1 Astrophysical turbulence and dynamo action

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Introduction

The gas in stars, accretion discs, and galaxies tends to be hot and sufficiently ionized to support electric currents. Sufficiently complex motions allow a conversion from kinetic into magnetic energy through the dynamo effect. An open question is the mechanism for producing fields on scales large compared with those of the motions. A leading contender is the helicity effect (or α effect)[1, 2], but certain simulations suggest that this effect becomes too weak and unimportant at large magnetic Reynolds numbers (high conductivity)[3, 4, 5]. Much of our recent work is devoted to showing that the helicity effect does indeed work if there are magnetic helicity fluxes out of the system or through the equator.

With the award of an Advanced Grant by the European Research Council (ERC), our group at Nordita has expanded significantly. Among the people working on the astrophysical turbulence and dynamo action project are Simon Candelaresi, Fabio Del Sordo, Alexander Hubbard, Enikö Madarassy, Dhrubaditya Mitra, Jörn Warnecke, and Violaine Vermersch (née Auger), who have also contributed to the publications listed below.

Results

In order to compute the α effect and turbulent diffusivity η_t, we have implemented the test-field method[6, 7] into the Pencil Code[8] and have applied it to turbulence with shear [1], to compute the full integral kernel in space [2] and time [3]. We have been able to extend the test-field method into the nonlinear regime [4, 5]; see also Figure 1. We have clarified issues concerning magnetic helicity fluxes [6] and have shown that they can be gauge-independent under certain conditions [7, 8]. Magnetic helicity is a topological invariant[9], so a pair of interlocked flux rings has finite magnetic helicity. However, we have now shown that magnetic helicity is more important than the qualitative topological configuration [9]; see Figure 2. In the Sun, much of this magnetic helicity is believed to be ejected via coronal mass ejections [10]; see Figure 3. In the Sun, the magnetic Prandtl number is very low ($\sim 10^{-5}$), which means that small-scale dynamos are very hard to excite[10, 11]. However, this is not the case for large-scale dynamos work that have now been show to work even at magnetic Prandtl number as low as 10^{-3} [11]. The test-field method has also been fruitful in elucidating passive scalar transport in rotating [12] and shear-flow [13] turbulence.

In some systems such as accretion discs, the flows leading to dynamo action can be driven by the magneto-rotational instability [14], see Figure 4, or by magnetic

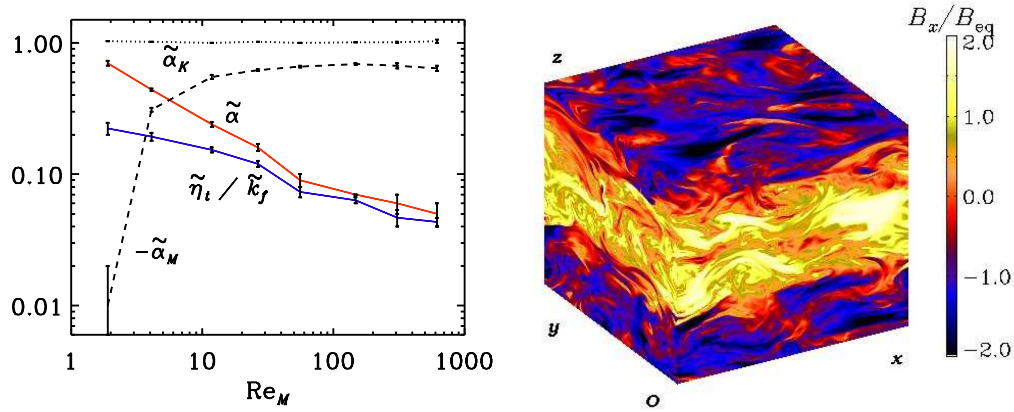

Figure 1: Dependence of α effect and turbulent magnetic diffusivity, $\eta_{\rm t}$, on the magnetic Reynolds numbers, as obtained by the test-field method in the nonlinear regime (left) for large-scale magnetic fields of equipartition strength (right) [4].

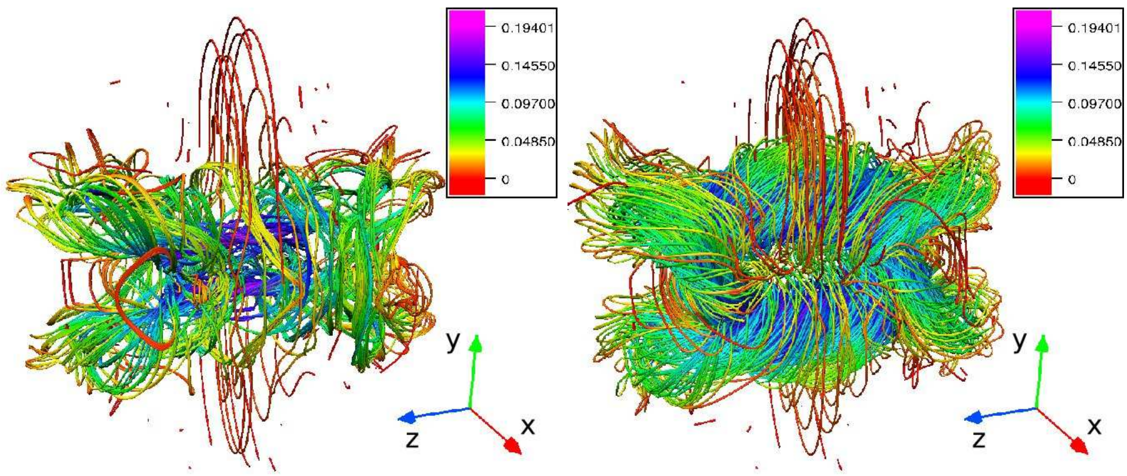

Figure 2: Magnetic field configurations of decaying triply-interlocked flux rings with zero helicity (left) and finite helicity (right). The configurations on the right decays much more slowly, because magnetic helicity conservation controls the decay rather than the qualitative degree to which the rings are interlocked [9].

