Occurrence and Luminosity Functions of Giant Radio Halos from Magneto-Turbulent Model

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ABSTRACT

We calculate the probability to form giant radio halos (~1 Mpc size) as a function of the mass of the host clusters by using a Statistical Magneto-Turbulent Model (Cassano & Brunetti, these proceedings). We show that the expected increase of the probability to find radio halos in the more massive galaxy clusters (\(M \geq 2 \times 10^{15} M_\odot\)) can be well reproduced. We calculate the evolution with redshift of such a probability and find that giant radio halos can be powered by particle acceleration due to MHD turbulence up to \(z \approx 0.5\) in a \(\Lambda CDM\) cosmology. Finally, we calculate the expected Luminosity Functions of radio halos (RHLFs). At variance with previous studies, the shape of our RHLFs is characterized by the presence of a cut-off at low synchrotron powers which reflects the inefficiency of particle acceleration in the case of less massive galaxy clusters.

Key Words: acceleration of particles - turbulence - radiation mechanism: non-thermal, galaxy clusters: general - radio continuum

I. Introduction

Radio observations of galaxy clusters indicate that the detection rate of radio halos (RHs) shows an abrupt increase with increasing the X-ray luminosity of the host clusters. In particular about 30-35% of the galaxy clusters with X-ray luminosity larger than \(10^{45}\) erg/s show diffuse non-thermal radio emission (Giovannini & Feretti 2002): these clusters have also high temperature (\(kT > 7\) keV) and large mass (\(\geq 2 \times 10^{15} M_\odot\)). Furthermore giant RHs are frequently found in merging clusters (e.g., Schuecker et al. 2001). These observations suggest that there is a connection between thermal and non-thermal phenomena in galaxy clusters.

Recent papers (Ensslin and Röttgering 2003; Kuo et al. 2004) have investigated the statistics of RHs and their connection with the thermal properties of the host clusters from a theoretical point of view. These works are based on assumptions in defining the condition of RHs formation from observational correlations and/or mass thresholds. Present data suggest that giant RHs may be accounted for by synchrotron emission from relativistic electrons reaccelerated by the turbulence generated in the cluster volume during merger events (Brunetti 2003; Brunetti this proceedings). Thus, with the aim to investigate the statistical properties and the connection between thermal and non-thermal phenomena in galaxy clusters, we have developed a statistical magneto-turbulent model (Cassano & Brunetti 2004, C&B model: Cassano & Brunetti these proceedings) in which we follow the formation of clusters of galaxies (making use of the extended Press & Schechter (1974) formalism) and estimate the injection of fluid turbulence and of fast magneto sonic (MS) waves during cluster mergers. Then we calculate the evolution of the electron spectra in the ICM and the resulting radio (synchrotron) and hard X-ray (Inverse Compton) emission spectra. By using our model we can thus investigate the probability of formation of RHs in a well defined physical framework, the evolution with redshift of such a probability and the expected Luminosity Functions of RHs (RHLFs). Here we apply the C&B model under the following assumptions:

- We focus the attention on the formation of giant RHs only (radius \(R_H \sim 500 h_{50}^{-1}\) Kpc).

- The magnetic field strength averaged over the emitting volume is assumed to be \(< B > \approx 0.5\) \(\mu G\), independent on the mass of the parent cluster.

The adopted cosmologies are: EdS \((H_o = 50\) Km \(s^{-1}Mpc^{-1}\), \(\Omega_{\nu,m} = 1\)) and \(\Lambda CDM\) \((H_o = 70\) Km \(s^{-1}Mpc^{-1}\), \(\Omega_{\nu,m} = 0.3\), \(\Omega_\Lambda = 0.7\), \(\sigma_8 = 0.9\)).

II. Occurrence of RHs: predictions vs observations

By making use of the C&B model we have run Monte Carlo simulations to obtain a sufficiently large number of merger trees in order to have a large synthetic population of galaxy clusters with a wide range of present day masses and temperatures. In this way we are able to statistically follow the cosmological evolution of the non-thermal emission and of the properties of the thermal ICM. Clusters with RHs in our synthetic population are identified with those objects with a synchrotron cut-off \(\nu_c \geq 10^2\) MHz in a region of 1 \(Mpc h_{50}^{-1}\) size. We have calculated the probability to form RHs \((z \leq 0.2)\) in two mass bins: \(\text{binA} = [1.8 - 3.6] \times 10^{15} M_\odot\) and \(\text{binB} = [0.9 - 1.8] \times 10^{15} M_\odot\) (EdS cosmology). These mass bins are consistent with those considered in the
Fig. 1.— Expected formation probability of RHs ($R_H \simeq 500h^{-1}\text{ kpc}, B \sim 0.5\mu \text{G}$) as a function of parameter $\eta_t$ in a EdS cosmology (solid lines with error bars) and in a $\Lambda$CDM cosmology (dotted lines) in the mass bins: binA=$[1.8 - 3.6]10^{15} M_\odot h^{-1}$ and binB=$[0.9 - 1.8]10^{15} M_\odot h^{-1}$ for EdS case and binA=$[1.9 - 3.8]10^{15} M_\odot h^{-1}$ and binB=$[0.945 - 1.9]10^{15} M_\odot h^{-1}$ for the $\Lambda$CDM model. The two bottom dashed lines mark the observed probabilities for RHs in the mass binB while the two top dashed lines mark the observed probabilities in the mass binA; observational regions already account for $1\sigma$ errors.

