*Cosmic Magnetic Fields:*
*From Planets, to Stars and Galaxies*
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# Magnetic fields and cosmic rays in galaxy clusters and large scale structures

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**Abstract.** In galaxy clusters, non-thermal components such as magnetic field and high energy particles keep a record of the processes acting since early times till now. These components play key roles by controlling transport processes inside the cluster atmosphere and beyond and therefore have to be understood in detail by means of numerical simulations. The complexity of the intra cluster medium revealed by multi-frequency observations demonstrates that a variety of physical processes are in action and must be included properly to produce accurate and realistic models. Confronting the predictions of numerical simulations with observations allows us to validate different scenarios about origin and evolution of large scale magnetic fields and to investigate their role in transport and acceleration processes of cosmic rays.

**Keywords.** Magnetic fields – cosmology – cosmic microwave background – large-scale structure of universe

## 1. Introduction

Magnetic fields have been detected in galaxy clusters by radio observations, via the Faraday rotation signal of the magnetized cluster atmosphere towards polarized radio sources in or behind clusters (see Carilli & Taylor 2002 for a recent review) and from diffuse synchrotron emission of the cluster atmosphere (see Govoni & Feretti 2004; Ferrari *et al.* 2008, for recent reviews). However, our understanding of their origin is still very limited. Furthermore most questions about their evolution and structures are still unanswered. Recent developments in interpretation of rotation measures help to understand the properties of magnetic fields in galaxy clusters but simulations are needed to overcome degeneracies in the model parameters needed to interpret the observations. Furthermore, the origin and the evolution of the population of cosmic rays within galaxy clusters are tightly connected to the dynamics of the system and to the evolution of the magnetic field. Therefore, cosmological MHD simulations are a valuable tool to investigate and distinguish different scenarios. See Dolag *et al.* (2008) for a recent review.

## 2. Observations

For a small sample of galaxy clusters, Faraday rotation can be observed towards several radio galaxies located at different radial distances with respect to the cluster center or along very elongated sources located at the center of galaxy clusters. Such examples can be used to infer the magnetic field structure over a range of length scales. Figure 1 is showing various examples of observations of rotation measure towards elongated radio sources within galaxy clusters, covering scales ranging from kpc to Mpc. Motivated by numerical simulations (Dolag *et al.* 2001), the observed magnetic field is often modeled with a radially-declining field strength and a power law spectral structure. From such interpretation of the observations, one can constrain the power law spectral index (Murgia

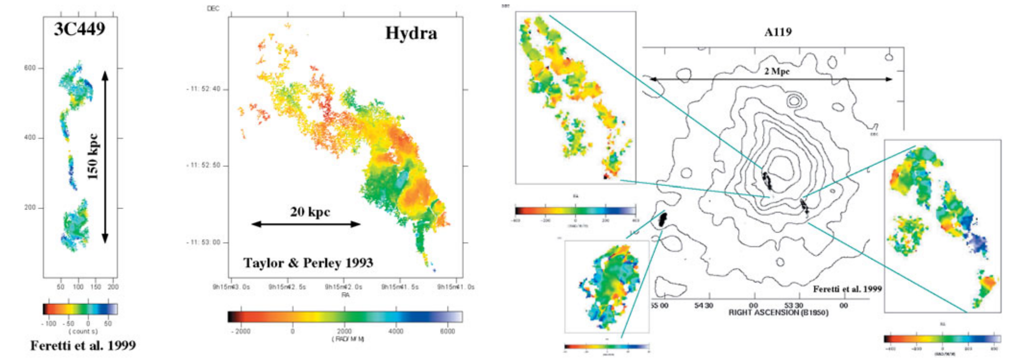


**Figure 1.** Various rotation measure maps. Left panel shows the central source in 3C449 (Feretti *et al.* 1995). Middle panel shows the central source in the strong cooling core of the Hydra cluster (Taylor & Perley 1993). Right panel shows 3 elongated radio sources within the galaxy cluster A119 (Feretti *et al.* 1999).

*et al.* 2004; Govoni *et al.* 2006) or directly reconstruct the power spectrum of the magnetic field (Vogt & Ensslin 2003, 2005). Given the sparse observational data available at the moment, a degeneracy exists between various parameters describing the assumed magnetic field model. Specially between the central value of the magnetic field and its rate of radial decline (see for example Guidetti *et al.* 2008, Bonafede *et al.* 2008). Therefore detailed predictions from simulations can be very useful to break these degeneracies. Simulations must therefore examine different possible magnetic field origins in galaxy clusters in order to test the robustness of such inferred magnetic field properties.

