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MAGNETIC TURBULENCE IN CLUSTERS OF GALAXIES

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RESUMEN

Los cúmulos de galaxias son grandes laboratorios de turbulencia en plasmas que nos permiten confrontar conceptos teóricos del origen del campo magnético con observaciones detalladas. La turbulencia magnética en éstos cúmulos puede ser estudiada a través de la emisión radio-sincrotrón del medio intra-cúmulo en forma de rélicas y halos de los cúmulos. El espectro de potencias de los campos magnéticos turbulentos se puede estudiar a través del análisis de la rotación de Faraday de las fuentes de radio extendidas. En el caso del núcleo frío Hydra A, el espectro magnético observado se puede entender en términos de una retroalimentación, mediada por la turbulencia, entre el enfriamiento del gas y la actividad del chorro de la galaxia central. Finalmente se discuten métodos para medir estadísticas de órdenes superiores del campo magnético usando correlaciones de parámetros de Stokes, los cuales nos permiten determinar el espectro de potencias de la fuerza de tensión magnética. Dicha cantidad estadística de cuarto orden ofrece una forma para discriminar diferentes escenarios de turbulencia magnética, y diferentes estructuras del campo magnético mediante observaciones polarimétricas en radio.

ABSTRACT

Galaxy clusters are large laboratories for magnetic plasma turbulence which permit us to confront our theoretical concepts of magnetogenesis with detailed observations. Magnetic turbulence in clusters can be studied via the radio-synchrotron emission from the intra-cluster medium in the form of cluster radio relics and halos. The power spectrum of turbulent magnetic fields can be examined via Faraday rotation analysis of extended radio sources. In case of the Hydra A cool core, the observed magnetic spectrum can be understood in terms of a turbulence-mediated feedback loop between gas cooling and the jet activity of the central galaxy. Finally, methods to measure higher-order statistics of the magnetic field using Stokes-parameter correlations are discussed, which permit us to determine the power spectrum of the magnetic tension force. This fourth-order statistical quantity offers a way to discriminate between different magnetic turbulence scenarios and different field structures using radio polarimetric observations.

Key Words: galaxies: clusters: general — magnetic fields — turbulence

1. INTRODUCTION

Clusters of galaxies are the largest known magnetized objects in the Universe. They are excellent laboratories to study the interaction and symbiosis of turbulent fluid motions and magnetic fields. Magnetic fields in clusters can be observed via the radio synchrotron emission of relativistic electron populations, which can be found predominately in merging clusters. Radio polarimetry opens the possibility to study the magnetic field properties in great detail, since the emission's intrinsic polarisation contains information of the magnetic field orientation in the plane of the sky, and the Faraday rotation imprinted by the magnetized plasma of the intra-cluster medium (ICM) reveals the magnetic field component along the line of sight. Unfortunately, no full 3-D observable of magnetic fields is available today.

The question of how the theoretical concepts of ICM magnetogenesis and the observational data can be compared arises. In most cases this has to happen in data space, since the observational process erases much of the information of the magnetic fields, whereas synthetic observations of simulated fields should always be possible. In a few cases the comparison can be done directly in theory space, in terms of magnetic properties, like the power spectrum. Usually, observations of spatially extended emission regions in conjunction with more or less plausible assumptions to fill in missing information are necessary for this to be possible. Since such observational results rely and depend on the assumptions made (sta-

