The quest for extragalactic magnetic fields

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Abstract We review the observational and theoretical constraints on extragalactic magnetic fields across cosmic environment. In the next decade, the combination of sophisticated numerical simulations and various observational probes might succeed in constraining the still elusive origin of magnetic fields on the largest scales in the Universe.

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1. Introduction - The mystery of magnetogenesis

Understanding the origin of observed magnetic fields on $\sim$ Mpc scales is still a challenge. While we roughly understand how primordial energy fluctuations of the cosmic microwave background (CMB) originated cosmic structures, we have yet no clear view of the origin of extragalactic magnetic fields (Subramanian 2016). Were the needed weak (and yet undetected) seed magnetic fields already present at the CMB, or were they only later released by forming galaxies? The observed properties of magnetic fields in galaxy clusters can roughly be reproduced by simulations, starting either from primordial fields or through the magnetisation from galactic winds and jets (e.g. Donnert et al. 2009, and references therein). On the other hand, the distribution of magnetic fields in cluster outskirts and in filaments is yet poorly constrained from observations and simulations, and there we expect the different scenarios of magnetogenesis to diverge, owing to the weaker (or absent) level of dynamo amplification (e.g. Vazza et al. 2014). Future observations should be able to kill alternative scenarios, by constraining the real distribution of magnetic fields across scales. In this contribution, we give a short overview of possible future ways to tackle this challenge, based on preliminary results of our ongoing campaign of large magneto-hydrodynamical (MHD) simulations of cosmic magnetism with ENZO (The Enzo Collaboration et al. 2013).

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Figure 1: Magnetic field strength as a function of gas overdensity in different seeding models. The colors mark the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentile of the distributions. The additional red arrows mark the observational constraints discussed in the main text.

2. Cosmological MHD simulations

Figure 1 shows the predicted distribution of simulated magnetic field strength across different bins in gas overdensity, for 3 of our ENZO resimulations of a 85^3Mpc^3 volume using 1024^3 cells/dark matter particles, metal-dependent gas cooling, feedback from star formation and active galactic nuclei (simulated using black-hole sink particles), and alternatively including: a) a primordial uniform field of $B_0 = 1$ nG (comoving); b) a primordial uniform field of $B_0 = 10^{-4}$ nG (comoving) with a run-time sub-grid modelling of dynamo amplification from solenoidal motions; c) magnetic seeding exclusively from star and AGN feedback, assuming a $\sim 10\%$ conversion of feedback energy into magnetic energy. Magnetic fields in high density regions are very similar in all models, yet the trends diverge in lower density regions. The same figure also shows where different observations should be sensitive to extragalactic magnetic fields (see below).

3. Observational techniques and constraints

Relativistic electrons accelerated by strong shocks in the cosmic web should emit continuum and polarised radio emission (e.g. Brown 2011). SKA-LOW and its pathfinders and precursors may detect the tip of the iceberg of such emission, provided that the magnetic fields are $\geq 10$ nG (Vazza et al. 2015b,a). Detections (or even robust upper limits) will constrain: a) the combination of magnetic fields and electron acceleration efficiency at shocks, $\propto B^2 \times \xi_e$; b) the distribution of magnetic fields on $\geq 10$ Mpc, yielding fundamental clues on their origin (Vazza et al. 2016); c) the magnetic field obliquity at shocks accelerating radio emitting electrons (Wittor et al. 2016).

Additionally, future large surveys in polarisation (e.g. with ASKAP, MEERKAT and SKA-MID) will probe the topology of extragalactic fields through Faraday Rotation ($\propto B_{\parallel} n_e$, where $B_{\parallel}$ is the magnetic field component along the line of sight and $n_e$ is the electron density), either with long exposures (Bonafede et al. 2015), or statistical techniques (Akahori et al. 2014). Our simulations suggest that detections should be feasible for $\geq 0.1 \mu$G fields in cluster outskirts.

The arrival direction at Earth of ultra-high energy cosmic rays (UHECRs) carries information in the large-scale distribution of magnetic fields (e.g. Dolag et al. 2005). With recent simulations, we showed that the distribution of UHECRs is sensitive to the magnetisation of voids. The simulated angular distribution of UHECRs gets too anisotropic compared to available observational constraints, if the magnetisation of voids exceeds $\sim 0.1$ nG (Hackstein et al. 2016).
Finally, extragalactic magnetic fields may also cause the oscillation of high-energy photons into axion-like particles (ALPs), a possibility that has been suggested to explain the lack of absorption in the spectra of distant blazars (Horns et al. 2012). In recent work (Montanino et al.) we simulated the propagation of ALPs in our MHD runs, finding that significant photon-ALPs conversions are produced in lines of sight crossing structures with $\sim 1 - 10 \text{ nG}$ on scales of a few $\sim \text{Mpc}$, i.e. in filaments and cosmic sheets along the line of sight of high-z sources.

4. Conclusion

In the near future the puzzle of magnetogenesis may be solved by combining complex simulations and observations of cosmic magnetic fields on different scales.

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