

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 Andrea Bracco (Post-doc)

Dr Dhruvaditya Mitra (assistant professor)

Dr Lars Mattsson (assistant professor)

Note that much of the work of Dhruvaditya 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.

Gravitational wave polarization. We study the influence of helical magnetic fields on the production of gravitational waves. Gravitational waves provide an as yet unexplored window into the earliest moments of the Big Bang, not obscured by the last scattering surface given by the hitherto studied cosmic microwave background. The production of gravitational radiation from cosmological turbulence was calculated analytically by Kosowsky et al. (2002) and Gogoberidze et al. (2007). Helical magnetic fields produce non-vanishing cross-polarization in the gravitational wave spectrum (Kahniashvili et al., 2005; Caprini & Durrer, 2006), which would be observable with LISA (Binétruy et al., 2012). Hindmarsh et al. (2017) have recently presented detailed numerical models of gravitational waves from phase transition nucleation bubbles produced during the electroweak phase transition (Kamionkowski et al., 1994; Nicolis,

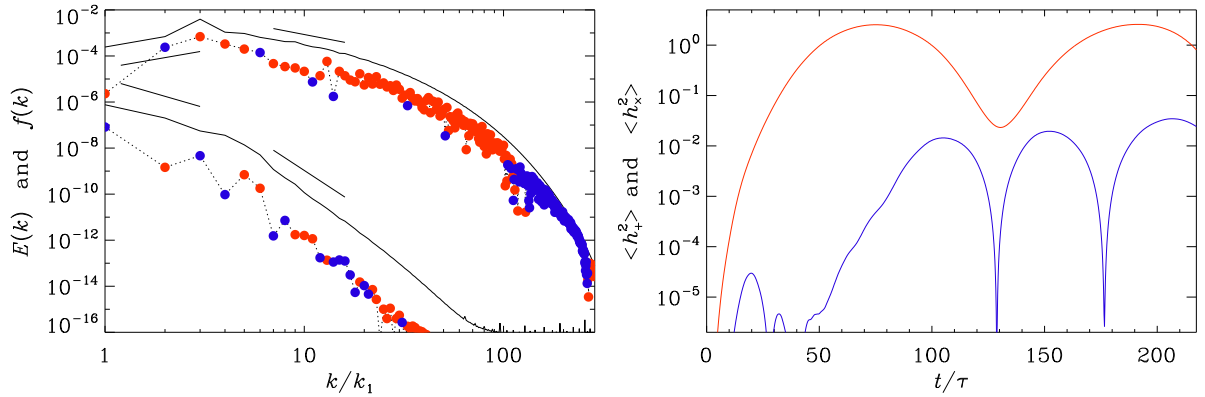


Figure 1: *Left*: preliminary kinetic and GW spectra (upper and lower black lines, respectively), along with kinetic helicity and GW polarization spectra. The slopes are $+1.5$ and -2.5 for $1.2 < k/k_1 < 3$ and -1.67 and -5.67 for $7 < k/k_1 < 16$, where k_1 is the smallest wavenumber of the computational domain. Red (blue) symbols denote positive (negative) values. *Right*: time series of $\langle \hat{h}_+^2 \rangle$ (red) and $\langle \hat{h}_-^2 \rangle$ (blue) with time t in units of the turnover time, $\tau = (u_{\text{rms}}/k_f)^{-1}$ and $k_f = 3k_1$ is the forcing wavenumber.

2004). Our new work involves the calculation of gravitational waves using the PENCIL CODE, where a gravitational wave solver has already been successfully implemented; see Figure 1.

Chiral MHD. The chiral magnetic effect leads to a current along a magnetic field if the number of left- and right-handed Fermions is unequal. This effect has received significant attention in just the last few years. We are now able for the first time to perform a comprehensive study of the chiral magnetic effect in real turbulence. Earlier theoretical studies applied to neutron stars and the early Universe did not result in realistic estimates for the turbulence. Thus, the use of simulations is absolutely critical to making significant progress. Our recent work on the early Universe has brought us a significant step forward. We will now focus on neutron stars, which may have several important advantages. First, only one sign of chirality will be produced. Second, the timescales are short, giving us ample time for the subsequent inverse cascade to yield large length scales. Together with the helicity produced from rotation and stratification, the end result may produce a realistic model of observed pulsars.

EB polarization in the Sun and in other types of turbulence. We are currently investigating the theoretical predictions of the solar EB-type polarization characteristics (Seljak & Zaldarriaga, 1997; Kamionkowski et al., 1997). This is a concept familiar from the analysis of the cosmic microwave background polarization data, but unfamiliar in the context of solar physics. The EB polarization signature is obtained by computing

$$\tilde{E} + i\tilde{B} = (\hat{k}_x - i\hat{k}_y)^2 (\tilde{Q} + i\tilde{U}), \quad (1)$$

where a tilde denotes the Fourier transform and the hats denote components of the unit vector of \mathbf{k} in the xy plane. The significance of the EB representation is that it leads to a separation into a parity even (E) and a parity odd (B) component. We have confirmed that for magnetically dominated turbulence, the EE correlation exceed the BB correlation by a factor of about 1.6, which is slightly less than the factor of two that has been found from the the foreground polarization detected with PLANCK (Adam et al., 2016), but more than what is theoretically expect (Caldwell et al., 2017), which we confirm for magnetically subdominant turbulence. A factor of two was already theoretically be explained by Kandel et al. (2017), but not with real turbulence simulations yet.

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). 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. We study the resulting feedback on the disk accretion rate and its dependence on the surface density, which has implications on understanding transitions from low to high accretion states in disks.

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 CODE¹, which is hosted by Github since 2015². 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 27,663 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 Beskow, 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 $\overline{B}/B_{eq} \approx 1$, 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_{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.

¹<http://www.nordita.org/software/pencil-code>

²<https://github.com/pencil-code>

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