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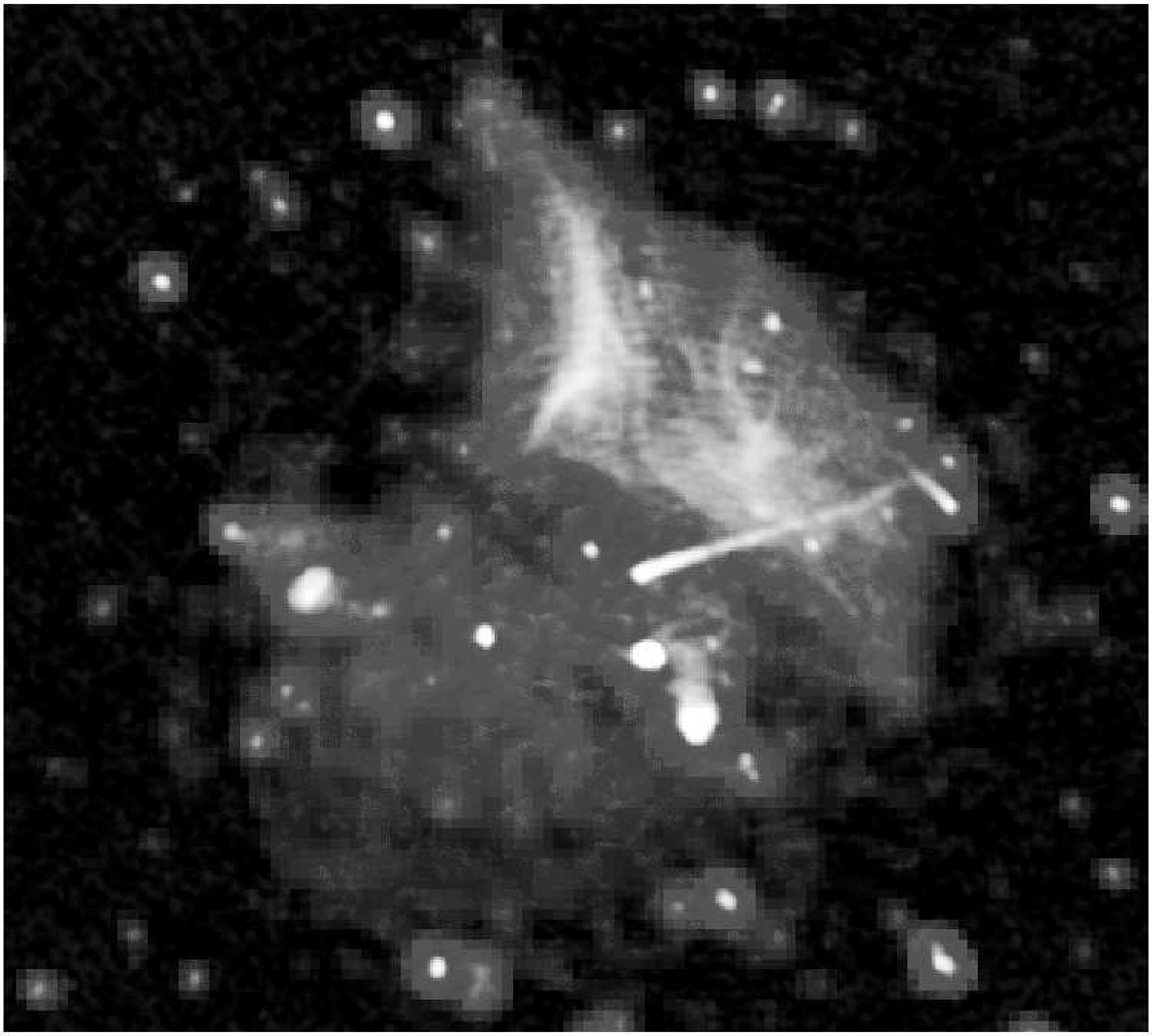

Fig. 1. Diffuse radio emission of Abell 2256. A Mpc-sized radio relic marks the probable location of a cluster merger shock wave (top-right structure), and a radio halo indicates the existence of turbulent magnetic fields in the cluster center (roundish central object). From Clarke & Enßlin (2006).

tistical isotropy, spherical symmetry of ICM density, etc.), any physical interpretation has to be aware of this.

