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OCCURENCE 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 expectations of this model are in good agreement with the observations for viable values of the parameters. In particular, the abrupt increase of the probability to find radio halos in the more massive galaxy clusters ($M \gtrsim 2 \times 10^{15} M_\odot$) 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∼0.5 in a ΛCDM 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 – clusters of galaxies – radio continuum – radiation mechanism: non-thermal – turbulence

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 ($\gtrsim 2\times\ 10^{15} M_\odot$). 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 assumpions 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 magnetosonic (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 applay 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 $< B >\sim 0.5$ μG, independent on the mass of the parent cluster.

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

II. OCCURENCE 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

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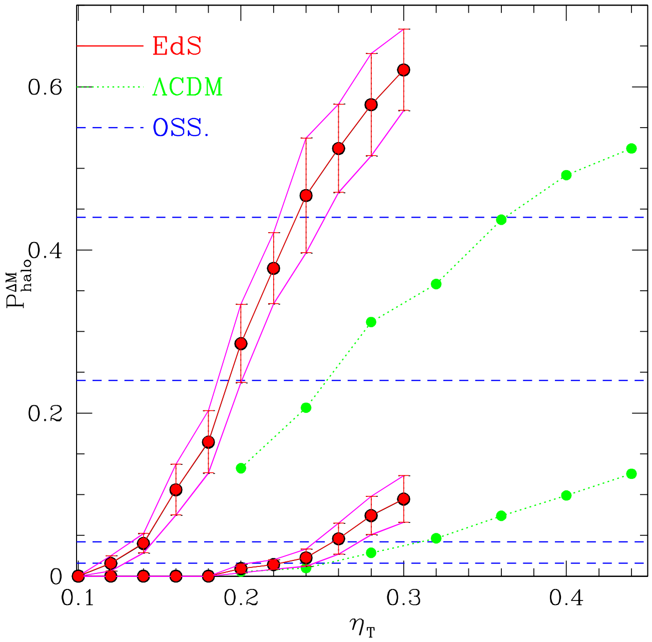

Fig. 1.— Expected formation probability of RHs ($R_H \simeq 500 h_{50}^{-1}$kpc, $B \sim 0.5\mu$G) as a function of parameter η_t in a EdS cosmology (solid lines with error bars) and in a ΛCDM cosmology (dotted lines) in the mass bins: binA=$[1.8 - 3.6]\,10^{15} M_\odot\, h_{50}^{-1}$ and binB=$[0.9 - 1.8]\,10^{15} M_\odot\, h_{50}^{-1}$ for EdS case and binA=$[1.9 - 3.8] \cdot 10^{15}$ $\mathrm{M}_\odot \mathrm{h}_{70}^{-1}$ and binB=$[0.945 - 1.9] \cdot 10^{15}$ $\mathrm{M}_\odot \mathrm{h}_{70}^{-1}$ for the ΛCDM 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 1σ errors.

the thermal ICM. Clusters with RHs in our synthetic population are identified with those objects with a synchrotron cut-off $\nu_b \gtrsim 10^2$ 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: binA=$[1.8 - 3.6] \times 10^{15} M_\odot$ and binB=$[0.9-1.8] \times 10^{15} M_\odot$ (EdS cosmology). These mass bins are consistent with those considerated in the 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 Mpc h_{50}^{-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 η_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 ΛCDM cosmology (green dotted lines). As expected, we find that at $z \leq 0.2$ the results are relatively indipendent

