Detailed project description: Astrophysical turbulence and dynamo action

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Abstract

Much of the astrophysics activity at Nordita focusses on the “Formation of active regions in the Sun” (VR breakthrough research grant) we now perform studies of “Particle transport and clustering in turbulent flows” (Research Council of Norway, FRINATEK research grant) and on Bottlenecks for the growth of particles suspended in turbulent flows (Knut & Alice Wallenberg Foundation, with Professor Mehlig from Gothenburg as PI). The latter is however forms the basis of a separate large resources computing application.

1 Background

The work in the astrophysics group at Nordita concerns mostly solar physics (dynamo, sunspot formation, and helioseismology). Our research group consists currently of the following people:

Mr Xiang-Yu Li (PhD student, Licentiate 20 May 2016)
Ms Illa R. Losada (PhD student, Licentiate 5 December 2014)
Dr Akshay Bhatnagar (Post-doc)
Dr Harsha Raichur (Post-doc)
Dr Jennifer Schober (Nordita fellow)
Dr Nishant Singh (Post-doc)
Dr Dhrubaditya Mitra (assistant professor)
Dr Lars Mattsson (assistant professor)

Note that much of the work of Dhrubaditya Mitra is within the project on “Bottlenecks for the growth of particles suspended in turbulent flows” and forms the basis of a separate application. However, the work of Mr Xiang-Yu Li is part of a different project on “Particle transport and clustering in turbulent flows” (Research Council of Norway, FRINATEK research grant).

2 Scientific content

PhD works. The work of PhD student Illa R. Losada is coming to an end within the coming year. Their work has therefore priority and requires significant amounts of computing time. Strongly stratified hydromagnetic turbulence has the tendency of spontaneously developing spots. It can also be described with with mean-field equation, as we have been able to show in previous work.

Classes of hydrodynamic and magnetohydrodynamic turbulent decay. Our work on decaying hydrodynamic and magnetohydrodynamic turbulence shows that we can classify our time-dependent solutions by their evolutionary tracks in parametric plots between instantaneous scaling exponents. Examples of spectra are shown in Figure 1, where we also show compensated spectra.

We have consider (i) hydrodynamic decay, (ii) nonhelical MHD decay, and (iii) helical MHD decay. In cases (ii) and (iii), the magnetic energy also drives kinetic energy through the Lorentz force. Case (iii) leads to standard inverse transfer.