The next question is in which theoretical framework the observational data should be interpreted. Here, a simplistic scenario for magnetogenesis is adapted and applied to observations. Namely, it is assumed that the observed magnetic fields are generated and maintained by a small-scale dynamo. It is driven by the turbulence, which, initially hydrodynamic, becomes magnetohydrodynamic when the small-scale dynamo saturates. In this picture, the magnetic fields strength and length-scale are usually related to the level of kinetic energy and turbulence injection scale, respectively. In the description of Subramanian, Shukurov, & Haugen (2006) of the saturated state of such a dynamo, the magnetic energy density and length scales are both smaller than their hydrodynamical counterparts, by some factors related to the critical magnetic Reynolds number for small-scale dynamo. Note that the alternative picture for the saturation of the small-scale dynamo developed by Schekochihin et al. (2004) on the basis of their MHD numerical simulations envisions comparable magnetic and kinetic energies and magnetic fields organized in long folded sheets with field reversal scale determined by the dissipation physics (the true magnetic Reynolds number). However, since the MHD description fails at small scales in weakly collisional cluster plasmas, one has to invoke some yet poorly understood plasma micro-physics mechanisms to determine the effective magnetic Reynolds number for the field reversals (Schekochihin & Cowley 2006). Here we do not discuss in detail these various scenarios and the uncertainties associated with them, but instead adopt the view that the magnetic turbulence in clusters can be parametrized by some effective magnetic Reynolds number of order $\sim 10^2$ (see further details in Enßlin et al. 2006). The bottom line of this talk is that this simplistic picture seems to be in good agreement with the observations so far. Novel methods to extract more information on fields from observations, in order to test this and other pictures further, are currently under development are are presented at the end.

2. CLUSTER RADIO HALOS AND RELICS

Many merging clusters of galaxies exhibit Mpc-sized synchrotron radio emission regions. These can be classified into two categories:

– Cluster radio halos are cluster wide, unpolarized emission regions. Their morphology strongly resembles the X-ray emitting gas morphology of clusters, indicating that they are volume-probes of magnetic fields and relativistic electrons. The origin of the electrons is unclear, they could be either maintained by Fermi-II re-acceleration (Giovannini et al. 1993; Brunetti et al. 2001), or freshly injected by hadronic interactions of a long-lived relativistic proton population (Dennison 1980).

– Cluster radio relics are typically peripheral, polarized emission regions, which sometimes exhibit filamentary structures. At least the Mpc-sized relics are probalbly due to Fermi-I acceleration of electrons at accretion or merger shock waves (Enßlin et al. 1998; Giacintucci et al. 2008). Since the electrons cool rapidly within only 10^8 years, they illuminate the magnetic fields only in sheet-like sub-volumes of the clusters.

An example of a cluster showing both phenomena, relics and halos, is given in Figure 1. There, Mpc-sized, filamentary magnetic structures can be seen within the relic region, very similar to the sheet like structures seen in slices through magnetic turbulence simulations in Schekochihin et al. (2004), see also Figure 3.

It is quite obvious why only merging cluster exhibit radio relics, since strong shock waves can only be found there. The rareness of radio halos lies certainly partly in the fact, that only clusters with well developed turbulence may be able to maintain sufficiently strong magnetic fields by a small scale dynamo.

In any case, cluster wide radio emission regions like halos and relics permit us to probe magnetic fields on the largest scales accessible so far. Halos are best suited to provide us with a global view on the field distribution in a galaxy cluster, whereas relics highlight small-scale details and the geometry of individual flux bundles.

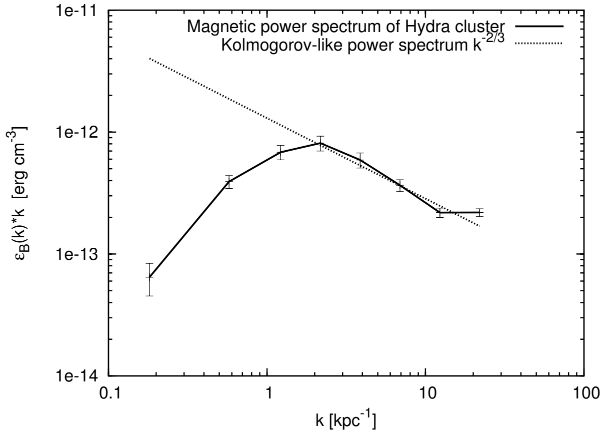

Fig. 2. The magnetic power spectra of the cool core of the Hydra cluster Vogt & Enßlin (2005).