## 3. Simulations

In previous work, non radiative simulations of galaxy clusters within a cosmological environment following the evolution of a primordial magnetic seed field were performed using Smooth-Particle-Hydrodynamics (SPH) codes (Dolag *et al.* 1999, 2002, 2005) as well as Adaptive Mesh Refinement (AMR) codes (Brueggen *et al.* 2005; Dubois & Teyssier 2008; Li *et al.* 2008). Although these simulations are based on different numerical techniques they show good agreement in the predicted properties of the magnetic fields in galaxy clusters, when the evolution of an initial magnetic seed field is followed. This work has also demonstrated, that the properties of the final magnetic field in galaxy clusters do not depend on the detailed structure of the assumed initial magnetic field. The spatial distribution and the structure of the predicted magnetic field in galaxy clusters is primarily determined by the dynamics of the velocity field imprinted by cluster formation (Dolag *et al.* 1999, 2002) and compares well with measurements of Faraday rotation.

Figure 2 shows a zoom-in from the full cosmological box down to the cluster. The structures in the outer parts get less pronounced due to the decrease in resolution, which is designed to capture only the very largest scales of the simulation volume. Each panel shows (in clockwise order) a zoom-in by a factor of ten. Finally the elongated box in the lower left panel marks the size of the observational frame shown on the left. For comparison we produced a synthetic Faraday Rotation map from the simulation and clipped it to the shape of the actual observations to give an indication of the structures resolved by such simulations. The simulation follows the evolution of a primordial magnetic seed field and the dynamical range spans over more than five orders of magnitude in spatial dimension. The gravitational force resolution of this MHD-SPH simulation is $\approx$ 3kpc and

