Radio haloes from simulations and hadronic models – I. The Coma cluster

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ABSTRACT

We use the results from a constrained, cosmological magnetohydrodynamic simulation of the Local Universe to predict the radio halo and the γ-ray flux from the Coma cluster and compare it to current observations. The simulated magnetic field within the Coma cluster is the result of turbulent amplification of the magnetic field during the build-up of the cluster. The magnetic seed field originates from starburst driven, galactic outflows. The synchrotron emission is calculated assuming a hadronic model. We follow four approaches with different distributions for the cosmic ray proton population within galaxy clusters. The radial profile of the radio halo can only be reproduced with a radially increasing energy fraction within the cosmic ray proton population, reaching >100 per cent of the thermal-energy content at ≈1 Mpc, for example the edge of the radio-emitting region. Additionally, the spectral steepening of the observed radio halo in Coma cannot be reproduced, even when accounting for the negative flux from the thermal Sunyaev–Zeldovich effect at high frequencies. Therefore, the hadronic models are disfavoured from the present analysis. The emission of γ-rays expected from our simulated Coma is still below the current observational limits (by a factor of ∼6) but would be detectable by FERMI observations in the near future.

Key words: galaxies: clusters: individual: Coma – intergalactic medium.

1 INTRODUCTION

Galaxy clusters are the largest gravitationally bound objects in the Universe. The thermal gas, which forms the dominant component in the intra-cluster medium (ICM), is mixed with magnetic fields and relativistic particles, as seen by radio observations that detected Mpc-sized diffuse radio sources, radio haloes and relics, in a fraction of X-ray luminous galaxy clusters in merging phase (e.g. Feretti 2003; Ferrari et al. 2008). A fraction of the energy dissipated during cluster mergers may be channelled into the amplification of the magnetic fields (e.g. Dolag, Bartelmann & Lesch 2002; Subramanian, Shukurov & Haugen 2006) and into the acceleration of relativistic primary cosmic ray electrons (CREs) and cosmic ray protons (CRPs) via shocks and turbulence (Ensslin et al. 1998; Blasi 2001; Brunetti & Lazarian 2007). CRPs have long lifetimes and remain confined within clusters for a Hubble time (e.g. Blasi, Amato & Caprioli 2007, and references therein). Consequently, they are expected to be the dominant non-thermal particle component in the ICM.

Primary and secondary particles in the ICM are expected to produce a complex emission spectrum from radio to γ-rays (see Brunetti 2008; Petroshian et al. 2008; Cassano 2009 for recent reviews).

Giant radio haloes are presently detected in a fraction of massive galaxy clusters at low and intermediate redshifts (e.g. Cassano et al. 2008) and their origin is still not fully understood. Extended and fairly regular diffuse synchrotron emission may be produced by secondary electrons injected during proton–proton collisions, since the parent relativistic protons can diffuse on large scales (e.g. hadronic or secondary models; Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000). Alternative models assume relativistic electrons to be re-accelerated in situ by magnetohydrodynamic (MHD) turbulence generated in the ICM during cluster–cluster mergers (e.g. re-acceleration models; Brunneti et al. 2001; Petroshian 2001). Unavoidable γ-ray emission, due to the decay of the neutral pions that are generated through proton–proton collisions, is expected in the context of hadronic models (e.g. Blasi, Gabici & Brunetti 2007 for review). γ-ray emission is also expected from those re-acceleration models that account for the general situation where both relativistic protons and electrons (including secondaries) interact with MHD turbulence (Brunetti & Blasi 2005), yet in this case the level of γ-rays is expected to be lower than that from standard hadronic models (Brunetti 2008; Brunetti et al. 2009).

Only upper limits to the γ-ray emission from clusters have been obtained so far (Reimer et al. 2003; Aharonian et al. 2009),
although the FERMI telescope will shortly provide the chance to obtain the first γ-ray detections of clusters and/or to put stringent constraints to the energy density of the CRp. Future deep observations with high-energy Cherenkov arrays are expected to provide complementary constraints. Most importantly, in a few years the Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA) will observe clusters at low radio frequencies with the potential to discover the bulk of the cluster-scaled synchrotron emission in the Universe (Enßlin & Röttgering 2002; Cassano, Brunetti & Setti 2006; Brunetti et al. 2008).