3. MAGNETIC TURBULENCE IN COOL CORES

Relaxed clusters also exhibit magnetic fields, where the strongest fields are actually found in the most relaxed clusters which developed a cool core structure. Cluster cool cores are central regions of clusters in which a cooling instability of the gas has developed. The strong energy losses due to X-ray emission of the dense central gas are partly compensated by an efficient energy feedback process. It is believed that gas condensing from the ICM and falling into the central galaxy feeds the central black hole. The black hole becomes thereby active and emits powerful radio jets. The radio bubbles inflated by these jets drive weak shocks into the cool core gas, and stir turbulence during their buoyant movement in the cluster atmosphere. This turbulence, on the one hand, heats the medium, and counteracts the cooling instability, thus providing a negative feedback. On the other hand, this turbulence should maintain some level of magnetization, and thereby imprint its characteristic properties (energy density, correlation length) onto the magnetic field.

In the simplistic picture of magnetogenesis adopted here, the turbulence maintains magnetic fields on length scales somewhat smaller than its own driving scale, which is the size of the radio bubbles. Thus field correlation length of a few kpc, and field strength of the order of $\sim 5\ \mu$G are expected in a typical cool core. The ICM fields seem also to play

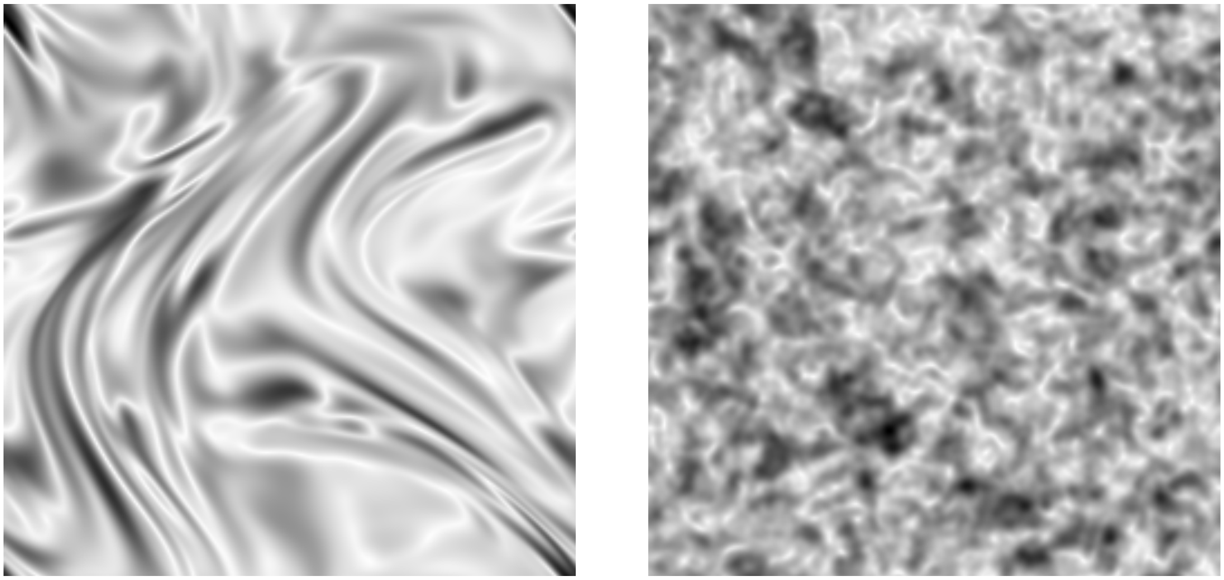

Fig. 3. Magnetic energy density in a MHD simulation (left, the data was taken from run S5 of Schekochihin et al. 2004) and in a Gaussian random field setup (right).

