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Magnetic fields in the intergalactic medium and in the cosmic web

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Abstract. In these proceedings we discuss advances in the theory and observation of magnetic fields in the intergalactic medium and in the cosmic web. We make the point that, despite perhaps unsurmountable obstacles in simulating a small-scale dynamo, currently most cosmological magnetohydrodynamical simulations paint a similar picture of magnetic field amplification in the cosmos. However, observations of magnetic fields in the intergalactic medium turn out to be very difficult. As a case in point, we present recent work on Faraday rotation measurement in the direction of a giant galaxy with the Low Frequency Array (LOFAR). These observations demonstrate the currently unique capability of LOFAR to measure Faraday rotation at the high accuracy and angular resolution required to investigate the magnetisation of large-scale structure filaments of the cosmic web.

Keywords. (galaxies:) intergalactic medium, (cosmology:) large-scale structure of universe, magnetic fields, methods: numerical, (magnetohydrodynamics:) MHD

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1. Introduction

Much has been written about the origin of cosmic magnetism, the processes that can seed fields in the early universe and the various mechanisms to amplify magnetic fields. Here we can refer to the review by Donnert *et al.* (2018). For want of clear indications to the contrary, it is almost always assumed that magnetohydrodynamics (MHD) is a good theory that describes the evolution of fields in the cosmos. Still one should mention some brave attempts to go beyonds the simplest descriptions, e.g. by Schekochihin *et al.* (2004).

Under the set of equations of MHD, it appears that in the presence of turbulence a few percent of the kinetic energy is transferred to magnetic energy in a fast operating small-scale fluctuation dynamo (Miniati & Beresnyak 2015). Such a turbulent dynamo has been shown to operate in galaxy clusters (e.g. Jaffe 1980; Roland 1981; Ruzmaikin *et al.* 1989; De Young 1992; Goldshmidt & Rephaeli 1993; Kulsrud *et al.* 1997; Sánchez-Salcedo *et al.* 1998; Subramanian *et al.* 2006). In such dynamos, magnetic fields are amplified though an inverse cascade up until a scale, where the field starts to act back onto the fluid flow. Simulations seem to agree that field amplification is primarily caused by compression in cosmological filaments, whereas at higher overdensities such as in galaxy clusters, turbulence is increasingly solenoidal and there are a sufficient number of eddy turn-overs for a dynamo to cause a fast amplification beyond what you would get via compression. The initial exponential increase in magnetic field strength is followed by a non-linear growth phase. The timescale of exponential growth is set by the magnetic Prandtl number and is determined by the spatial resolution and the algorithm. The real growth rate thus may never be determined by direct numerical simulations. Moreover, on smaller scales magnetic fields may get injected by galactic outflows and active galaxies. Galactic winds can transport magnetic fields into the circum-galactic medium where it can be stripped and enter the ICM (Donnert *et al.* 2009; Xu *et al.* 2009). The modelling of this is still in its infancy.

A recent example of such simulation work is presented in Vazza *et al.* (2018) where it was demonstrated how a small-scale dynamo develops (see Fig. 1). Interestingly but not unexpectedly, a significant non-Gaussian distribution of field components is found which results from the superposition of plasma that has gone through different amplification histories. Evidence for the presence of a dynamo is the anti-correlation of magnetic field strength and its curvature $\vec{K}$,

$$\vec{K} = \frac{\left(\vec{B}\cdot\nabla\right)\vec{B}}{\vec{B}^2}, \tag{1.1}$$

so that $\vec{B}\vec{K}^{\frac{1}{2}} = \text{const}$ (Schekochihin *et al.* 2004) which can be tested in simulations of small-scale dynamos.

2. Observations of Faraday rotation from giant radio galaxy

On the observational side, progress has been fairly slow which is largely due to the fact that measuring extragalactic fields is unreasonably difficult. On scales of galaxies and beyond, magnetic fields are best traced via radio observations. Cluster magnetic fields were first inferred from upper limits on the diffuse synchrotron emission by Burbidge (1958). Later estimates based on the Rotation Measure (RM) of background sources to the Coma cluster obtain central magnetic fields of $3-7\mu$G. Consequently, the ICM is a high $\beta = 8\pi n_{\rm th} k_{\rm B} T/B^2 \approx 100$ plasma, meaning that thermal pressure is much larger than magnetic pressure. There are attempts to measure the magnetic fields in cluster outskirts using Faraday rotation of the polarised emission from radio relics (e.g. Kierdorf *et al.* 2017). Radio relics or cluster radio shocks trace shock waves in merging galaxy clusters and sometime show large degrees of polarisation and μG magnetic fields.

In these proceedings, we would like to bring attention to a recent attempt by O'Sullivan *et al.* (2019) to analyse the FRII radio galaxy (J1235+5317) at redshift $z = 0.34$ with a linear size of 3.4 Mpc whose polarised emission may have been rotated by intergalactic magnetic fields. This work was conducted with the Low Frequency Array (LOFAR) whose broad bandwidth provides excellent precision to measure Faraday rotation and, at the same time, is sensitive to emission on large angular scales. On the downside, LOFAR observations suffer from Faraday depolarisation, which renders many sources undetectable in polarisation (Farnsworth *et al.* 2011). Figure 2 shows the RM distributions of this giant radio galaxy. The mean and standard deviations of the RM are +7.42 rad m^{-2} and 0.07 rad m^{-2} for the North-Western radio lobe, and +9.92 rad m^{-2} and 0.11 rad m^{-2} for the South-Eastern radio lobe.† The mean RM difference between the two lobes is 2.5 ± 0.1 rad m^{-2}. Next, we relied on dynamical modelling of the radio lobes to infer the density of the ambient gas, which came out to be $n_{\rm e} \sim 10^{-7}$cm^{-3}. This suggests that the radio galaxy is expanding into a very underdense region. However, the observed Faraday depolarisation of ~ 0.1 rad m^{-2} which is most likely caused by plasma local to the source, requires $n_{\rm e} \sim 10^{-5}$cm^{-3} with a turbulent magnetic field of strength ~ 0.09 μG at a distance of about 1.5 Mpc from the host galaxy. Hence, we are either underestimating the density of the external medium or the depolarisation does not occur

† The RM errors are 0.04 rad m^{-2} and 0.06 rad m^{-2}, for the NW and SE lobes, respectively.