The theoretical picture for the generation of non-thermal cluster emission is very complex and modern numerical simulations provide an efficient way to obtain expectations to compare with present and future observations. Advances in this respect have been recently obtained by including aspects of cosmic ray physics into cosmological Lagrangian simulations (Pfrommer et al. 2007; Pfrommer, Enßlin & Springel 2008), mostly focusing on the acceleration of CRe and CRp at shocks and on the production of secondary electrons from such a CRp population.

Hadronic models are based on a well-known physical process, the production of secondary particles through proton–proton collisions at relatively high energies. Thus, they can be adequately implemented into cosmological simulations and compared with observations, provided the properties of the population of parent CRp are modelled correctly. On the other hand, turbulent re-acceleration is based on complex processes that happen at small scales, often unresolved in present simulations, and a correct implementation of this scenario would require complex subgrid modelling which is presently not available. In this paper, we investigate the non-thermal emission from secondary particles in a Coma-like cluster extracted from a cosmological simulation and, for the first time, compare numerical predictions and observations.

2 THE SIMULATION

We use results from one of the constrained, cosmological MHD simulations presented in Donnert et al. (2009) from which we select the simulated counterpart of the Coma cluster. The initial conditions for a constrained realization of the local Universe were the same as used in Mathis et al. (2002). Briefly, the initial conditions were obtained based on the IRAS 1.2-Jy galaxy survey (see Dolag et al. 2005, for more details). Its density field was smoothed on a scale of 7 Mpc, evolved back in time to z = 50 using the Zeldovich approximation and used as a Gaussian constraint (Hoffman & Ribak 1991) for an otherwise random realization of a Λ cold dark matter cosmology (ΩM = 0.3, Λ = 0.7, h = 0.7). The IRAS observations constrain a volume of ≈115 Mpc centred on the Milky Way. In the evolved density field, many locally observed galaxy clusters can be identified by position and mass. The Coma cluster in particular can be clearly identified by its global properties and gives an excellent match to the observed Sunyaev–Zeldovich (SZ) decrement, especially in the non-radiative simulations used in this paper (Dolag et al. 2005). The similarity in morphology of the simulated and observed Coma cluster is coincidental, as this structure is far below the constraints originally imposed by the IRAS galaxy distribution. The original initial conditions were extended to include gas by splitting dark matter particles into gas and dark matter, obtaining particle of masses $6.9 \times 10^8 M_\odot$ and $4.4 \times 10^9 M_\odot$, respectively. The gravitational softening length was set to 1 kpc.

Our MHD simulation follows the magnetic field through the turbulent amplification driven by the structure formation process. For the magnetic seed fields, a semi-analytic model for galactic winds was used. Here, we used the result of the 0.1 Dipole simulation (Donnert et al. 2009), which gives a reasonable match to the observed magnetic field in the Coma cluster. In Fig. 1, we compare the magnetic field profile predicted for the Coma cluster from our simulations with models that best reproduce the Rotation Measurement observed in five extended sources within the Coma cluster (preliminary results from Bonafede et al. 2009, Bonafede et al. in preparation) with a magnetic field radial profile:

$$\langle B(r) \rangle = B_0 \left[ \frac{n_{\text{gas}}(r)}{n_0} \right]^{\eta}$$

where $n_{\text{gas}}$ is the gas density and $\eta$ in the range [0.5–1.5]. Our simulations are in good agreement with $\eta \approx 1.0$. This profile gives an average magnetic field over the central $Mpc^3$ of $\sim 1.9 \mu G$, which is consistent with the equipartition estimate derived from the radio halo emission (Thierbach, Klein & Wielebinski 2003).

3 SECONDARY ELECTRONS IN GALAXY CLUSTERS

In this paper, we focus on hadronic models that can be implemented reasonably well in present simulations, providing a chance to test this scenario in the case of the Coma cluster.