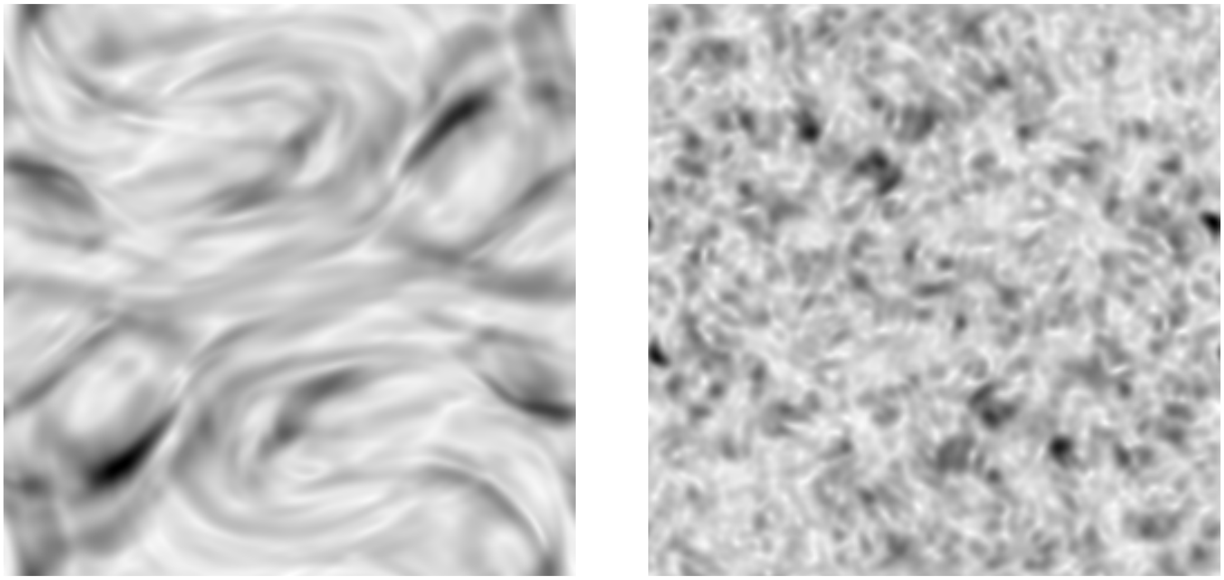

Fig. 4. Magnetic tension force density in a MHD simulation (left, the data was taken from run S5 of Schekochihin et al. 2004) and in a Gaussian random field setup (right).

some role in stabilizing the rising bubbles against disruptive instabilities (Ruszkowski et al. 2008).

A Faraday rotation based determination of the magnetic field strength could actually confirm these expectations. In the case of the Hydra A cluster, Vogt & Enßlin (2005) measured the magnetic power spectrum, as shown in Figure 2, while assuming statistically isotropic magnetic fields and that the mean magnetic energy density scales linearly with that of the cluster gas atmosphere. The observed Kolmogorov-like power law indicates a turbulent origin of the fields. The field strength of 7 μG and length scale of 3 kpc fit well with the expectations for a steady state turbulence level mediating the energy feedback between the radio bubbles and the X-ray cooling cool core gas (Enßlin & Vogt 2006). A similar consistency between the Faraday signature of cool core magnetic fields and their strength and

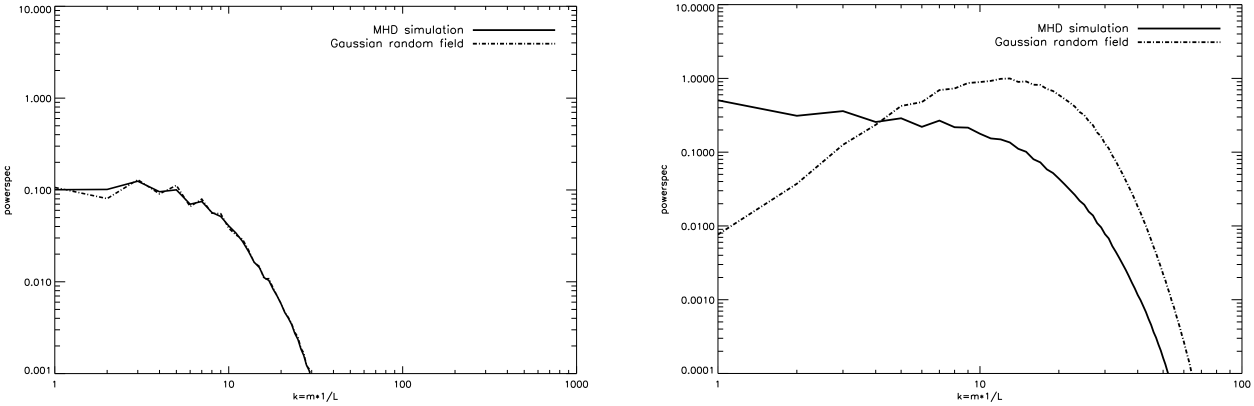

Fig. 5. Left: The magnetic power spectra of the two field configurations are very similar, although the visual inspection of the fields reveals significant differences. Right: The magnetic tension force power spectrum of the two field configurations differ substantially, and thereby permit to discriminate the different turbulence scenarios.

length scale expected in this scenario could also be demonstrated for a number of other clusters (Enßlin & Vogt 2006).