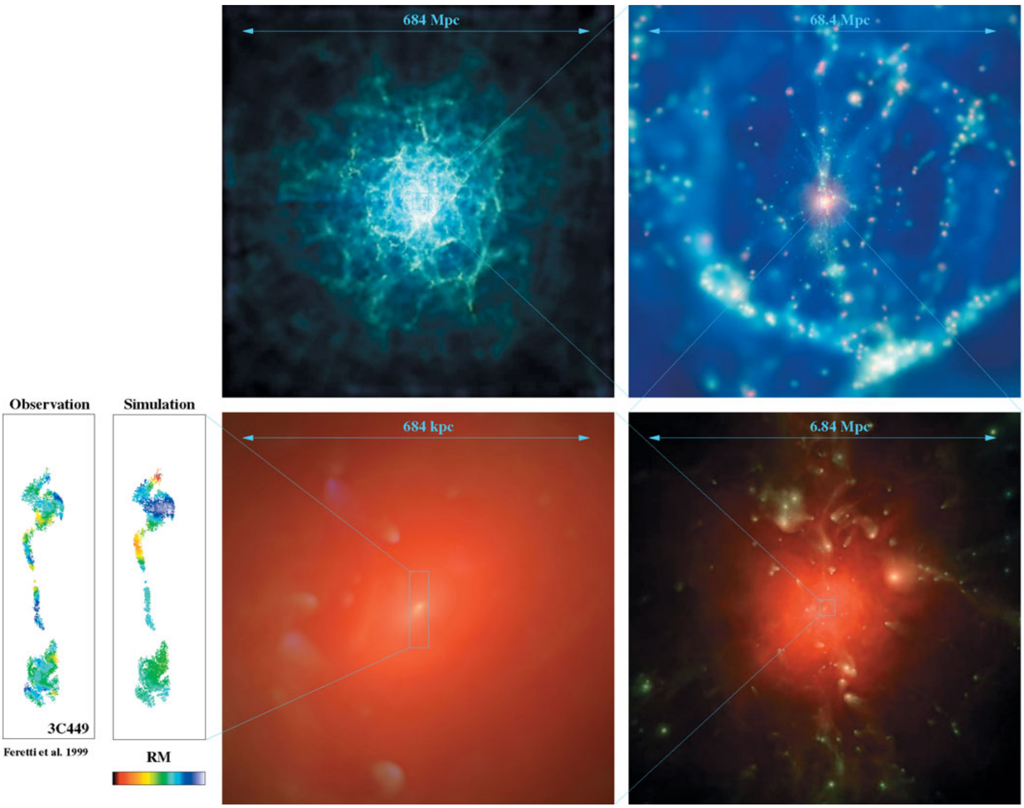


**Figure 2.** Zoom into the cluster simulated within the cosmological box. Clockwise, each panel displays a factor 10 increase in imaging magnification, starting from the full box (684 Mpc) down to the cluster center (680 kpc). On the very large scale, the density of the dark matter particles are shown, whereas in the high resolution region the temperature of the gas is rendered to emphasize the presence and dynamics of the substructure. The last zoom extracts a region of the same size of an observed radio jet 3C449 (Feretti *et al.* 1999) with infered rotation measure. Taken from Dolag & Stasyszyn (2008).

the galaxy cluster at redshift zero is resolved by several millions of particles within the virial radius.

Recently Donnert *et al.* 2008 performed cosmological, magneto-hydrodynamical simulations to follow the evolution of magnetic seed fields originating from galactic outflows during the star-burst phase, further processed by structure formation. Several simulations where performed, exploring the effect of various parameters of the adapted, semi-analytic model, relevant for the strength of the magnetic seed field from the galactic outflows. Also two control runs where performed, exploring the effect of the detailed magnetic field configuration assumed within the galactic outflows as well as on details of the seeding and galaxy identification strategy. It was found that the strength and structure of magnetic fields observed in galaxy clusters are well reproduced for a wide range of model parameters for the magnetized, galactic winds and do only weakly depend on the exact magnetic structure within the assumed galactic outflows. Figure 3 shows the final magnetic field for various models of the galactic outflows and a reference simulation following the evolution of a primordial magnetic field. Although the evolution of a galactic wind originating magnetic seed fields within the galaxy clusters shows no significant differences to that obtained by previous studies, it is clear to see that the magnetic field pollution

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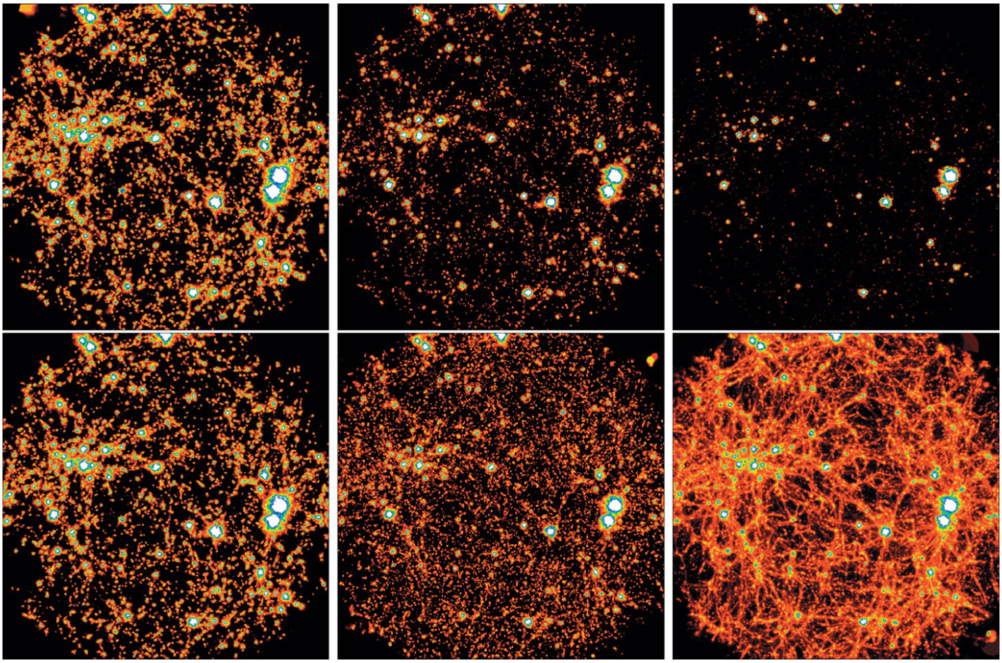

**Figure 3.** Visualization of the magnetic field strength in the simulation box at redshift $z = 0$. Every image shows a region of 204 Mpc, using the same arbitrary color bar. Shown are the results of the *Dipole* (top left), *0.1 Dipole* (top middle), *0.01 Dipole* (top right), *Quadrupole* (bottom left), *Multi Seed* (bottom middle), and the *Control* simulation (bottom right), respectively. See Donnert *et al.* (2008) for more details.

in the diffuse medium within filaments varies strongly between the models and in general is below the level predicted by scenarios with pure primordial magnetic seed field. Figure 4 shows a comparison of the predicted rotation measure signal of galaxy clusters for two different simulations, following magnetic seed fields from galactic outflows and from primordial origin, respectively.