The spectrum of CRp was taken to be a power law, $N(E) = K_p E^{-\alpha_p}$, and the spectrum of the secondary electrons resulting from proton–proton collisions was calculated under stationary conditions considering synchrotron and inverse Compton losses (Brunetti & Blasi 2005, and references therein). Following Dolag & Enßlin (2000), we adopted the slope of the spectral index of the Coma halo, $\alpha = 1.25$, obtained with $\alpha_p = 2.6$ for the hadronic models (this also accounts for the logarithmic increase of the proton–proton cross-section with proton energy). Such CRp collisions also produce $\gamma$-rays from the decay of secondary neutral pions, which are a direct measure of the CRp and of the unavoidable secondary electron injection process into the ICM. We calculate the $\gamma$-ray flux from our simulated Coma cluster by adopting $\alpha_p = 2.6$ and the formalism described in Pfrommer & Enßlin (2004).

There are several potential sources of CRp in the ICM, including shocks, AGN and galaxies (Ensslin et al. 1998; Völk & Atoyan 1999; Ryu et al. 2003). An adequate modelling of the CRp-injection process by all these sources in simulations is challenging and, consequently, we treat the spatial distribution of CRp in our MHD
simulations as a free parameter. Thus, we follow four approaches chosen to encompass a range suggested by theoretical and observational findings, but restrict to large magnetic fields in the ICM that provide the most favourable case for hadronic models as it minimizes the CRp-energy requirement necessary to generate a fixed synchrotron luminosity. In Model 1, we assume that the energy density of the CRp is a constant fraction of the thermal-energy density of the ICM. In Model 2, we adopt a radius-dependent ratio between CRp and thermal-energy density following results from cosmological simulations of CRp acceleration at structure formation shocks by Pfrommer et al. (2007). In both these models, we use the magnetic field strength and spatial distribution from our MHD simulations of the Coma cluster. In Model 3, we adopt the radius-dependent energy density of CRp as in Model 2 and an artificial magnetic field by assuming a radial scaling of the field strength in the form \( B \propto \sqrt{r_c} \) within the radio-emitting region (Fig. 1). In the last model, Model 4, we used the magnetic field from our MHD simulations, but fit the radial profile of the CRp-energy density in the simulated cluster to match the synchrotron brightness profile measured for the Coma radio halo; in this case, we limit the CRp-energy density so that it stays smaller than the thermal-energy density of the ICM at large radii.

For these models, the overall normalization of the CRp-energy density is chosen to match the observed radio luminosity of the Coma radio halo at 1.4 GHz, \( 7.76 \times 10^{25} \text{W Hz}^{-1} \) (Deiss et al. 1997).

4 THE RADIO HALO OF COMA

The Coma cluster hosts the prototype of giant radio haloes (e.g., Giovannini et al. 1993), and in this section we compare the radio properties from the simulated Coma cluster with the observed ones. We calculate simulated radio images by using a map-making algorithm (Dolag et al. 2005) that allows us to project the predicted emission of every smoothed particle hydrodynamics particle along the line of sight, considering an integration depth of \( \pm 4 \) Mpc around the centre of the simulated Coma cluster. The resulting images of radio emission for our models are shown in Fig. 2.

4.1 Radial profile and cosmic ray energy budget

The radial distribution of the fraction between the energy density of CRp and thermal gas for Models 1–4 is reported in Fig. 3. Provided that the magnetic field strength in the central cluster regions is sufficiently large (i.e. \( >5 \mu \text{G}, \) as in our cases), Models 1–3 generate enough synchrotron luminosity at 1.4 GHz to match that of the Coma halo with reasonable requests in terms of energy density in the CRp (about 1 to 10 per cent of that of the thermal gas).

