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)
Ms Sarah Jabbari (PhD student, Licentiate 19 May 2014)
Ms Illa R. Losada (PhD student, Licentiate 5 December 2014)
Dr Harsha Raichur (Post-doc)
Dr Jennifer Schober (Nordita fellow)
Dr Nishant Singh (Post-doc)
Dr Dhrubaditya Mitra (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 works of PhD students Sarah Jabbari and 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, as is seen in Figure 1, which is from a paper by Losada et al, which is in preparation. This is not a usual instability, but a secondary one of the turbulent background state. It can also be described with with mean-field equation, as we have been able to show in previous work.

The latest work by Jabbari et al. has shown that spot formation proceeds through the development of current sheets which leads to sharp structures; see Figure 2. There are many parallels with turbulent reconnection and our work makes direct contacts to these.

Helioseismology and other topics. Our other research covers various topics ranging from coagulation of particles in turbulent flows (work with Li and Mitra; supported by the Norwegian Research Council and the Wallenberg foundation, respectively), to magnetic flux concentrations in the Sun (mentioned

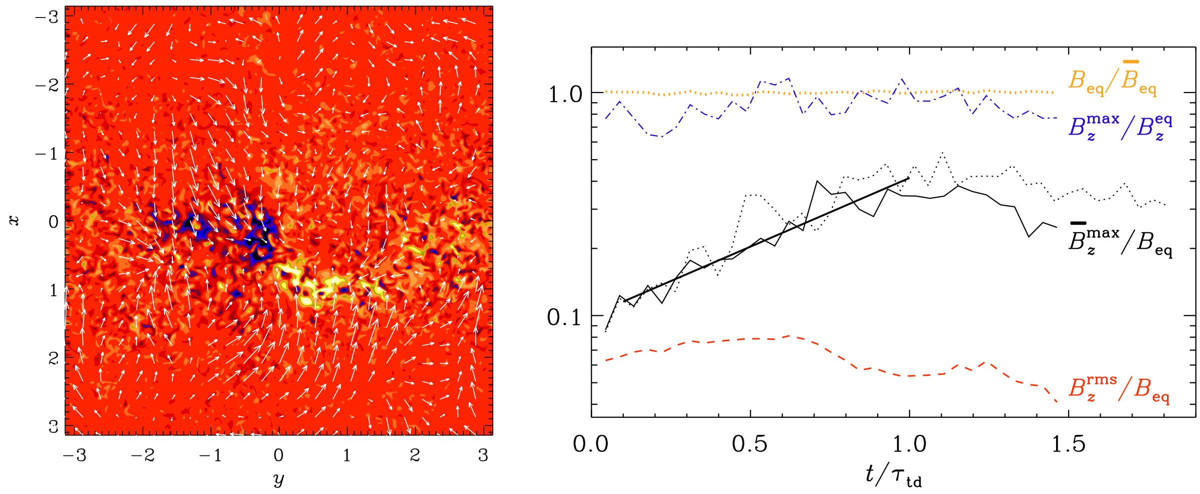

Figure 1: Left: instantaneous value of $B_{\rm eq}$ normalized by the temporal average $\overline{B}_{\rm eq}$ (orange dotted line). The dotted black line near the curve for $\overline{B}_z^{\rm max}/B_{\rm eq}$ shows this same quantity for $1152^2\times 2304$ meshpoints. Right: evolution of $\overline{B}_z^{\rm max}/B_{\rm eq}$ vs. time showing exponential growth (black solid line), compared with that of $B_z^{\rm rms}/B_{\rm eq}$ (red dashed) and $B_z^{\rm max}/B_{\rm eq}$ (blue dash-dotted).