## 4. Magnetic Field Structure

The complexity of the atmosphere of galaxy clusters reflects their hierarchical buildup within the large scale structure. The infall of thousands of objects with various sizes and their subsequent disruption within the cluster potential is being the source of shocks and turbulence, steering up the intra cluster medium. All these processes directly act on the magnetic field causing its re-distribution and amplification. Therefore all cosmological MHD simulations predict that the final structure of the magnetic field in galaxy clusters reflects these process of structure formation, and no measurable memory on the initial magnetic field configuration survives within galaxy clusters. In general, such models predict a magnetic field profile similar to the density profile. Thereby the predicted rotation measure profile agrees well with the observed one (see Fig. 4). Early findings of the shape of the magnetic field profiles based on MHD-SPH simulations (Dolag *et al.* 2001,2002,2005) are in good agreement with more recent simulations using different numerical methods – as Adaptive Mesh Refinement (AMR) codes – (Brueggen *et al.* 2005; Dubois & Teyssier 2008; Li *et al.* 2008).

Such numerical experiments predict a slope of the magnetic field power spectra similar to what would be expected for a Kolmogorov spectra (Dolag *et al.* 2002, Brueggen *et al.*

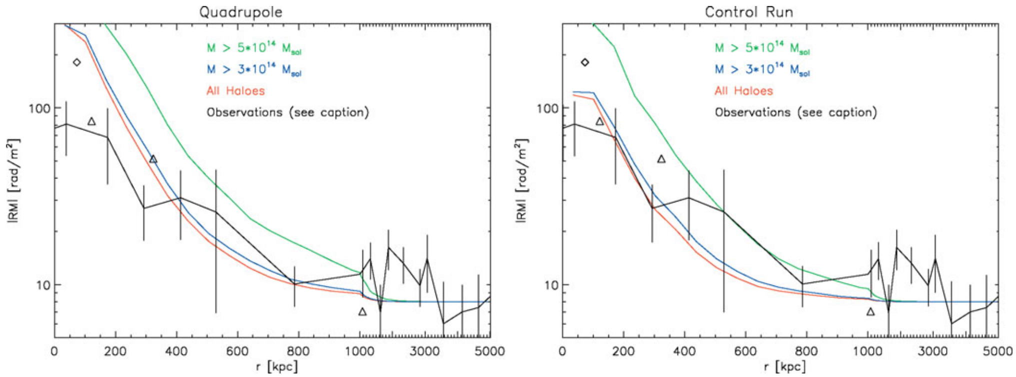


**Figure 4.** Rotation Measure as function of distance to the cluster center averaged over a sample of simulated clusters compared with observations. Solid line is drawn from combining three observational samples based on Abell clusters (Kim *et al.* 1991; Clarke *et al.* 2001; Johnston-Hollitt & Ekers 2004). We also included in the plot the values inferred from three elongated sources (triangles) observed in the single galaxy cluster A119 (Feretti *et al.* 1999) and one elongated source within the Coma cluster (diamond) (Feretti *et al.* 1995). Left panel is for a run which follows galactic outflows, right panel for one which follows a primordial magnetic seed field. See Donnert *et al.* (2008) for more details.

2005). In general this is in line with observations (Vogt & Ensslin 2003, 2005), however there are indications that the magnetic field spectra in observations might be more complex and on average has a slightly different slope in different galaxy clusters. There are even indications that the power spectra within individual galaxy clusters is either not a strict power law or the power law index varies with position (Murgia *et al.* 2004; Govoni *et al.* 2006).