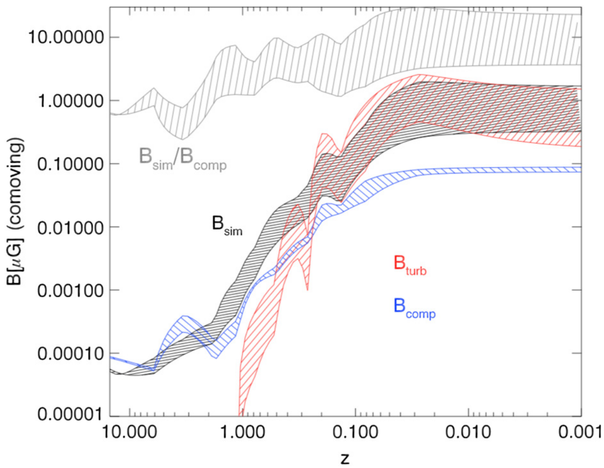

Figure 1. Magnetic field growth in a cosmological MHD simulation performed with the ENZO code. The black curve shows the magnetic field strength in innermost comoving Mpc^3 as a function of redshift. In comparison, there is the prediction from compression alone (blue) and from dynamo amplification (red) Beresnyak & Miniati (2016), assuming a 4% amplification efficiency. The grey curve shows the ratio between the simulated field and the expectation from compression alone. The dashed areas show the scatter. From Vazza *et al.* (2018).

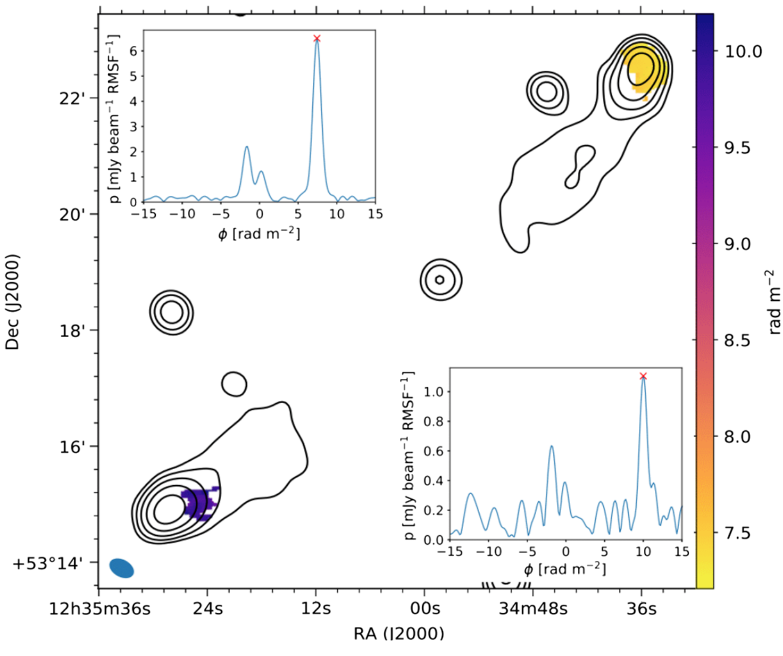

Figure 2. Faraday RM distribution of the NW and SE lobes, overlaid by the total intensity contours starting at 5 mJy/beam and increasing in factors of two. Insets: The absolute value of the Faraday dispersion function for the NW lobe (top) and SE lobe (bottom). From O'Sullivan *et al.* (2019).

in the environment close to the source. Better models for the evolution of radio jets within a realistic cosmological environment may help refine these estimates in the future. With the current value, the estimated magnetic field strength is unable to account for the observed difference of the mean RM of 2.5 rad m^{-2} between the two lobes. We then

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searched a catalogue of cosmological filaments that is derived from optical spectroscopic observations and found an excess of filaments that intersect lines-of-sight towards the Northwestern lobe. If magnetised plasma in these filaments causes the RM difference between the lobes and assuming a path length through each filament of 3 Mpc, and a magnetic field coherence length of 300 kpc, this would imply a density-weighted magnetic field strength inside the filaments of 0.3 μG.

We then compared this result with predictions from cosmological simulations and found that the probability of a RM contribution as large as 2.5 rad m^{-2} is only $\sim$ 5%. This estimate assumed magnetic field strengths in the cosmological filaments of 10 to 50 nG, as suggested from MHD simulations that started out with primordial magnetic fields of $\sim$1 nG, close to current upper limits from the Cosmic Microwave Background. Alternatively, the RM difference could come from variations in the Milky Way and finer observations of Milky Way RMs are needed to obtain better constraints.

3. Conclusions

There remains the hope that with the advent of the Square Kilometre Array (SKA) and the LOFAR upgrade this field will gain fresh momentum (e.g. Bull *et al.* 2018). Large samples of RMs from radio galaxies with known redshifts will permit more advanced statistical analyses, such as RM structure functions (e.g. Akahori *et al.* 2014). Only then will we be able to disentangle the effect of the Milky Way on RM measurements for filaments and the intergalactic space.

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