However, a drawback of hadronic models, that was already discussed in the literature, is that the radial distribution of the synchrotron emission generated from secondary electrons is expected to be much steeper than observed in radio haloes, with most of the radio luminosity generated in the cluster-core region (e.g. Brunetti 2004). Fig. 4 shows a comparison of the simulated and observed radial profile of the radio emission from the Coma cluster. In line with previous simulations (Dolag & Enßlin 2000) and analytical expectations (e.g. Brunetti 2004), we obtained a radial profile that is far too steep assuming that CRp contain a constant fraction of the energy density of the thermal pool (Model 1). Flatter radial profiles of the radio emission, and thus fairly extended radio haloes, are generated only by Models 2 and 3, yet the expected radio brightness at 0.5–1 Mpc distance from the cluster centre is still \( >10 \) times fainter than that observed in the Coma halo. This picture also arises from the point-to-point scatter plot between radio surface brightness and the X-ray brightness from thermal emission (Fig. 5); the solid line is the observed correlation obtained by Govoni et al. (2001).

To reproduce the radial profile as measured at 1.4 GHz by Deiss et al. (1997) out to 0.5–1 Mpc distance, we allow the energy density of CRp to vary with distance from the cluster centre in Model 4. The resulting radial distribution of CRp energy relative to that of the thermal pool is shown in Fig. 3 and highlights an expected energetic problem of hadronic models: to considerably increase the synchrotron emissivity at large distance from cluster centre, where the generation of secondary particles is inefficient due to the small number density of (target) thermal protons, a secondary model requires the energy density of CRp to be extremely large, comparable with (or even larger than) the thermal pool. Considering the profile measured with high sensitivity by Westerbork observations at 330 MHz (green, dashed line in Fig. 4; Govoni et al. 2001) makes this point even more problematic.

As a matter of fact, the observed radial profile of the Coma halo drops smoothly by less than a factor of 10 at 0.3 \( r_{\text{vir}} \). We expect this also considering results from simulations that attempt to combine secondaries and shock-accelerated electrons, which does not help significantly, as can be seen by comparing the shape of the observed profile (Fig. 4) with those in Pfrommer et al. (2008) (their fig. 9).\(^1\)

4.2 The spectrum

The radio spectrum of the Coma halo shows a steepening at higher frequencies (Thierbach et al. 2003) that has been interpreted as a signature of stochastic re-acceleration of the emitting electrons (Schlickeiser, Sievers & Thiemann 1987; Brunetti et al. 2001). On the other hand, it has also been argued that the steepening is due to incorrect estimation of the flux of the radio halo at the highest frequencies due to the SZ decrement (e.g. Enßlin 2002). The latter results in a flux reduction of the cosmic microwave background photons in the cluster region by Compton scattering with the cluster-thermal electrons, which diminishes the radio flux at higher frequencies, although other authors conclude that this is not sufficient to explain the spectral steepening in the Coma halo (Reimer et al. 2004; Brunetti 2004).

Our numerical simulations can be used to investigate the SZ decrement on the synchrotron spectral properties. Fig. 6 shows the radio and inverse Compton spectrum from the SZ effect inside the cluster gas. The red line is the prediction of the total flux from our models, where the SZ signal is extracted from the region of the radio halo at 1.4 GHz, \( \approx 500 \) kpc in radius. The deviation from a pure power law at higher frequencies is due to the SZ flux decrement (the dotted line marks the corresponding power law with \( \nu^{-1.25} \)), while the flattening at lower frequencies is due to the energy-dependent cross-section of proton–proton collisions. We plot the absolute of the inverse Compton flux, although it corresponds to negative flux at frequencies smaller than \( \approx 2 \times 10^5 \) MHz. In black we show

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\(^1\) Also note that the upturn in the profile of fig. 9 in Pfrommer et al. (2008) is due to the presence of a very bright shock-like feature south-east of the centre of their simulated cluster (see their fig. 8) and is not indicative of an upturn in the distribution of the truly diffuse halo emission. On the other hand, our Fig. 4 refers to the observed brightness of the diffuse Coma halo emission, that is smooth and fairly symmetric.
Figure 2. Synthetic synchrotron maps of the simulated Coma cluster (4 Mpc a side) at 1.4 GHz. The four models displayed from left to right are constant CRp energy fraction (Model 1), scaled CRp energy fraction (Model 2), scaled magnetic field (Model 3) and fitted CRp energy fraction (Model 4). The overall normalization of the CRp energy fraction is chosen to match the observed total radio luminosity of Coma.