The left part of Fig. 5 shows the magnetic field power spectrum obtained from a high resolution galaxy cluster simulation. As these simulations – due to the adaptive nature of the method used – resolve much smaller scales in the central region than in the outer parts, the power spectra is constructed from the measurement within a consecutive sequence of boxes with increasing resolution and decreasing size, centered on the center of the galaxy cluster. For guidance, the dotted straight line marks the expectations from a Kolmogorov like power spectra. In general the slope of the power spectra in the region of interest (e.g. tens of kpc) is predicted to be close to Kolmogorov like slope but with some indications of a curved shape, reflecting the complex dynamics acting during structure formation.

The right part of Fig. 5 shows the evolution of various quantities for a galaxy cluster, starting from early times on. For example, the middle panel shows the evolution of the virial mass and the mean, mass weighted temperature. The sudden increase of mass at a age of the universe of 5 respectively 11 G Years mark the two mayor merging events the cluster undergoes in its evolution. This is also reflected in the increase in temperature which happens delayed by $\approx 0.5 - 1$ G Year, which correspond to the time delay between start of the merger event and the core passage. The lower panel shows the fraction of the cluster material which undergoes shocks as measured by the build in shock detection scheme (Pfrommer *et al.* 2006). Interestingly, in general the cluster is just more and more relaxing, as indicated by the overall decrease of the amount of shocked gas in the cluster, independent of the major merging events (black line). However, if one looks at the fraction of high Mach number shocks inside the cluster, a clear excess, driven by the merger events is visible which are mainly initiated short after core passage (green line).

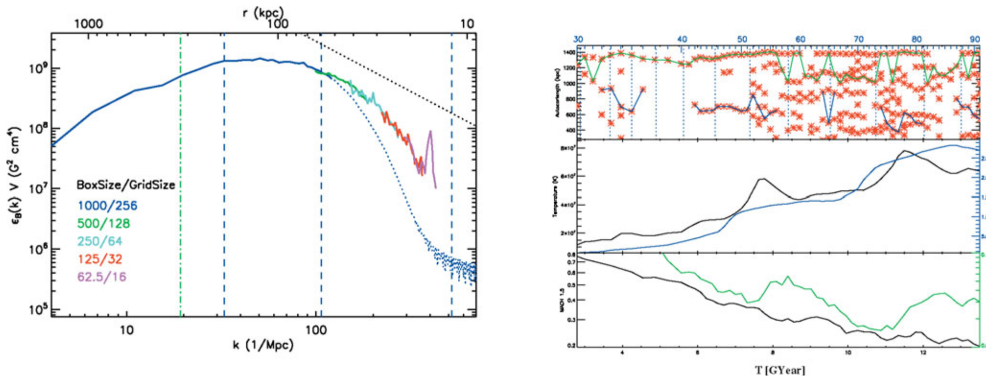


**Figure 5.** Left panel shows the magnetic field power spectrum from a simulated galaxy cluster. To scope with the adaptive resolution of the simulation the spectrum is constructed from calculating the power spectra within a series of boxes centered on the cluster with decreasing size and increasing resolution. The straight, dotted line marks the slope expected from Kolmogorov spectrum. The right panel shows the evolution of a galaxy cluster undergoing two major merging events. Here, every point in the upper panel marks the corresponding length scale of a extrema detected within the computed autocorrelation function at each time-step. The middle panel shows the evolution of the cluster mass and the averaged (mass weighted) cluster temperature. The lower panel shows the evolution of shocks with different Mach numbers within the cluster atmosphere. For more details see Pakmor & Dolag 2009.

It is interesting to know that it takes a relatively long time (e.g. more than 2 GYears) until this excess is completely gone. This has strong implications on the magnetic field structure, as can be seen in the upper panel. Here every dot correspond to the associated length scale of an extrema in the auto-correlation function of the magnetic field. So each point marks a length scale of individual structures present within the magnetic field. Clear to see that the first major merging event initiates a whole bunch of structures in the magnetic field, which – given by the low numerical dissipation of the SPH MHD code – does not vanish until the next major merger happens. By investigating a whole set of simulated galaxy clusters we find that only within a small number of clusters the magnetic field can relax to a more ordered configuration between merger events, which otherwise always initiate new structures within the magnetic field. For more details see Pakmor & Dolag 2009.