4. MEASURING THE MAGNETIC TENSION FORCE SPECTRUM

A detailed investigation of magnetic field statistics in galaxy clusters should also try to extract higher-order correlation functions. Specially meaningful would be a measurement of the tension force power spectrum. The tension force is $\mathbf{F} = \mathbf{B} \cdot \nabla \mathbf{B}$, where $\mathbf{B}$ is the magnetic field. This quantity measures how strong the magnetic back-reaction forces are localized or distributed through out the volume. It also conveys information about the geometrical structure of the magnetic fields because it involves the field gradient along the field's own local direction. In particular, measuring the tension force spectrum allows one to distinguish folded filamented magnetic fields (such as found in numerical simulations) from isotropically tangled fields sometimes naively assumed on the basis of the power spectra alone. Thus, statistics of the tension force are very discriminative of magnetic turbulence scenarios.

This is illustrated by Figure 3, where a field configuration of a MHD-turbulence simulation is confronted to divergence-free Gaussian random fields with the same magnetic power spectra, as shown in Figure 5. The spatial distribution of the tension forces in the two scenarios is presented in Figure 4. The two tension force spectra differ, as Figure 5 confirms, in that the forces are stronger and more concentrated on small scales in the Gaussian random field as compared to the simulation.

If one assumes that the magnetic fields are radio-synchrotron illuminated by a spatially homogeneous cosmic ray electron population, observables on the magnetic fields are available. The polarized radio intensity emitted by the synchrotron process is, similarly to the tension force, quadratically dependent on the magnetic field strength. Thus, its spectrum is a fourth order function of the magnetic field, as the tension force spectrum is. What is not clear ab initio is if the polarization signal contains all information in order to reconstruct the tension spectrum. Actually, it can be shown that this is not the case, since the synchrotron emission is insensitive to the line-of sight component of the field which enters, however, in the tension spectrum. This missing information can only be replaced by a plausible assumption, e.g. in our work the assumption of statistical isotropy of the fields.

Polarised emissivity maps are shown in Figure 6. Waelkens et al. (in prep.) –see also Enßlin et al. (2006)– managed to demonstrate that the cross- and auto- correlation functions of the Stokes I, Q and U parameters of the synchrotron emission contain enough information to reconstruct the tension force power spectrum. This is possible under the assumptions of statistically homogeneous and isotropic magnetic fields, and a spatially homogeneous cosmic ray electron distribution with a spectral index close to -3. In such circumstances, which are not too artificial in many environments, the tension force spectrum can be measured, and the measured spectra indeed permit us to discriminate the two magnetic turbulence scenarios. This is illustrated by Figure 7.

Since Faraday rotation suppresses the radio halo polarisation signal, cluster radio relics are probably a likely place where this method can be applied. It should also be possible to investigate the magnetic

