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Origins of Cosmic magnetism

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Abstract. The standard picture for the origin of magnetic fields in astrophysical systems involves turbulent dynamo amplification of a weak seed field. Dynamos convert kinetic energy of motions to magnetic energy. While it is relatively easy for magnetic energy to grow, explaining the observed degree of coherence of cosmic magnetic fields generated by turbulent dynamos, remains challenging. We outline potential resolution of these challenges. Another intriguing possibility is that magnetic fields originated at some level from the early universe.

Keywords. magnetic fields, galaxies: magnetic fields, galaxies: clusters: general, early universe

1. Introduction

The universe is magnetized from planets, stars, nearby and high redshift galaxies, the plasma in galaxy clusters and perhaps even the inter galactic medium in void regions devoid of galaxies! Understanding the coherence of magnetic fields detected in these astronomical systems presents an outstanding challenge of modern astrophysics. The general paradigm for extragalactic magnetogenesis involves dynamo amplification of a seed magnetic field due to electromagnetic induction by motions of a conducting plasma. The seed itself could be due to a cosmic battery effect or more intriguingly primordial. We briefly review the dynamo paradigm and then touch upon a possible primordial scenario.

Plasma in all astrophysical systems are turbulent. In galaxies, turbulence is driven by supernovae explosions and in galaxy clusters during its formation by collapse and mergers. Turbulence combined with large scale shearing motions in a highly conducting fluid of galaxies and clusters, generically leads to dynamo action, a process referred to as a turbulent dynamo. Turbulent dynamos are conveniently divided into the small-scale (or fluctuation) dynamos and large-scale (or mean-field) dynamos. The distinction depends respectively on whether the generated magnetic field is ordered on scales smaller or larger than the scale of the turbulent motions. The small-scale dynamos would be relevant for the magnetization of galaxy clusters and young galaxies, while the large-scale dynamo for understanding the system scale magnetic fields in disk galaxies.

2. Small-scale dynamos

In a highly conducting plasma, magnetic flux through any area moving with the fluid is conserved. Consider a flux tube containing plasma of density ρ, magnetic field strength B, area of cross section A and going through fluid parcels separated by a length l. Flux conservation implies $BA =$ constant. Mass conservation in the flux tube gives $\rho A l =$ constant, which implies $B/\rho \propto l$. In any turbulent flow, fluid parcels random walk away from each other and l increases due to random stretching, and if ρ is roughly constant, then B increases. This of course comes at the cost of $A \propto 1/\rho l \propto 1/B$ decreasing, the field being concentrated on smaller and smaller scales l_B at least in one direction, till decay rate due to resistive diffusion, η/l_B^2 is of same order as growth rate due to random stretching v/l. Here v and l are the velocity and coherence scale respectively of turbulent eddies, while η is the resistivity of the plasma. This gives $l_B \sim l R_m^{-1/2}$ where the magnetic Reynolds number $R_m = vl/\eta$ is typically very large in astrophysical systems, which also implies a resistive scale $l_B \ll l$.

Kazantsev (1967) first showed that a specialized short correlated random flow can be a dynamo and cause net magnetic field growth on the very rapid eddy turn over time l/v, provided the R_m exceeds a very modest critical value $R_c \sim 100$. This growth due to the small scale dynamo has since been verified by many direct numerical simulations where a seed field is introduced into a turbulent flow (Haugen *et al.*, (2004), Schekochihin*et al.*, (2004), Bhat & Subramanian (2013)). Thus generically turbulence in the interstellar or intra cluster medium, which have $R_m \gg R_c$, is expected to rapidly amplify magnetic fields on a timescale $l/v \sim 10^7$ yr in galaxies (with $v \sim 10$ km s^{-1} and $l \sim 100$ pc) and $l/v \sim 3 \times 10^8$ yr in galaxy clusters (with $v \sim 300$ km s^{-1} and $l \sim 100$ kpc), much smaller than their age. However as $l_B \ll l$, the field in the growing phase is extremely intermittent and concentrated in to the small resistive scales. The big challenge is then whether these fields can become coherent enough on dynamo saturation to explain for example observations of the Faraday rotation inferred in galaxy clusters and young galaxies.

