (e.g. Ohno *et al.* 2002; Fujita *et al.* 2003; Brunetti *et al.* 2004)[4] and the resonant (mainly transit-time-damping) interaction with fast modes

[4]In this case it must be postulated an injection of Alfvén modes at quasi-resonant (small) scales to have quasi-isotropic distribution of the modes (see Yan & Lazarian 2004).

under the assumption that the collisionless scale of the IGM is much smaller than the Coulomb ion mean free path (e.g. Brunetti & Lazarian 2011a)[5]. In these cases the efficiency of particle acceleration is self-regulated by the back-reaction (damping) of particles on the spectrum of turbulence (Brunetti *et al.* 2004; Brunetti & Lazarian 2011a). Stronger turbulence induces more efficient acceleration leading to a faster growth of the energy density of cosmic rays with time. This – however – increases the damping of turbulence and the interaction approaches a quasi-asymptotic (and very complex) regime where cosmic rays get in (quasi) equipartition with turbulence and self-regulate their (re)acceleration.

According to a more standard approach, the damping of turbulence in the IGM is dominated by the interaction with the hot IGM. In this case it is calculated that only a fraction ($\sim$10%) of turbulence goes into the (re)acceleration of cosmic rays (e.g. Cassano & Brunetti 2005; Brunetti & Lazarian 2007). This scenario is motivated (i) by the idea that the compressible part of the MHD turbulence contributes the most to particle acceleration in the IGM and (ii) by the fact that fast modes are strongly damped (via transit-time-damping) in a hot (and high beta) plasma such as the IGM. This scenario allows prompt calculations of particle acceleration by MHD turbulence in the IGM. In Brunetti & Lazarian (2007) we considered the advances in the theory of MHD turbulence to develop a comprehensive picture of turbulence in the IGM and to study the reacceleration of relativistic particles considering all the relevant damping processes. We have shown that the ensuing cluster-scale radio emission generated in merging clusters is in very good agreement with the present observations of radio halos.

More recently we extended our investigation to the case of the (re)acceleration of cosmic ray protons and of the secondary electrons generated in the IGM via pp collisions (Brunetti & Lazarian 2011b). These calculations were motivated by the fact that cosmic ray protons are long-living particles that are confined (and accumulated) in clusters (Völk *et al.* 1996; Berezinsky *et al.* 1997). The consequence is the unavoideable generation of secondary particles and γ-rays (at some level) in the IGM (e.g., Blasi & Colafrancesco 1999; Miniati 2003; Pfrommer & Enßlin 2004). Calculations in Brunetti & Lazarian (2011b) allow a self-consistent treatment of the interaction between compressible turbulence and cosmic rays in the IGM and a complete modeling of the non-thermal spectrum from galaxy clusters. Figure 1 shows the expected spectrum in the case of a Coma-like cluster where the energy content of compressible turbulence and cosmic ray protons is assumed $\approx$18% and few % of that of the IGM, respectively. The spectrum in Fig. 1 is calculated by assuming the magnetic field in the Coma cluster (strength and radial profile) as derived from RM (Bonafede *et al.* 2010). Under these conditions the expected γ-ray emission is about 5–7 times below the upper limits from the first 18 months of observations with the FERMI satellite. A detection with FERMI after $\sim$2 yrs of observations would be reconciled by 'postulating' a magnetic field $\approx$2.5 times smaller than that from the RM.

[5] In this case it is proposed that the perturbations of the magnetic field generated by turbulence-driven plasma instabilities reduce the effective mean free path.

3. Halo-merger connection and future observations

The formation and evolution of radio halos depend on the dynamics of the hosting clusters (see Brunetti *et al.* 2009 for a more detailed discussion). Observations prove this tight connection, namely that all radio halos are observed in dynamically disturbed systems (e.g. Govoni *et al.* 2004; Cassano *et al.* 2010a, 2011). Merger-turbulence decays at smaller scales in about one eddy turnover time, few 10^8 yrs, implying a temporal connection between mergers (the duration of cluster–cluster interaction is >Gyr), turbulent (re)acceleration and radio halos (the particle acceleration time-scale required for the acceleration of radio emitting electrons is 10^8 yrs). Compressible turbulence dissipates most of its energy in few eddy turnover times, as soon as galaxy clusters becomes more relaxed. It implies that radio halos must fade away in more relaxed systems in a relatively short (<Gyr) time. Obviously the situation becomes more complex thinking of the process of cluster formation that would generate a more complex evolution of cluster turbulence (e.g. Paul *et al.* 2011; Vazza *et al.* 2011). Future cosmological simulations that include a proper treatment of cosmic ray acceleration/cooling will shed light on this connection.

A different (yet connected) point is whether all merging clusters should host giant radio halos. Observations show several cases of merging clusters that do not host detectable radio halos (e.g., Cassano *et al.* 2010a; Russell *et al.* 2011). From a 'naive' point of view these systems could be very young mergers where the decay of turbulence at smaller scales and the acceleration of particles are not started yet.

We may suggest a more physical explanation in the context of turbulent models. The frequency where a steepening is predicted in the spectra of radio halos, $\nu_{\rm max}$ (§ 2.1), is determined by the fraction of turbulent energy converted into electron re-acceleration. Only the most energetic merger-events in the Universe can generate giant radio halos with $\nu_{\rm max} \geq 1$ GHz (Cassano & Brunetti 2005). The generation of these radio halos in less massive systems ($M_v \leq 1$–$2 \times 10^{15}\, M_\odot$) or in clusters at higher redshifts ($z \geq 0.4$–0.5) is rare and we expect that halos in these systems are mainly generated with their spectra steepening at lower frequencies and are difficult to observe at higher frequencies (Cassano *et al.* 2006). Interestingly most disturbed systems without observable radio halos are clusters with $L_{\rm X} \leq 7$–8×10^{44}erg/s (Cassano *et al.* 2010a; Russell *et al.* 2011), thus we might guess that these systems have halos that glow up when observed at lower radio frequencies (e.g. with LOFAR, LWA).