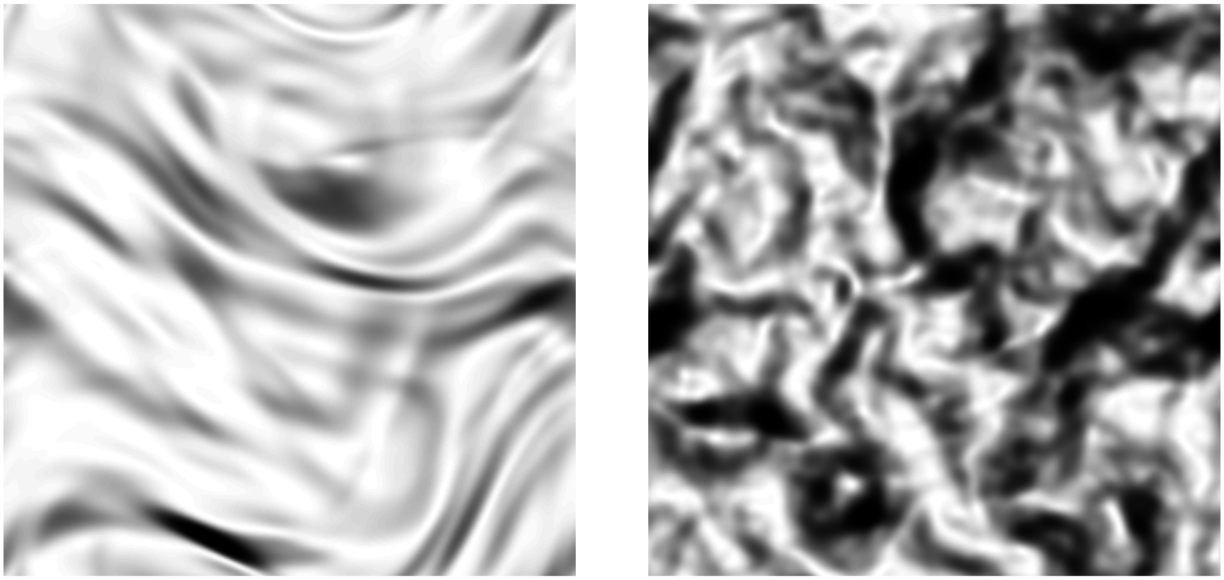

Fig. 6. Polarized intensity of the radio synchrotron emission from the magnetic fields of the MHD simulation (left, the data was taken from run S5 of Schekochihin et al. 2004) and of the Gaussian random field setup (right).

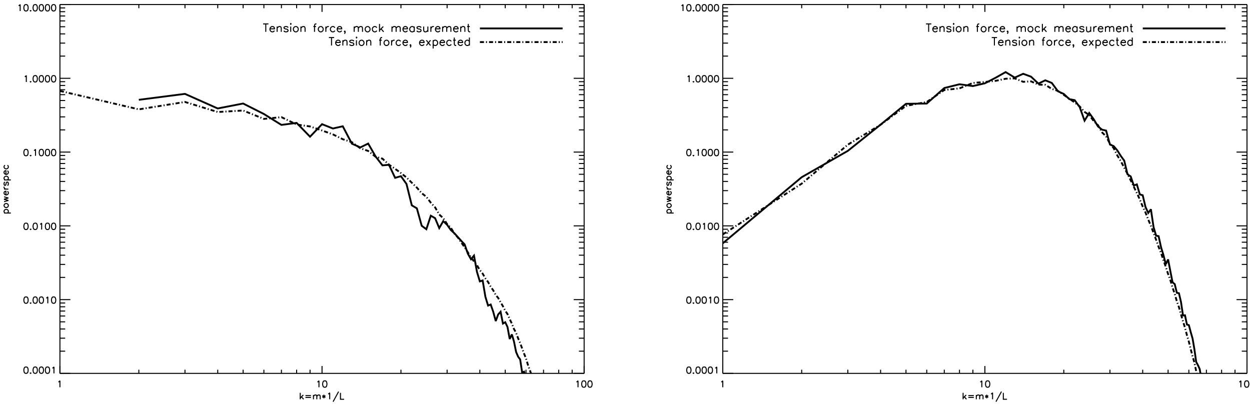

Fig. 7. Magnetic tension force spectrum recovered from the polarized intensity in comparison to the correct one. The case of magnetic fields of the MHD simulation is shown on the left and that of the Gaussian random field setup on the right.

fields inside the radio bubbles, since these seem to be Faraday rotation free.

5. OUTLOOK

With the upcoming sensitive radio telescopes of the next generation like LOFAR, LWA, eVLA, and SKA, the number of detected cluster radio halos and relics should strongly increase (Enßlin & Röttgering 2002; Brüggen et al. 2003; Cassano & Brunetti 2005). Also many more details of the fields should become visible due to higher sensitivity, resolution and the development of new observational techniques, like the Faraday tomography. Therefore, the intra-cluster medium should become a very good test bed for theories of turbulent magnetogenesis.

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