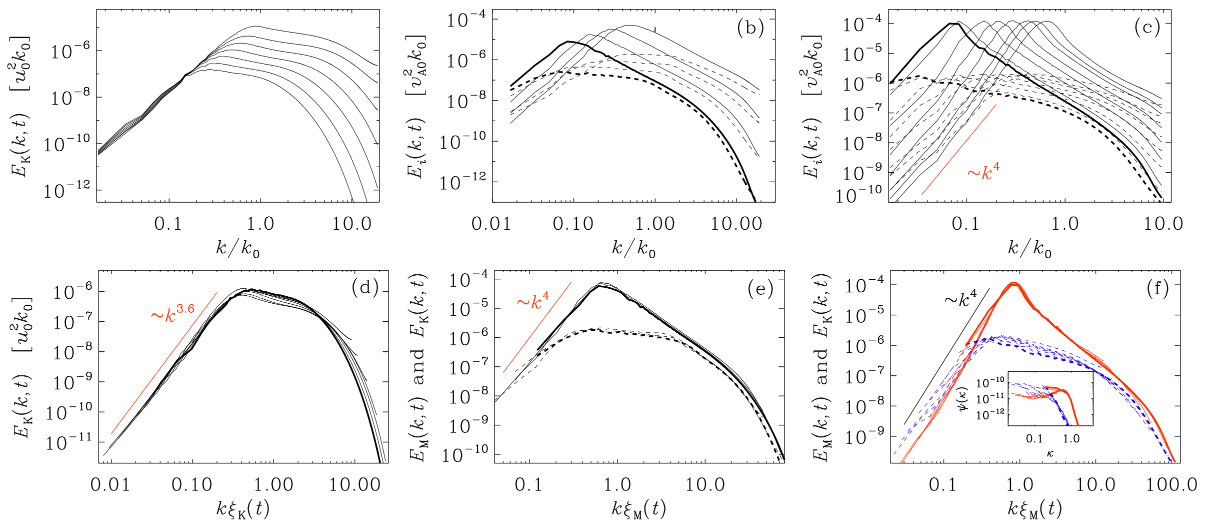

Figure 1: $E_{\rm K}(k,t)$ for different t in a hydrodynamic DNS (a), compared with $E_{\rm M}$ (solid) and $E_{\rm K}$ (dashed) in MHD without helicity (b), and with (c). Panels (d)–(f) show collapsed spectra using $\beta = 3$ (d), $\beta = 1$ (e), and $\beta = 0$ (f).

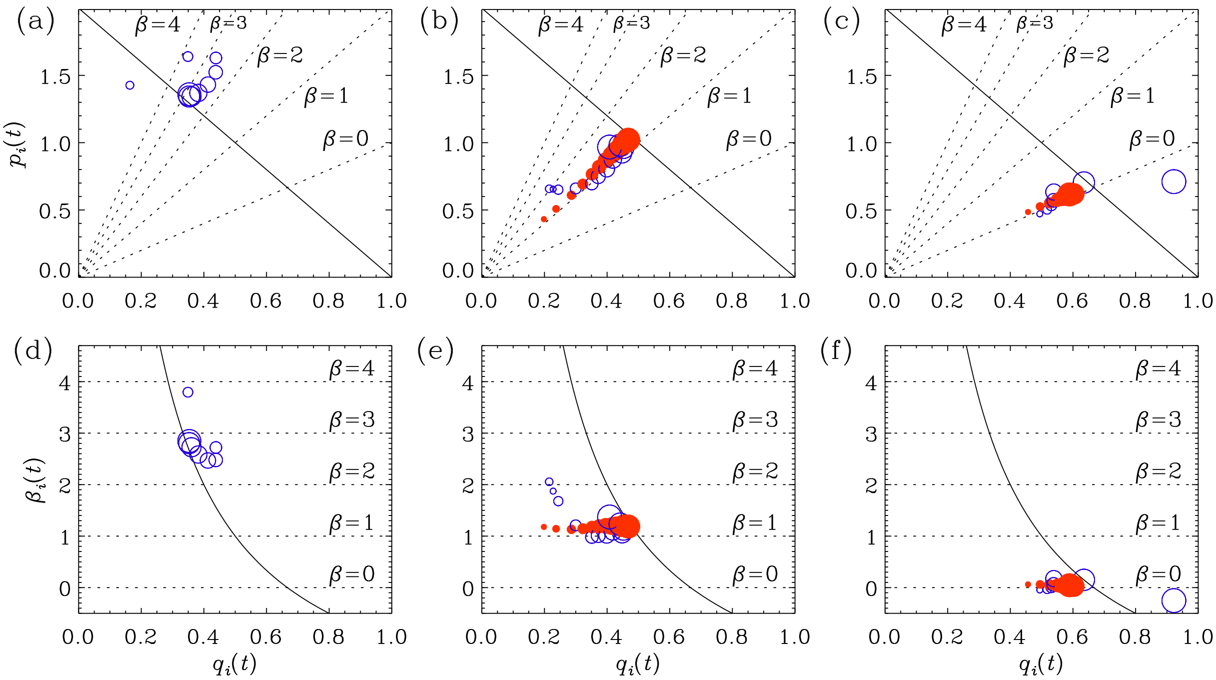

Figure 2: pq diagrams for the cases (i)–(iii) shown in Figure 1. Panels (d)–(f) show the corresponding βq diagrams. Open (closed) symbols corresponds to $i = \mathrm{K}$ (M) and their sizes increase with time.

Our solutions (i)–(iii) describe different tacks in the pq diagram; see Figure 2. The temporal decay of kinetic and magnetic energies follows power laws $\mathcal{E}_i(t) \sim t^{-p_i}$ for $i = \mathrm{K}$ or M. The exponents are obtained by integrating the spectra over k, $\mathcal{E}(t) \equiv \int E(k,t)\, dk = \xi^{-(\beta+1)} \int \phi\, d(k\xi) \propto t^{-p}$, and since $\xi \propto t^q$, this yields

$$p = (1+\beta)\, q. \tag{1}$$

Thus, in a pq diagram, a certain value of β corresponds to a line $p(t) \propto q(t)$ with the slope $\beta + 1$.