observations from Thierbach et al. (2003) and Battistelli et al. (2002) of the Coma cluster in the radio and microwave band, respectively. We also evaluate the fluxes integrated over the relevant sizes according to the individual observations (red symbols). The observed shape of the radio spectrum, with the steepening at $2 \times 10^3$ MHz, cannot be explained by our secondary models, even including the SZ decrement for these frequencies, although the simulated SZ signal almost perfectly fits observations in the microwave regime. The blue dashed line shows the inverse Compton decrement, assuming an isothermal beta model for the thermal gas of Coma with emission region of 5 Mpc radius [as done in Enßlin (2002)], which would be needed to cause the steepening at 5 GHz. This size is about one order of magnitude more extended than the radio emission. Additionally, we show in green the expected spectrum from stochastic electron acceleration (Schlickeiser et al. 1987).

5 γ-RAY SPECTRUM AND LIMITS
Maps of the predicted γ-ray emission from our simulated Coma cluster are shown in Fig. 7. In Fig. 8 we show the differential and integral γ-ray flux as a function of energy of the photons. Here,
Figure 3. This panel shows the energy density fraction of the CRp as function of radius for the different models as indicated in the plot. See text for more details.

Figure 4. We show the radial profile for the radio emission resulting from the different models compared with the observed profile. See text for more details.

We also included the observed limits from VERITAS and EGRET (Reimer et al. 2003; Perkins 2008) (see Table 1).

We find that the $\gamma$-ray emission produced in the case of Model 4, that allows a reasonable match at least with the Deiss et al. profile of the Coma halo (for $<0.7–1$ Mpc distance from cluster centre), is a factor of $\sim 6$ below present upper limits. As well, matching the radial profile of the Coma halo as measured by high-sensitivity observations at 330 MHz would require an even larger energy budget of CRp with respect to that in Model 4 and, consequently, a larger $\gamma$-ray emission. Thus, as soon as future $\gamma$-ray observations will reach sensitivities slightly deeper than present upper limits, they will allow complementary tests to the hadronic origin of the radio-emitting electrons in the Coma cluster. For instance, the expected sensitivity of the FERMI Gamma Ray Telescope will be sufficient to constrain Model 4 after 1-yr observations.

An alternative possibility is that particle acceleration in the Coma cluster is due to MHD turbulence in the ICM, remarkably the steepening of the synchrotron spectrum in Fig. 6 is in line with the expectations from this scenario (e.g. Schlickeiser et al. 1987; Brunetti et al. 2001). A possibility is that relativistic protons and their secondary products are accelerated by MHD turbulence (Brunetti & Blasi 2005), in which case $\gamma$-ray emission from neutral-pion decay is still expected but the ratio between $\gamma$-rays and synchrotron emission is substantially smaller than in the standard secondary-model case (Brunetti et al. 2009). Following Reimer et al. (2004), we adopt a simple approach to obtain an upper limit to the expected $\gamma$-ray emission from the Coma cluster: we limit the synchrotron emission produced through a standard secondary electron model to that measured at high frequencies, 4.85 GHz, and assume that the emission at lower frequencies is amplified by the effect of turbulent acceleration. Results are given in Table 1 that reports the upper $\gamma$-ray fluxes obtained in such scenario, that are about a factor of 4 below those expected in the case of the hadronic model.

6 CONCLUSIONS

The hadronic model for the origin of radio haloes is based on the rate of secondary products generated through collisions between high-energy CRp and thermal protons in the ICM, and present numerical simulations provide a way to compare model predictions with observations. Based on a constrained, cosmological MHD simulation of the local universe we investigated the predicted properties of the radio halo of the Coma cluster within the framework of the hadronic model. We follow four approaches, chosen to span the reasonable range suggested by theoretical and observational findings, and...
focusing on the case of high magnetic field values that represent the most favourable way for hadronic models.