These radio halos with very steep spectrum are predicted to be more frequent in galaxy clusters, since they can be generated in connection with less energetic mergers, e.g. between less massive systems or minor mergers in massive systems, that are more common in the Universe. *The existence of these radio halos is the most important expectation of turbulent models and it stems from the fact that turbulent acceleration is a poorly efficient process* (e.g. Brunetti *et al.* 2008). Crucial tests will come from future surveys with LOFAR (Cassano *et al.* 2010b; Rottgering *et al.* 2010).

4. γ-rays from galaxy clusters and origin of radio halos

The confinement of cosmic ray protons in galaxy clusters leads to the important expectation that clusters must be γ-ray emitters due to the production of secondary

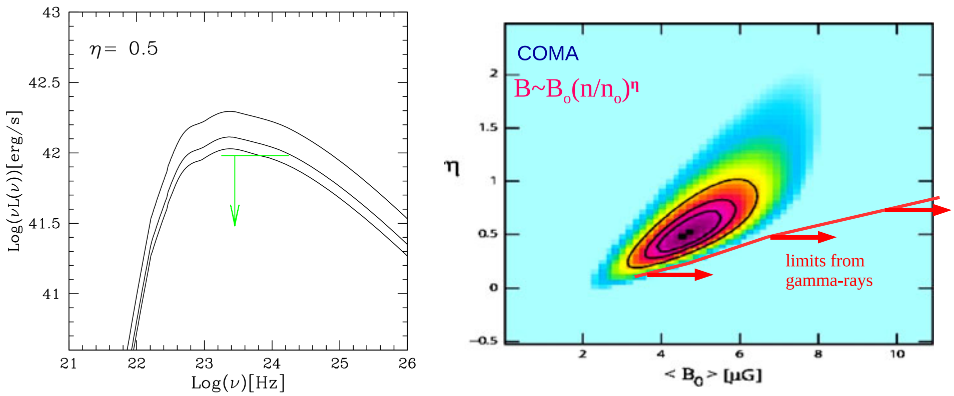

Figure 2. *Left*: γ-ray emission (π^{o} decay) from the Coma cluster assuming secondary models 'forced' to reproduce the radio brightness and luminosity of the halo. Calculations assume $\eta = 0.5$ and $B_o = 4.7, 6.4, 7.1$ μG (from top to bottom). *Right*: Comparison between the minimum B_o from γ-ray upper limits (assuming secondaries) and the magnetic field derived from RM (contours refer to 1, 2, 3σ conf. level, from Bonafede *et al.* 2010).

particles (Völk *et al.* 1996; Berezynsky *et al.* 1997). The ratio of γ-rays (π^{o} decay) and radio emission from secondary electrons depends on the properties of the magnetic field in the IGM. Consequently limits on γ-rays from nearby clusters combined with constraints from RM allow for testing secondary models for radio halos (e.g., Ackermann *et al.* 2010; Donnert *et al.* 2010a; Jeltema & Profumo 2011 for recent attempts).

A step in this direction can be obtained by *adding* the constraints given by the spatial profile of the synchrotron brightness of radio halos. It is well known that giant radio halos have flat brightness distributions (e.g. Govoni *et al.* 2001; Murgia *et al.* 2009; Brown & Rudnick 2011) implying that most of the emission is produced from the external regions where the magnetic field is smaller. This immediately leads to a larger ratio gamma/radio emission in the case of radio halos with flatter radio profiles.

Here we report on the case of Coma. We assume secondary models for the origin of the radio halo and 'force' the model to reproduce the observed halo's radio profile and luminosity at 330 MHz (see also Donnert *et al.* 2010a). This, combined with the FERMI limits, allows for obtaining corresponding (lower) limits on the cluster's magnetic field. In Fig. 2, we report a comparison between the magnetic field in the cluster center B_o ($B = B_o(n/n_o)^{\eta}$, n the IGM density), derived from RM, and the minimum value of B_o that is required by secondary models to have γ-ray emission (still) consistent with the FERMI upper limits. This starts putting tension on a secondary origin of the halo: the limits on B_o imposed by FERMI (18 months of observations, Ackermann *et al.* 2010) are inconsistent with the values of B_o derived (at 1, 2, 3σ level) from RM. Future FERMI data will be crucial as γ-ray upper limits 50% deeper imply values of B_o 1.5–2 times larger (depending on η).

5. Conclusions

Present observations put constraints on the nature of giant radio halos. Constraints come from the combination of (i) the spectral and statistical properties of the population of radio halos, (ii) estimates of B from RM, and (iii) upper limits on γ-ray emission from radio-halo clusters. The scenario for the origin of radio halos based on particle acceleration by merger-driven turbulence in galaxy clusters shows a good correspondence with the combination of these constraints.

The physics of the interaction between turbulence and particles is however very complex leaving many aspects of this scenario still unexplored. We have discussed some open questions, e.g. *which is the fraction of the energy of turbulence that goes into particle (re)acceleration in the IGM? How radio halos are generated and fade away in connection with cluster mergers? Why several merging clusters do not host observable radio halos?*

We conclude that observations with future radiotelescopes and deeper constraints in the γ-ray band will have the potential to test this model and (eventually) to further increase present difficulties with other scenario.

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