Observational studies and thus allow us to compare our expectations with observations. In Fig.(1) we report the probability to form a giant ($\simeq 1 \text{ Mpc } h^{-1}$ size) RH (red points) in the two mass-bins (including the statistical error estimated from our Montecarlo simulations) as a function of the parameter $\eta_t$, which gives the fraction of energy of the turbulent motions injected by cluster merger which is channeled in the form of MS waves in the C&B model.

The dashed blue lines mark the range of the observed probabilities (Giovannini et al. 1999) in the binA (top dashed region) and in the binB (bottom dashed region), respectively. For a comparison in Fig.(1) we also report the probability to form a RH ($z \leq 0.2$) in a $\Lambda$CDM cosmology (green dotted lines). As expected, we find that at $z \leq 0.2$ the results are relatively independent from the considered cosmology, with the $\Lambda$CDM model being slightly less efficient. The main result is that in both EdS and $\Lambda$CDM models it is possible to find a unique interval of $\eta_t$ in which the model reproduces the observed probability for both the cluster-mass bins.

Fig. 2.—Probability to form giant RHs ($> 1 \text{ Mpc } h^{-1}$ size) as a function of the cluster mass in two relevant redshift bins: $z=0-0.2$ (red lines) and $z=0.2-0.4$ (black lines) in a $\Lambda$CDM cosmology. Calculations are obtained for $\eta_t = 0.3$.

In particular, in agreement with observations and independently from the adopted cosmology, we find that 20-30% of clusters in the binA can form a RH and that only 2-3% of galaxy clusters in the binB host a RH. Given the requested values of $\eta_t$ (Fig.(1)), we find that the relatively high occurrence of RHs observed in massive clusters can be well reproduced by our particle acceleration model under reasonable conditions, i.e. that a fraction of 20-30% of the energy of the turbulent motions injected during cluster merger (which corresponds to a few percent of the thermal energy) is in the form of MS waves.

III. Radio Halos Statistics and cluster mass

In the previous Section we have found that the probability to form a RH has a strong dependence on the mass of the host cluster, it goes from few % for $M < 1.9 \times 10^{15} M_\odot$ to 20-30% for $M \geq 2 \times 10^{15} M_\odot$, in agreement with observations (Fig.(1)).

Now we calculate the probability to find RHs as a function of the cluster mass from our synthetic population of galaxy clusters in a $\Lambda$CDM cosmology: this is a crucial point of our model and marks the difference with previous studies (e.g., Ensslin & Röttgering 2002)). As an example, in Fig.(2) we report this probability in two redshift bins $z=0-0.2$ (black lines) and $z=0.2-0.4$ (red lines). Clusters with mass $< 10^{15} M_\odot$...
mergers between massive subclusters are expected to inject turbulence on larger volumes, of the order of $V_H$, and thus the efficiency of the generation of RHs is not reduced and this further favour massive objects as the parent clusters of RHs.

More quantitatively, it can be shown (Cassano & Brunetti 2004) that the acceleration efficiency $\chi$ (within $V_H$), triggered by a major merger event scales about with $\chi \propto M^{0.75-1.25}$ (0.75 for $M \geq 3 \times 10^{15} M_\odot$, 1.25 for $M < 10^{15} M_\odot$). Since the maximum energy of the accelerated electrons is $\gamma_e \propto (B^2 + B_{CMB}^2)$, where $B_{CMB} = 3.2 \cdot (1 + z)^4 \mu G$ is the strength of the equivalent magnetic field of the CMB, and the break frequency is $\nu_0 \propto \gamma_e^2 B$, one has:

$$\nu_0 \propto M^{1.5-2.5} \frac{B}{(B^2 + B_{CMB}^2)^2}$$

and consequently massive clusters are statistically favourite to have $\nu_0 \gtrsim 10^9$ MHz (which is the adopted condition to define the presence of a RH).