Our main conclusions are as follows.

(i) In agreement with previous findings, hadronic models may produce the synchrotron radio luminosity of the Coma halo with energy densities of CRp between 1 and 10 per cent of the thermal ICM. However, the radial brightness profile of the generated synchrotron emission is much steeper than that seen in the observations of the Coma halo; consequently, the simulated radio haloes come out much smaller than the observed one. This also leads to a slope in the thermal X-ray versus radio brightness point-to-point correlation that is significantly steeper than the observed one.

(ii) The observed flat radial brightness profile and the fairly large extent of the observed radio halo can only be obtained with hadronic models by strongly increasing the CRp-energy density outside the core of the cluster. In this case, however, the resulting CRp-energy density at $\approx 1$ Mpc (e.g. the rim of the observed radio halo) would equal (or exceed) that of the thermal ICM.

(iii) Our simulated Coma cluster matches almost perfectly the observed SZ decrement. But this SZ decrement is still not enough to explain the spectral steepening observed in the spectrum of the
radio halo at large frequencies, contrary to the previous claims in the literature.

In summary, we find that a purely hadronic model is disfavoured by current observations of the Coma cluster. In principle, the energy problem might be alleviated if the magnetic field strength was almost constant with cluster radius up to the rim of the observed radio halo (see Pfrommer & Enßlin 2004), however such models are not among the best-fitting ones inferred from present radio measurement observations.

At the same time, we have shown that hadronic models cannot explain the spectral steepening of the Coma radio halo; regardless of the model assumptions, an SZ effect matching observations produce a negligible SZ decrement at 2.7 and 5 GHz in the region of the halo.

The $\gamma$-ray flux generated by the hadron interaction in case of Model 4, which alone roughly matches the radial profile of the halo, at least that measured at 1.4 GHz, is only a factor of ~6 below the current limits; thus incoming $\gamma$-ray observations will shortly provide additional constraints to the models.

Given the difficulties encompassed by the hadronic scenario to reproduce present observations of the Coma halo, we conclude that most of the radio emission we observe should originate from relativistic electrons accelerated by other mechanisms. One possibility is that electrons are re-accelerated in situ by MHD turbulence within the ICM. It is well known that this scenario provides a unique way to explain the steepening of the radio spectrum of the halo at higher frequencies (Fig. 6), yet in this case predictions of the $\gamma$-ray flux from the Coma cluster are more difficult (Brunetti et al. 2009). The presence of the spectral steepening at high frequency limits the contribution from secondary electrons that should produce a flatter spectral shape. Thus, following Reimer et al. (2004), an upper limit to the $\gamma$-ray emission expected from the Coma cluster may be estimated by requiring that the emission from secondaries does not outweigh the flux measured at 4.85 GHz. Such constrain leads to upper limits to the expected $\gamma$-rays about four times below the expectations in the case of pure hadronic models.

As a final comment, we also stress that the energy requirements of CRp derived for hadronic models and the predicted $\gamma$-ray emission depend on the value of the magnetic field in the Coma cluster. As already stressed, we assume relatively large values of $B$ in the ICM, yet both the energy density of CRp and the $\gamma$-ray emission depend on $\langle B^2 + B_{\text{cmb}}^2 \rangle / R_{1+w}$, (1)

where $\langle \cdot \rangle$ indicates averaged quantities (weighted for $X_{\gamma}\rho^2$) in the synchrotron-emitting volume. Consequently, if the magnetic field outside the cluster core of the Coma cluster (where $B^2 < B_{\text{cmb}}^2$; Fig. 1) is ~50 per cent smaller than that assumed, the CRp-energy density and the expected $\gamma$-ray emission would result about 1.5–2 times larger.

This, combined with the fact that larger $\gamma$-ray fluxes are expected if the profile of the Coma halo at 330 MHz is adopted, implies that a non-detection of the Coma cluster with FERMI after 1 year of observations would further strengthen our conclusions that disfavour purely hadronic models for the origin of the radio halo.

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