## 5. Radio Emission

The diffuse radio emission within galaxy clusters is produced by synchrotron radiation of relativistic electrons with the cluster magnetic fields. Such diffuse emission – often refered to as giant radio haloes – is detected over regions spanning Mpc in size. For recent reviews see Govoni & Feretti 2004 and Ferrari *et al.* 2008. One basic problem in explaining this phenomena is that the cooling time of such relativistic electrons is much shorter than their diffusion time over the region of interest. Therefore they basically have to be produced locally within the whole radio emitting region. One, often discussed mechanism to produce such relativistic electrons is the so called secondary model, where the relativistic electrons are a product by scattering of cosmic ray protons with thermal protons. Cosmic ray protons can for example be produced within accretion shocks and then advected into the cluster, or directly produced within merger shocks. Due to their larger mass compared to the cosmic ray electrons they can diffuse throughout the radio emitting region within the galaxy cluster without undergoing significant energy losses.

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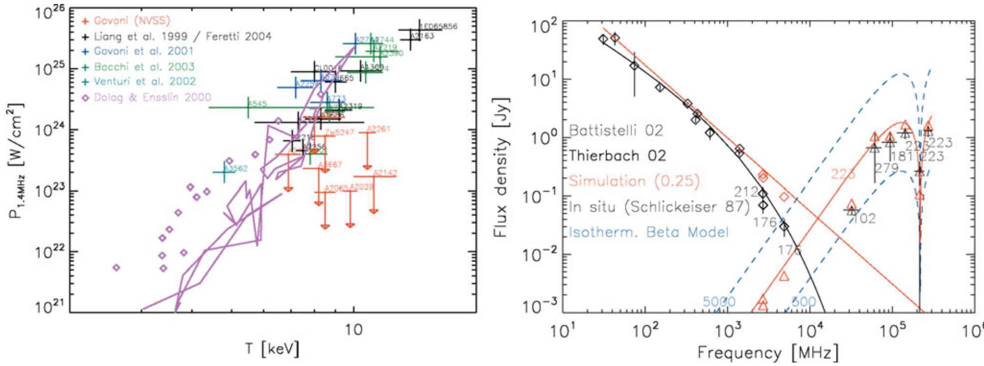


**Figure 6.** The left panels shows the total power of radio halos observed at 1.4 MHz vs. cluster temperature. We plot the data and upper limits from literature as indicated. For the simulations we plotted the predictions based on a secondary model (Dolag & Ensslin 2001) for individual clusters at redshift zero (diamonds) as well as the evolutionary track of an individual clusters undergoing two major merging events (solid line). The right panel shows the spectrum of a simulated Coma cluster compared to observations. The declining solid line marks the radio flux expected from a secondary model. The rising line marks the predicted (negative) flux from the SZ effect of the cluster atmosphere. The diamonds and triangles are the expected total flux from the clusters, evaluated over the size of the individual observations at the different frequencies. See Pakmor & Dolag 2009 and Donnert *et al.* 2009 for more details.

The left panel of figure 6 shows a comparison of observed radio luminosity of clusters as function of the mean cluster temperature (data points with error bars) with the predicted relations from a set of simulations (diamonds) assuming a simple, secondary models where the local energy density of cosmic ray protons is a fixed fraction of the thermal energy (see Dolag & Ensslin 2001). Although the scaling between radio luminosity and temperature of the simulated clusters agree well with the observed ones, there are no indications that simulations would be able to produce the class of galaxy clusters, for which no radio emission is observed. In fact, the scatter in the predicted scaling relation is very small, as also found in previous studies (Dolag & Ensslin 2001, Miniatti *et al.* 2001, Pfrommer *et al.* 2007). Additional we show a evolutionary track of the galaxy cluster which is undergoing two major merger events (see also right panel of Fig. 5). Clear to see that the merger events lead to very elongated loops along the scaling relation which can not bridge the gap between the clusters with and without observed radio emission. It is not unexpected that the amplification of the magnetic field during the merging event can not be accounted for the presence/non presence of radio emission as also the temperature gets boosted during the merger event and therefore the cluster evolves nearly along the observed correlation.