IV. Evolution of radio halos with redshift

The probability to form RHs depends on the combination of the energy losses suffered by relativistic electrons (mainly due to IC losses $\propto (1 + z)^4$) with the acceleration efficiency powered by the turbulence generated during cluster mergers (which depends on the merger history).

In this Section we calculate the evolution with redshift of the probability to form RHs in a ΛCDM cosmology. As an example, in Fig.(3) we report the probability to form a giant RH ($\simeq 700$ Kpc in a ΛCDM cosmology) with redshift in the mass bin $[1.9 - 3.8] \times 10^{15} M_\odot$ for a representative value of $\eta_t (\eta_t = 0.3)$. The occurrence of RHs decreases with redshift due to the higher IC energy losses. We note however that such a decrease is not dramatic since in a ΛCDM Universe major mergers develop at slightly higher redshift with respect to a EdS Universe. For instance, in the considered case the formation rate of RHs is 20-36% at relatively low redshift and decreases to 10% at higher redshifts ($0.3 \leq z \leq 0.4$).

V. The Luminosity Functions of Radio Halos (RHLFs)

We have already shown that the observed probability to find RHs with the cluster mass is well reproduced by the C&B model (see Sec.2). In Cassano & Brunetti 2004 (see also Cassano & Brunetti these proceedings) it has also been shown that the typical synchrotron and IC luminosity of RHs can be well reproduced by the model assuming that during mergers a few percent of the thermal energy of the cluster is in the form of

![Fig. 3.](image)

Probability to form giant RHs ($\sim 1 Mpc$ $h_{70}^{-1}$ size) with redshift in the mass bin $[1.9 - 3.8] \times 10^{15} M_\odot h_{70}^{-1}$ in a ΛCDM cosmology. Calculations are performed for $\eta_t = 0.3$.
Fig. 4.— RHLFs ($n_H(P) \times P$) expected by the C&B model. Results are shown for the redshift bins $0 \leq z \leq 0.2$ (black curve with points) and $0.2 \leq z \leq 0.4$ (red curve with points). The expected Local RHLF (blue curve with points) is also reported together with the Local RHLF from Ensslin & Röttgering (2002) (solid blue line) for a comparison.

MS waves ($i.e., \eta_t > 0.1 - 0.2$). Given these promising results, in this Section we derive the expected luminosity functions of giant RHs (RHLFs). First we use the probility to form RHs with the cluster’s mass $P_{\Delta M}$ (Fig. 2) to estimate the mass functions of RHs ($dN_H(z)/dMdv$):

$$\frac{dN_H(z)}{dM dv} = \frac{dN_d(z)}{dM dv} \times P_{\Delta M} = n_{PS} \times P_{\Delta M}, \quad (2)$$

where $n_{PS} = n_{PS}(M, z)$ is the Press & Schechter (1974) mass function (we use $n_{PS}$ since our model is based on Press & Schechter formalism). The RHLF is given by:

$$\frac{dN_H(z)}{dV dP_{1.4}} = \frac{dN_H(z)}{dM dv} \frac{dP_{1.4}}{dM} \quad (3)$$

In order to derive $dP_{1.4}/dM$ in Eq. (3), we combine the observed correlations between radio power at 1.4 Ghz ($P_{1.4\,GHz}$) and bolometric X-ray luminosity ($L_X$) (e.g., Feretti 2003) and between $L_X$ and the virial mass, $M_{200}$ (e.g., Arnaud & Evrard 1999). The used $P_{1.4\,GHz}$-M correlation is obtained collecting the data from all the known clusters with giant RHs and converting them in a $\Lambda$CDM cosmology. In Fig.(4) we report the Local (here calculated for $z < 0.05$) RHLF (number of RHs per $Gpc^3$ as a function of the radio power) expected by our model and the expected RHLFs in the bins $0 \leq z \leq 0.2$ and $0.2 \leq z \leq 0.4$ (lines with points). Our RHLFs are compared with the Local (RHLF)$_{EKR}$ (blue solid line) of Ensslin & Röttgering (2002). The (RHLF)$_{EKR}$ is obtained combining the X-ray observed luminosity function of clusters with the radio luminosity - X-ray luminosity correlation and assuming that a constant fraction $f_{rh} = 1/3$ of galaxy clusters have RHs. The most important difference between the two luminosity functions is that our RHLF shows a cut-off/flattening at low radio powers. We stress that the flattening at low powers is a unique feature of particle acceleration models since it marks the effect of the decrease of the efficiency of the particles acceleration in the case of the less massive galaxy clusters and consequently the presence of a synchrotron cut-off $\nu_b < 10^2$ MHz.

Future radio observations (e.g., with LOFAR and LWA) should be able to test the presence of such a low-power cut-off in the RHLFs and the evolution of the RHLFs with redshift.

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