Spectral analysis of magnetic fields in simulated galaxy clusters

Paola Domínguez-Fernández\textsuperscript{1}, Franco Vazza\textsuperscript{3,1,2} and Marcus Brüggen\textsuperscript{1}

\textsuperscript{1}Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany  
email: pdominguez@hs.uni-hamburg.de  
email: mbrueggen@hs.uni-hamburg.de  
\textsuperscript{2}Istituto di Radio Astronomia, INAF, Via Gobetti 101, 40121 Bologna, Italy  
email: franco.vazza2@unibo.it  
\textsuperscript{3}Dipartimento di Fisica e Astronomia, Università di Bologna, Via Gobetti 92/3, 40121, Bologna, Italy

Abstract.

We introduce a new sample of galaxy clusters obtained from a cosmological simulation covering an unprecedented dynamical range. All the clusters in our sample show a clear signature of small-scale dynamo amplification. We show that it is possible to use dynamo theory for studying the magnetic spectrum in the intracluster medium. We study if the intrinsic variations on the spectra depend on the dynamical history of each cluster or on some host cluster properties.

Keywords. galaxy: clusters, general – methods: numerical – intergalactic medium – large-scale structure of Universe

1. Introduction

Galaxy clusters evolve mainly via two mechanisms: accretion of gas and galaxies, and via mergers occurring approximately every few Gyr. These mechanisms directly affect the diffuse, hot, weakly magnetised gas observed in clusters referred as the Intracluster Medium (ICM) (e.g. Kravtsov & Borgani 2012, Brunetti & Jones 2014) by driving shocks through it and therefore, every merger event can be a source of turbulence. In particular, these events effectively affect the structure of the magnetic fields that permeate galaxy clusters.

We know from radio observations that the strength of magnetic fields in the ICM is of the order of \( \mu \)G and the coherence scales are of the order of 10-50 kpc (e.g. Feretti, et al. 2012, Govoni et al. 2017). These coherent large-scale fields indicate that the mechanism which leads to this final structure cannot be solely due to gas compression. In fact, a small-scale dynamo would be a more suitable mechanism to generate observed, large-scale magnetic fields. While the origin of magnetic fields in the Universe remains an open question, a small-scale dynamo seems to play a key role in amplifying magnetic fields in galaxy clusters (e.g. Beresnyak & Miniati 2015), independent of where the seed fields come from.

2. Methods and Results

We studied the formation of seven massive galaxy clusters in a cosmological MHD simulation with the ENZO grid code (The Enzo Collaboration; Bryan et al. 2014) using the Dedner cleaning method, and eight adaptive mesh refinement (AMR) levels to increase the dynamical resolution. Each cluster was selected in a comoving volume of \((260 \text{ Mpc})^3\) and further refined in most of the volume in which the clusters form with a maximum spatial resolution of \(\Delta x_{\text{max}} = 3.95 \text{ kpc (comoving)}\). We assumed a simple uniform seed field of cosmological origin of 0.1 nG (comoving) at \(z = 30\) (for a detailed description see Vazza et al. 2018). In this work, we will only discuss the results from non-radiative cosmological simulations to focus on the growth of magnetic fields by the turbulence induced by structure formation processes.

We analyse clusters with different dynamical states at redshift \(z = 0\), namely clusters with ongoing mergers, relaxed ones and clusters that have suffered a recent major merger. The baseline model we tested with our cosmological simulation relies on an analytic solution for the magnetic power spectrum derived from dynamo theory (Kazantzev 1967, Kulsrud & Anderson 1992). Our tests (Domínguez-Fernández et al., to be submitted) show that all spectra can be fitted well by an equation which is directly derived from dynamo theory (see Eq. in Fig. 1). In Fig. 2 we show the best-fit of the magnetic energy spectra of all of the clusters in our sample.
Figure 1. Left: Magnetic energy spectra of all of our cluster sample at \( z = 0 \). The solid lines correspond to the data and the scatter plots show our best-fit. Right: Projection of the magnetic field strength in galaxy cluster E4 at \( \Delta x_{\text{max}} \)

Discussion

1) Regardless of the dynamical state of each cluster, the magnetic energy spectral shape is in good agreement with dynamo theory. As a first approximation, this indicates that this model can be used for a detailed analysis of a cluster evolution where a small-scale dynamo can be acting in addition to gas compression and shocks.

2) The normalization of the magnetic energy spectrum overall is determined by the dynamical state of each cluster. Relaxed clusters have the highest value for the magnetic spectrum, followed by post-merger clusters, and then merging clusters. This result is tentatively consistent with the fact that in relaxed system a small-scale dynamo would have to be active for longer dynamical times. Nevertheless, we do not observe a clear dependence on the virial mass of each cluster due to the small number of clusters in our sample.

3) Our analysis shows that the magnetic power spectra does not retain information on the last major-merger, as minor mergers are also injecting turbulence during the formation of each cluster.

4) We refer the reader to the complete work (Domínguez-Fernández et al., to be submitted) where a detailed analysis on the cluster sample is done and where also the evolution of a merging cluster is studied.

5) The resulting power spectrum shows that in general the three-dimensional components of the magnetic field are non-Gaussian. This results from having different magnetic field components being continuously injected by the accretion of substructures (Vazza et al. 2018) rather than from the presence of highly intermittent MHD turbulence (e.g. Shukurov et al. 2017). This has direct consequences for Faraday Rotation measurements and illustrates the importance of reliable simulations of magnetic fields in galaxy clusters for an accurate modelling of future polarisation surveys (e.g. Johnston-Hollitt et al. 2015).

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