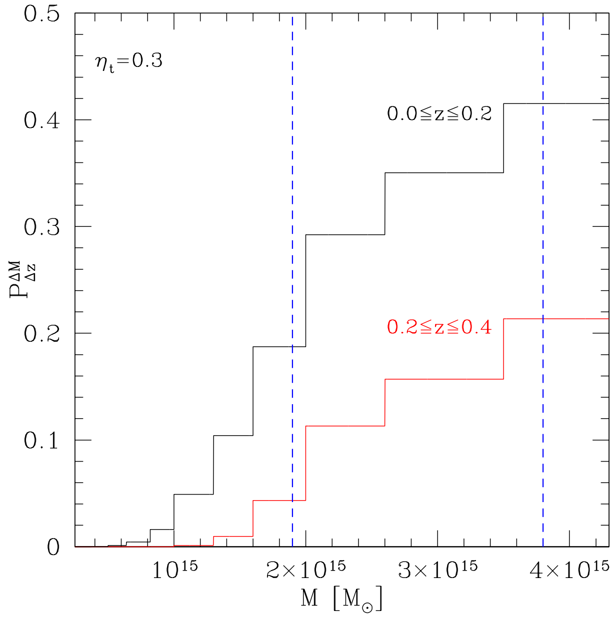

Fig. 2.— Probability to form giant RHs ($> 1 Mpc\, h_{50}^{-1}$ size) as a function of the cluster mass in two relevant redshift bins: z=0-0.2 (red lines) and z=0.2-0.4 (black lines) in a ΛCDM model. Vertical dashed lines mark the $[1.9 - 3.8] \times 10^{15} M_\odot$ mass bin of Fig.(1). Calculations are obtained for $\eta_t = 0.3$.

from the considered cosmology, with the ΛCDM model being slightly less efficient. The main result is that in both EdS and ΛCDM models it is possible to find a unique interval of η_t in which the model reproduces the observed probability for both the cluster-mass bins. In particular, in agreement with observations and indipendently 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 η_t (Fig.(1)), we find that the relatively high occurence 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 probabilty 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 $M \gtrsim 2 \times 10^{15} M_\odot$, in agreement with observations (Fig.(1)).

Now we calculate the probability to find RHs as a function of the cluster mass from our synthetic popu-

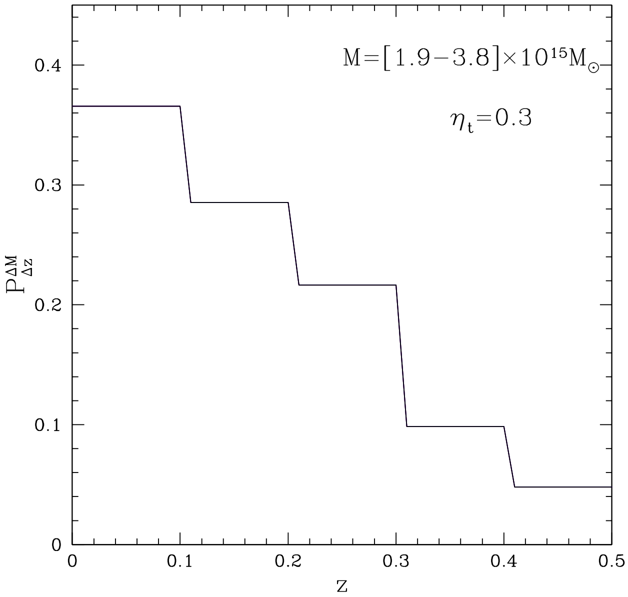

Fig. 3.— Probability to form giant RHs ($\sim 1 Mpc\, h_{50}^{-1}$ size) with redshift in the mass bin $[1.9-3.8]\times 10^{15} M_{\odot} h_{70}^{-1}$ in a ΛCDM cosmology. Calculations are performed for $\eta_t = 0.3$.

lation of galaxy clusters in a ΛCDM 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 $<< 10^{15} M_{\odot}$ have a negligible probability to form giant RHs; on the other hand, such a probability is found to reach ∼40% for clusters with masses $> 3 \times 10^{15} M_{\odot}$ in the 0-0.2 redshift bin. For a comparison with Fig.(1) we also mark in Fig.(2) the mass bin $[1.9 - 3.8] \times 10^{15} M_{\odot}$ (vertical blue dashed lines).

Thus, the important finding of these calculations is that only massive clusters can host giant RHs ($R_H \geq$ 500 kpc h_{50}^{-1}) and that the probabilty to form these diffuse radio sources presents an abrupt increase for clusters with about $M \gtrsim 2 \times 10^{15} M_{\odot}$ (Fig.(1) and Fig.(2)). These findings can be simply explained in the framework of our model. Infact, it can be shown that in the C&B model the energy of the turbulence injected in galaxy clusters is expected to roughly scale with the thermal energy of the clusters (Cassano & Brunetti 2004; Cassano & Brunetti these proceeding Fig(2)). This seems reasonable and immediately implies that the energy density of the turbulence is an increasing function of the mass of the clusters, i.e. $\mathcal{E}_t \propto T \propto M^a$ (a=0.56-0.67), and thus particle acceleration is favoured in massive clusters.