We have used direct numerical simulations of fluctuation dynamos in forced compressible turbulence with various values of R_m, fluid Reynolds number R_e and up to rms Mach number of $\mathcal{M} = 2.4$, to directly measure the resulting Faraday rotation measure (RM) and the degree of coherence of the magnetic field (Subramanian *et al.* 2006; Bhat & Subramanian 2013; Sur *et al.* 2018). The measured values of a normalized RM, $\bar{\sigma}_{RM}$, normalized by that expected in a model where fields with the rms strength B_{rms} are assumed to be coherent on the forcing scale of turbulence, are shown in Fig. 1 for some of these runs. At dynamo saturation, for a range of parameters, we find $\bar{\sigma}_{RM} \sim 0.40 - 0.55$, or an rms RM contribution which is about half the value expected if the field is coherent on the turbulent forcing scale. This arises in spite of the highly intermittent nature of the field. The left panel of Fig. 1, also shows that when regions with the field above $2B_{rms}$ are excluded from the RM computation for the subsonic case, there is only a modest 20% decrease of $\bar{\sigma}_{RM}$ (Bhat & Subramanian 2013). Thus the dominant contribution to the RM in this case (and also when the flow is transonic) comes from the general sea of volume filling fields, rather than from the rarer, strong field structures. However, in the supersonic case, strong field regions as well as moderately overdense regions contribute significantly to RM. The density dependence is illustrated in the right panel of Fig. 1, where the $\bar{\sigma}_{RM}$ contribution by various overdensity ranges is shown for the cases with $\mathcal{M} = 1.1$ and 2.4 (Sur *et al.* 2018). Our results can account for the observed RMs in galaxy clusters and in young galaxies just as due to fluctuation dynamo action. We also find that the coherence scale of the generated intermittent field is about 1/3 to 1/4 of the velocity coherence scale for the parameters so far explored, and so not too small.

3. Mean-field dynamos

Magnetic fields with coherence scales larger than that of the stirring can be amplified if the turbulence is helical. In disk galaxies, supernovae drive turbulent motions which become helical due to the rotation and vertical stratification of the disk. Helical turbulent motions of the gas draw out any toroidal field in the galaxy into a loop and twists it to look like a twisted Omega (called the α-effect). These lead to the generation of poloidal magnetic fields from toroidal fields. The shear due to galactic differential rotation winds up radial component of the poloidal field to generate a toroidal component. The combination of these two effects lead to a mean-field dynamo generation of disk galaxy magnetic fields on the differential rotation time scales of about $10^8 - 10^9$ yr.

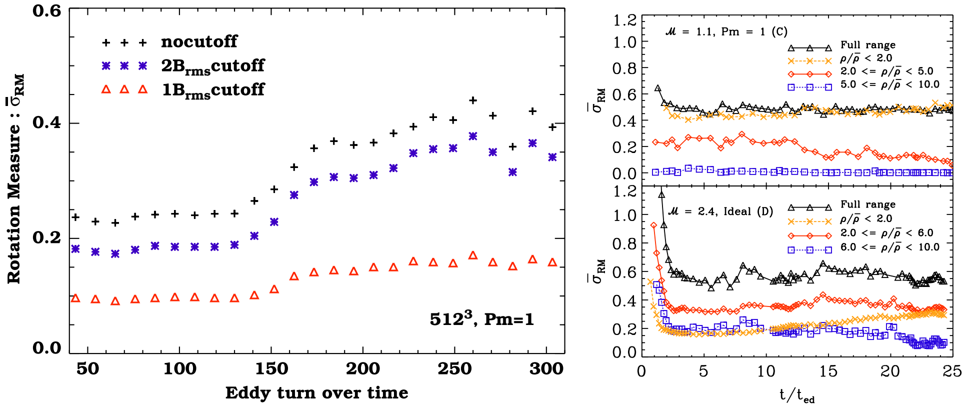

Figure 1. Left panel shows the time evolution $\bar{\sigma}_{RM}$ for a 512^3 subsonic run with $\mathcal{M} = 0.14$, $R_m = R_e = 622$ from Bhat & Subramanian (2013). The stars and triangles show respectively the result of excluding regions with field above $2B_{rms}$ and B_{rms} while the crosses correspond to not imposing any cutoff. The right panel shows the corresponding results from Sur *et al.* (2018) of higher Mach number flows, with also overdensity cuts as indicated in the figure.