Chiral MHD. We have programmed the equations of chiral MHD, which is relevant to the early universe where fermion chirality couples to magnetic helicity Boyarsky et al. (2012, 2015) This work is currently being carried out by our new post-doc, Jennifer Schober. Large-scale three-dimensional simulations have already been performed.

Effect of convection on magnetized disk accretion. We use radiation magnetohydrodynamic simulations in a shearing box to study the energy conversion from Keplerian rotation to turbulent magnetic energy by the combined magneto-rotational and dynamo instabilities to heat and radiation near the disk surfaces. We start with a non-uniform, mostly toroidal magnetic field near the midplane of the disk. This field develops into a turbulent field through the magneto-rotational instability which in turn re-amplifies the magnetic field through the dynamo instability (Brandenburg et al., 1995; Brandenburg, 2008). Most of the earlier simulations have ignored radiative cooling, which is however important when trying to understand global stability of the disk (local dissipation should increase with increased local surface density in the disk). We therefore include radiation transport including the H^- opacity as well as partial hydrogen ionization, both of which lead to convection near the surfaces.

Coronal mass ejections from a global turbulent dynamo. Dynamos in spherical geometry have displayed recurrent CME-like ejection phenomena Warnecke et al. (2011, 2012). They have also displayed surprising magnetic helicity reversals with distance from the stellar surface that agree qualitatively with solar wind measurements (Brandenburg et al., 2011). We are currently repeating earlier isothermal models, but now with larger latitudinal and longitudinal extents. Next, we improve those models to include thermodynamics and allow for a significant temperature and density jump at the surface. We search for similarities with actual CMEs, study the relation with actual surface magnetic fields, and explore possibilities to utilize such models in space weather prediction.

Magnetic helicity reversal above the solar surface. Magnetic helicity is a topological invariant in magnetohydrodynamics (MHD) and has therefore been used for a long time to characterize the solar magnetic field's complexity. Being a conserved quantity, the underlying dynamo can only produce equal amounts of positive and negative magnetic helicities separated in space (north and south) and/or in scale (large and small wavenumbers Brandenburg and Subramanian, 2005). In addition to using solar surface vector magnetograms, one can use the strong wavelength dependence of Faraday rotation to infer magnetic twist in the corona at long wavelengths (infrared to sub-millimeter radio wavelengths), where Faraday depolarization becomes significant (Brandenburg & Stepanov, 2014). We use vector magnetograms of the solar surface to compute the wavenumber dependence of solar magnetic helicity, verify that its integral value is compatible with that from independent measurement techniques, and study its variation with the solar cycle and solar latitude (Pipin & Pevtsov, 2014; Zhang et al., 2014, 2016). Next, we assess the feasibility of using infrared and radio measurements to infer the magnetic helicity of coronal magnetic fields.

Code and test case For all runs, the Pencil Code will be used. The code uses explicit sixth order finite differences. The time step is third-order. Power spectra are computed during the run, but our current parallelization of the Fourier transform requires that the meshpoint number is an integer multiple of the product of processor numbers in the y and z directions and the product of processor numbers in the x and y directions.

3 Requested resources

Almost all the problems described above will principally use the Pencil Code[1], which is hosted by Google–Code since 2008[2]. This is an open-source code developed by myself, my current and former coworkers, some of whom are part of this project, as well as others that have been invited to join the effort. The performance of this code has been discussed at several international conferences; see, e.g.,

[1]`http://www.nordita.org/software/pencil-code`
[2]`http://pencil-code.googlecode.com`

http://www.nordita.org/~brandenb/talks/misc/PencilCode09.ppt. The code has been optimized over the years and is still being improved in terms of performance and new features are also being added. All of the 21,209 revisions since 2001 are publicly available through our svn repository. We have adapted and optimized this code for spherical polar coordinate system (Mitra et al., 2009). This addition to the code is used in several of the problems listed in the previous section. The code runs well on all the different platforms.