buoyancy [15]. We have recently also studied another topological invariant called cross-helicity, and found that is can lead to a new dynamo effect [16] and that cross helicity might be measurable in the Sun to infer the magnitude of magnetic diffusivity [17]. Results from dynamo simulations suggests that large-scale magnetic fields are produced in a distributed fashion and are not concentrated in thin tubes at the bottom of the convection zone. Future work will need to verify our initial results [18] that diffusive fields can lead to magnetic flux concentrations at the surface to produce ultimately sunspots.

It is important to have accurate calculations of the magnetic field. Some recent

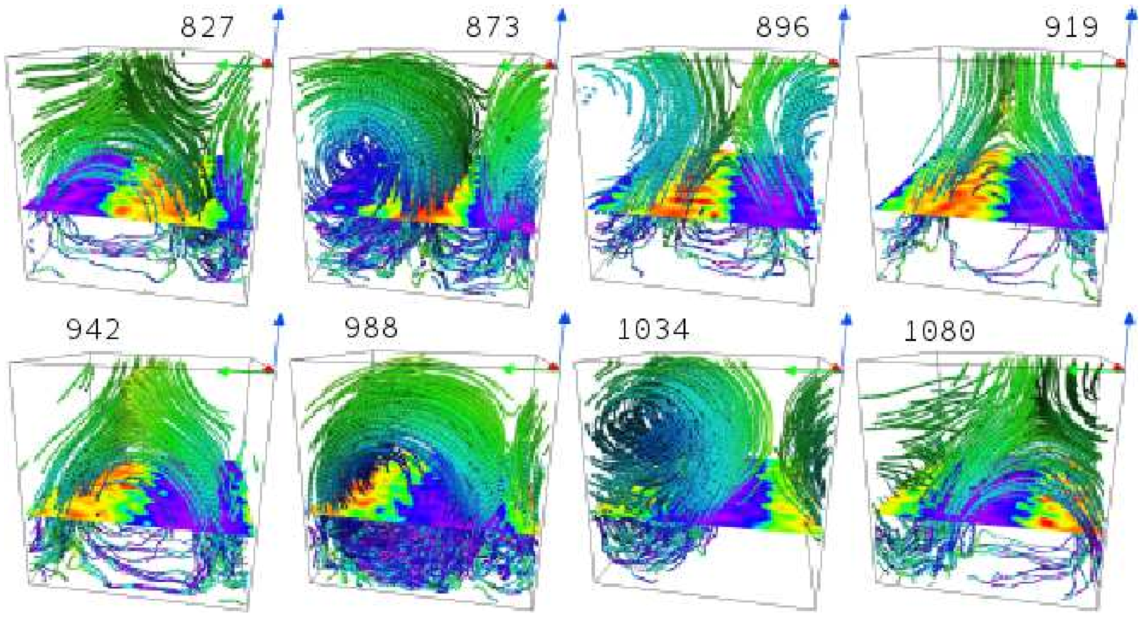

Figure 3: Arcade formation above a helical dynamo. The different times show the recurrent development and emergence of plasmoid structures [10].

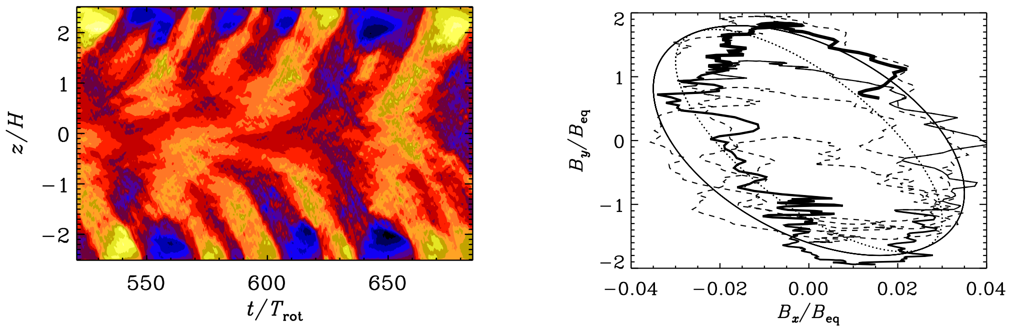

Figure 4: Space-time diagram of the $\overline{B}_y$ component of the mean magnetic field driven by the magneto-rotational instability (left). Note the $3\pi/4$ phase shift between $\overline{B}_x$ and $\overline{B}_y$ (right) [14].

work has utilized Euler potentials[12], but in the presence of numerical diffusion such results are now shown to be incorrect [19]. Finally, our work has implications for understanding cosmological magnetic field that can be generated in the early Universe during the electroweak phase transition or during inflation [20].

Publications

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