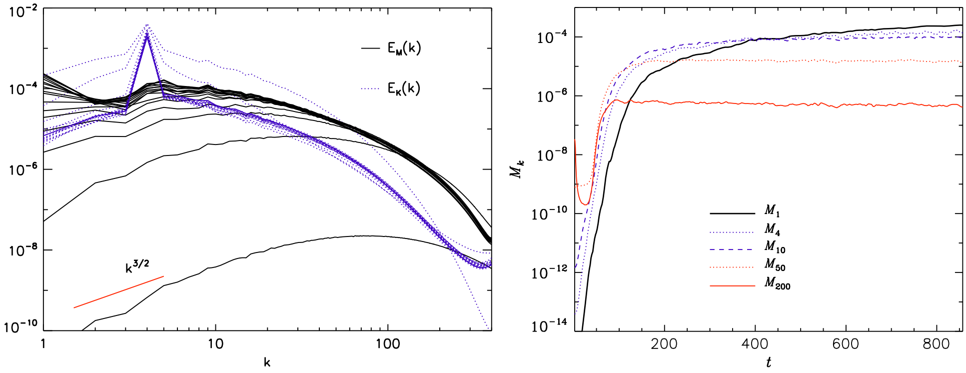

Figure 2. Left panel: time evolution of the magnetic spectra $E_M(k)$ and kinetic spectra $E_K(k)$ from Bhat *et al.* (2016) for a 1024^3 simulation of helically forced (at $k = 4$), turbulence with $\mathcal{M} = 0.135$, $R_m = 10R_e = 3375$. Right panel: The time evolution of different modes of the magnetic spectra $M_k(t)$ for $k = 1, 4, 10, 50$, and 200. Initially all scales grow together, with magnetic power peaked on small scales. Lorentz forces act to order the field on larger and larger scales as the dynamo saturates.

This idea faces two important challenges. First, magnetic fluctuations due to the fluctuation dynamo in a disk galaxy grow on small scales much faster ($10^7 yr$) than the growth time of the mean field. Lorentz forces can then become important to saturate the field growth much before the mean field has grown significantly. Can the large-scale field then grow at all? Bhat *et al.* (2016) examined this issue using direct simulations of magnetic field amplification due to fully helical turbulence in a periodic box. The results of one such run where both the fluctuation and mean-field dynamos arise in a unified manner is shown in Fig. 2. We find that initially scales both larger and much smaller than the stirring scale grow together as an eigenfunction dominated by small scales. But crucially on saturation of small scales due to the Lorentz force, larger and larger scales come to dominate due to the mean-field dynamo action. Finally system scale fields (here the scale of the box) develop provided small-scale magnetic helicity can be efficiently removed (see below), which in this simulation is due to resistive dissipation.

The second challenge is that in the highly conducting galactic plasma, magnetic helicity which measures the linkages between field lines, is nearly conserved. Then when helical motions writhe the toroidal field to generate a poloidal field, an oppositely signed twist develops on smaller scales, to conserve magnetic helicity and Lorentz forces due to this twist try to unwind the field and quench the dynamo. Large-scale dynamos only work by shedding this small-scale magnetic helicity. This can happen due to resistivity, but on a time scale that exceeds the age of the universe! It can also happen if the small-scale helicity is transported out of the system by helicity fluxes. One such flux is simply advection of the gas and its magnetic field out of the disk. Such advection can be larger from the optical spiral region, where star formation and galactic outflows are expected to be enhanced. Chamandy *et al.* (2015) solved the mean-field dynamo equation incorporating both such an advective flux and a diffusive flux. The helicity fluxes allow the mean-field dynamo to survive, but stronger outflow along spiral arms led to a suppression of mean field generation there and an interlaced pattern of magnetic and gaseous arms develops, as seen in the galaxy NGC6946 (Beck & Hoernes 1996). Interestingly a wide spread magnetic spiral only results if the optical spiral is allowed to wind up and thus here we are constraining spiral structure theory using magnetic field observations!

4. Primordial magnetic fields

An intriguing possibility is that magnetic fields are an early Universe relic, arising during inflation along with density fluctuations, or being generated in QCD or electroweak phase transitions (for a review see Subramanian 2016). A number of problems have been raised about inflationary magnetogenesis. A model by Sharma *et al.* (2018) which addresses these, predicts a blue magnetic field spectrum $d\rho_B/d\ln k \propto k^4$ and requires a low energy scale of inflation and reheating. The field is also helical and so orders itself considerably as it decays. A scenario with reheating at a temperature of 100 GeV leads to present day field strengths of order $B_0 = 4 \times 10^{-11}$ G with a coherence scale of 70 kpc. Such models can be constrained by space gravitational wave detectors like LISA in the future.

In summary the origin of cosmic magnetism on galactic and extragalactic scales is still an area of active research with many interesting ideas which will continue to fascinate astronomers of the future.

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