On Beskow, we run production runs with $1024^2 \times 1536$ meshpoints on 6144 cores, while on Hebbe, most of our production runs tend to have 512^3 meshpoints and can require typically 512 processors. A typical run requires at least $500,000$ time steps, but it can sometimes be much more, depending on circumstances. With $4.2 \times 10^{-4} \mu$s per meshpoint and per timestep on Besko, this means 4 days of wallclock time at a cost of 600,000 CPU hours, while with $3.5 \times 10^{-3} \mu$s per meshpoint and per timestep, this means 3 days of wallclock time at a cost of 30,000 CPU hours per run.

To address properly the critical question of the dependence on the magnetic Reynolds number we have to use high resolution runs. As we move from 256^3 and 512^3 to $1024^2 \times 1536$ mesh points (and correspondingly higher magnetic Reynolds numbers), we see the emergence of small-scale dynamo action at all depth. This does not yet affect the 512^3 runs, where the red line shows still a well-developed maximum of $\overline{B}/B_{\rm eq} \approx 1$, but for the $1024^2 \times 1536$ the maximum is now only one third of that. We expect that this value will not decrease further, and that it will actually become bigger at larger stratification, but this needs to be shown. Note that the last of these runs is for a deeper domain, so as to include more safely the deep parts where it is important to reach values of $\overline{B}/B_{\rm eq}$ below 0.01, but this appears not to be possible due to small-scale dynamo action.

To confirm our ideas and to understand the effects of small-scale dynamo action, we plan to perform about 2 big runs per month on Beskow, which requires at least 1000 kCPU hours, and about 5 intermediate ones on the other 3 machines, which requires 150 kCPU hours on each of them.

Computationally, all machines are comparable, but there can be unpredictable changes that hamper scientific progress. Most important is the waiting time in the queue and occasional opportunities when jobs start immediately. On Hebbe, the disk quotas restrict the ease with which we can run, while on Gardar there have been several periods when the machine was not functioning properly.

References

Boyarsky, A., Fröhlich, J., & Ruchayskiy, O., Phys. Rev. Lett. **108**, 031301 (2012).

Boyarsky, A.; Fröhlich, J., & Ruchayskiy, O., "Magnetohydrodynamics of chiral relativistic fluids," *Phys. Rev. D* **92**, 043004 (2015).

Brandenburg, A., "The dual role of shear in large-scale dynamos," *Astron. Nachr.* **329**, 725-731 (2008).

Brandenburg, A., & Stepanov, R., "Faraday signature of magnetic helicity from reduced depolarization," *Astrophys. J.* **786**, 91 (2014).

Brandenburg, A., & Subramanian, K., "Astrophysical magnetic fields and nonlinear dynamo theory," *Phys. Rep.* **417**, 1-209 (2005).

Brandenburg, A., Nordlund, Å., Stein, R. F., & Torkelsson, U., "Dynamo generated turbulence and large scale magnetic fields in a Keplerian shear flow," *Astrophys. J.* **446**, 741-754 (1995).

Brandenburg, A., Subramanian, K., Balogh, A., & Goldstein, M. L., "Scale-dependence of magnetic helicity in the solar wind," *Astrophys. J.* **734**, 9 (2011).

Mitra, D., Tavakol, R., Brandenburg, A., & Moss, D., "Turbulent dynamos in spherical shell segments of varying geometrical extent," *Astrophys. J.* **697**, 923-933 (2009).

Pipin, V. V., & Pevtsov, A. A., "Magnetic Helicity of the Global Field in Solar Cycles 23 and 24," *Astrophys. J.* **789**, 21 (2014).

Warnecke, J., Brandenburg, A., & Mitra, D., "Dynamo-driven plasmoid ejections above a spherical surface," *Astron. Astrophys.* **534**, A11 (2011).

Warnecke, J., Brandenburg, A., & Mitra, D., "Magnetic twist: a source and property of space weather," *J. Spa. Weather Spa. Clim.* **2**, A11 (2012).

Zhang, H., Brandenburg, A., & Sokoloff, D. D., "Magnetic helicity and energy spectra of a solar active region," *Astrophys. J. Lett.* **784**, L45 (2014).

Zhang, H., Brandenburg, A., & Sokoloff, D. D., "Magnetic helicity and energy spectra of a solar active region," *Astrophys. J.* **819**, 146 (2016).