In general, the infall of subclusters through a main cluster, which is not very massive, injects turbulence in a volume V_t (calculated using *Ram Pressure Stripping*, Fujita, Takizawa, Sarazin 2003; Cassano & Brunetti 2004) which is found to be smaller than that of giant RHs, V_H ($V_H = 4\pi R_H^3/3$), and thus the efficiency of the mechanism is reduced by about a factor of V_t/V_H in the case of less massive clusters. On the other hand, major 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 χ (within V_H), triggered by a major merger event scales about with $\chi \propto M^{0.75-1.25}$ (0.75 for $M \geq 3 \cdot 10^{15} M_{\odot}$, 1.25 for $M < 10^{15} M_{\odot}$). Since the maximum energy of the accelerated electrons is $\gamma_b \propto \chi/(B^2 + B_{CMB}^2)$, 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 $\nu_b \propto \gamma_b^2 B$, one has:

$$\nu_b \propto M^{1.5-2.5} \frac{B}{(B^2 + B_{CMB}^2)^2} \qquad (1)$$

and consequently massive clusters are statistically favourite to have $\nu_b \gtrsim 10^2$ 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 dependes 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 η_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 develope 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 redhifts ($0.3 \leq z \leq 0.4$).

V. THE LUMINOSITY FUNCTIONS OF RADIO HALOS (RHLFS)

We have alredy 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)

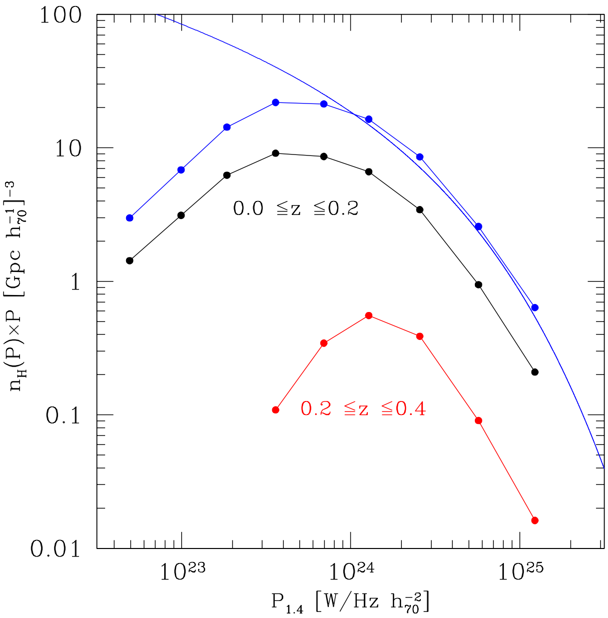

Fig. 4.— RHLFs ($n_H(P) \times P$) expected by the C&B model. Results are shown for the redshift bins $0 \leq z \leq 0.2$ (black curve with points) and $0.2 \leq z \leq 0.4$ (red curve with points). The expected Local RHLF (blue curve with points) is also reported together with the Local RHLF from Ensslin & Röttgering (2002) (solid blue line) for a comparison.

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 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 $P^{\Delta z}_{\Delta M}$ (Fig.2) to estimate the mass functions of RHs ($dN_H(z)/dMdV$):

$$\frac{dN_H(z)}{dM\,dV} = \frac{dN_{cl}(z)}{dM\,dV} \times P^{\Delta z}_{\Delta M} = n_{PS} \times P^{\Delta z}_{\Delta M}, \qquad (2)$$

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:

$$\frac{dN_H(z)}{dV\,dP_{1.4}} = \frac{dN_H(z)}{dM\,dV} \bigg/ \frac{dP_{1.4}}{dM}. \qquad (3)$$

In order to derive $dP_{1.4}/dM$ in Eq.(3), we combine the observed correlations between radio power at 1.4 Ghz ($P_{1.4GHz}$) 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 $P_{1.4GHz}$-M correlation is obtained collecting the data from all the known clusters with giant RHs and converting them in a ΛCDM 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 $(RHLF)_{E\&R}$ (blue solid line) of Ensslin & Röttgering (2002). The $(RHLF)_{E\&R}$ is obtained combining the X-ray observed luminosity function of clusters with the radio luminosity - X-ray luminosity correlation and assuming that a costant 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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