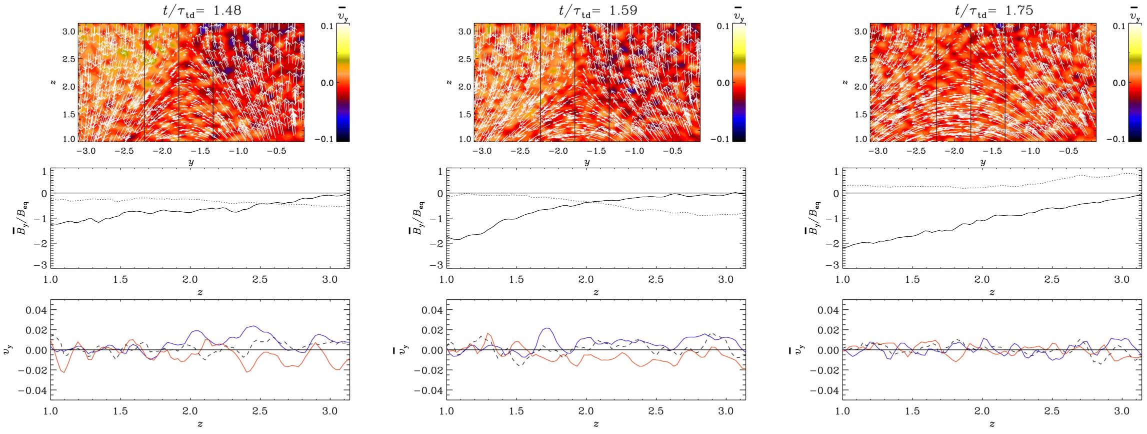

Figure 2: Formation of current sheet and magnetic reconnection (upper panel) at $\mathrm{Re}_M = 130$, the time evolution of $\overline{B}_y$ (middle panel), and the time evolution of V_y (lower panel).

above and supported through two VR grants) and helioseismology (Singh; also supported through VR, and Raichur, supported by Nordita). The work has been highly successful as is evidenced by the papers published in just the last 12 months, and promises to be even more vigorous owing to the expansion of the research to include coagulation studies.

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.

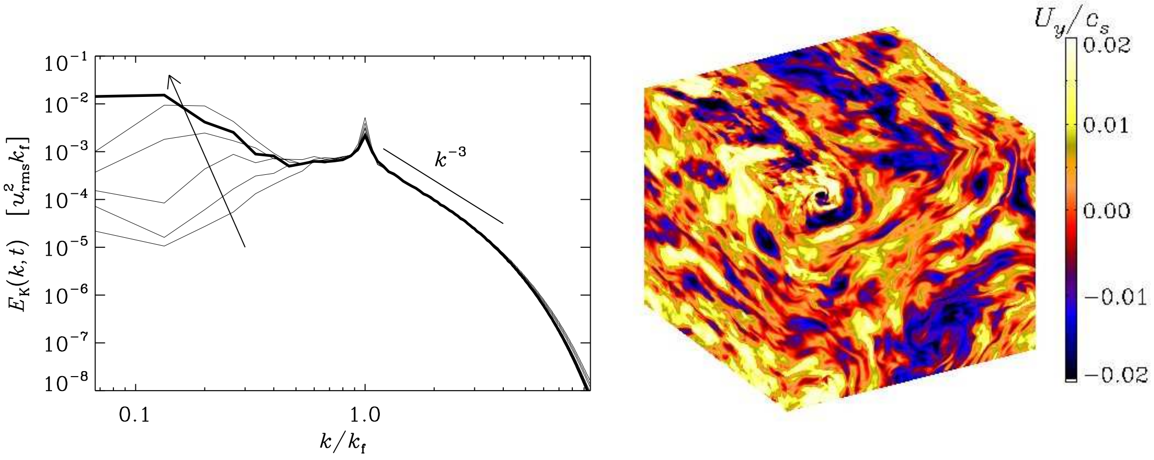

Figure 3: Left: Inverse transfer seen in kinetic energy spectra at different times. Right: Axial flow component on the periphery of the domain.

Inverse hydrodynamic cascade. A new type of inverse cascade has been discovered and is currently being prepared for publication jointly with Nobumitsu Yokoi from Tokyo; see Figure 3.

There are various other aspects of solar convection that are currently being investigated at the more theoretical level Brandenburg (2015), but related large-scale simulations have already been started.

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., `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 Abisko, Gardar, and Triolith, 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

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

[2] `http://pencil-code.googlecode.com`

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 Abisko and Triolith, 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

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

A. Boyarsky, J. Fröhlich and O. Ruchayskiy, ArXiv: 1504.04854.

Brandenburg A. 2015, ApJ, submitted, arXiv:Stellar mixing length theory with entropy rain arXiv:1504.03189

Mitra, D., Tavakol, R., Brandenburg, A., & Moss, D. 2009, ApJ, 697, 923