The right panel of Fig. 6 shows the expected radio spectrum for a simulated Coma cluster from a secondary model. The observed spectrum (diamonds with error bars) show a power law like behavior with a steepening above $\approx$ 1GHz. At higher frequencies we also plotted the observed (negative) flux caused by the Sunyaev Zeldovich (SZ) effect (triangles with error bars), which, if strong enough, could lead to such a spectral signature (dotted line). The solid red lines show the prediction of the radio emission from the secondary model and the expected (negative) SZ flux at higher frequencies for a simulated Coma cluster. The diamonds and the triangles are the expected, total flux convolved with the observed area for each frequency. Clear to see that the predicted (negative) SZ flux gives a perfect match to the observational data points for the SZ measurements, but the influence on the spectra of the radio observations is negligible and therefore can not

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explain the spectral steepening observed. Additionally we plot the spectrum predicted from a so-called reacceleration model (Schlickeiser *et al.* 1987) as a black, curved line. In these models CR electrons are accelerated via resonant coupling to merger induced MHD turbulence. This mechanism modifies the CR electron spectrum by moving parts of the trans-relativistic population to energies which contribute to the observed synchrotron emission. This model is able to fit the observed cut-off remarkable well.

## 6. Conclusions

The increasing amount of available radio data – both, for rotation measures as well as for diffuse radio emission – are driving our understanding of magnetic fields and cosmic rays in galaxy clusters. The improvements in the interpretations of these data over the last years are revealing a quite complex structure of the magnetic fields within galaxy clusters. Also the improvements in the numerical methods are producing more robust predictions for the magnetic field in galaxy clusters, which are helping to interpret the observations. Therefore, in the last years, a consistent picture of the magnetic fields in clusters of galaxies has been emerged from both, numerical work and observations.

Simulations of individual processes like shear flows, shock/bubble interactions or turbulence/merging events predict consistently a super-adiabatic amplification of magnetic fields within such processes. This now has been largely confirmed through direct cluster simulations within a cosmological context. It is worth mentioning that this common result is obtained by using a variety of different codes, which are based on different numerical schemes. Within this context, various observational aspects are reproduced. Moreover, the overall amount of amplification of the magnetic field driven by the structure formation process lead to a final magnetic field strength at a level, sufficient to link models that predict magnetic field seed by various different processes with the magnetic fields observed in galaxy clusters. In fact, the imprint of structure formation onto the magnetic field within galaxy clusters is such strong, that no measurable properties of the initial magnetic seed fields remain inside galaxy clusters. Therefore the only place we can hope to still find signs of the original process of magnetization are mildly non linear regimes of structure formation like filaments (Dolag *et al.* 2001, 2005; Donnert *et al.* 2008). The detailed structures of the magnetic field within individual clusters are driven by the actual merger history, where major merger events initiate significant structures within the magnetic field which are – in absence of any dissipation – only slowly relaxed. The induced magnetic field power spectra appears to be not a strict power law, however, when approximated locally as a power law, the slope is close to the expectations from a Kolmogorov like spectra (see Dolag *et al.* 2001, Brueggen *et al.* 2005, Pakmor & Dolag 2009).

Such models of magnetic field in galaxy clusters allow also to constrain the origin of cosmic rays within galaxy clusters when confronted with observations of the diffuse radio emission. Although so called secondary models are able to produce sufficient radio emission, a detailed comparison shows that they fail to produce some key observational aspects. Most striking they overproduce the number of galaxy clusters which are expected to show radio emission as well as the fail to produce the observed spectral shape for the diffuse radio emission (see Dolag & Ensslin 2001, Donnert *et al.* 2009). All this demonstrate the power of such cosmological MHD simulations to learn more about non thermal components like magnetic fields and cosmic rays within galaxy clusters and the large scale structure.

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## Discussion

GAENSLER: What can your models predict about diffuse radio emission *between* clusters of galaxies?

DOLAG: In these models such diffuse emission is extremely small. Such emission is thought to be produced by shocks and directly involve phenomena which are (yet) not included in the presented simulations.

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de Gouveia dal Pino: I missed a point regarding the cosmic-ray (CR) flux injection hypothesis. Could you clarify this point? Also, it seems you have a nice tool to explore cosmic-ray propagation and more important ultra-high energy CR propagation.

Dolag: We assumed a simple model in which we inject CR protons as fixed fraction of thermal energy. Using results from direct simulations (which, at the moment, come with different predictions by different groups working on this) do not significantly change the main conclusions.

Kronberg: In your models can you identify a "cluster-pause" – i.e., the cluster equivalent of the solar/ISM magnetopause, and the galaxy's interface "galactopause" to the ISM?

Dolag: No.

Klaus Dolag

On the boat trip

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