Detailed project description:
Astrophysical turbulence and dynamo action

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Abstract

A new astrophysics activity at Nordita focusses on the calculation of the stochastic gravitational wave (GW) background. Specifically, we determine, using numerical simulations and analytical approach, the strengths of the resulting GW field at the present time for a range of GW sources associated with turbulent stresses in the energy-momentum tensor. Another activity concerns the interaction of particles with turbulence and the growth of cloud droplets. This activity is supported by a grant on Bottlenecks for the growth of particles suspended in turbulent flows (Knut & Alice Wallenberg Foundation, with Professor Mehlig from Gothenburg as PI).

1 Background

The work in the astrophysics group at Nordita covers a broad range of topics from gravitational wave physics and the early universe to solar physics and meteorology. Our research group consists currently of the following people:

Ms Illa R. Losada (PhD student, Licentiate 5 December 2014)
Dr Akshay Bhatnagar (Post-doc)
Dr Upasana Das (Nordita fellow)
Dr Joonas Nättilä (Nordita fellow)
Dr Lars Mattsson (assistant professor)
Dr Dhrubaditya Mitra (assistant professor)
Dr Alexandra Veledina (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.

2 Scientific content

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, 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.

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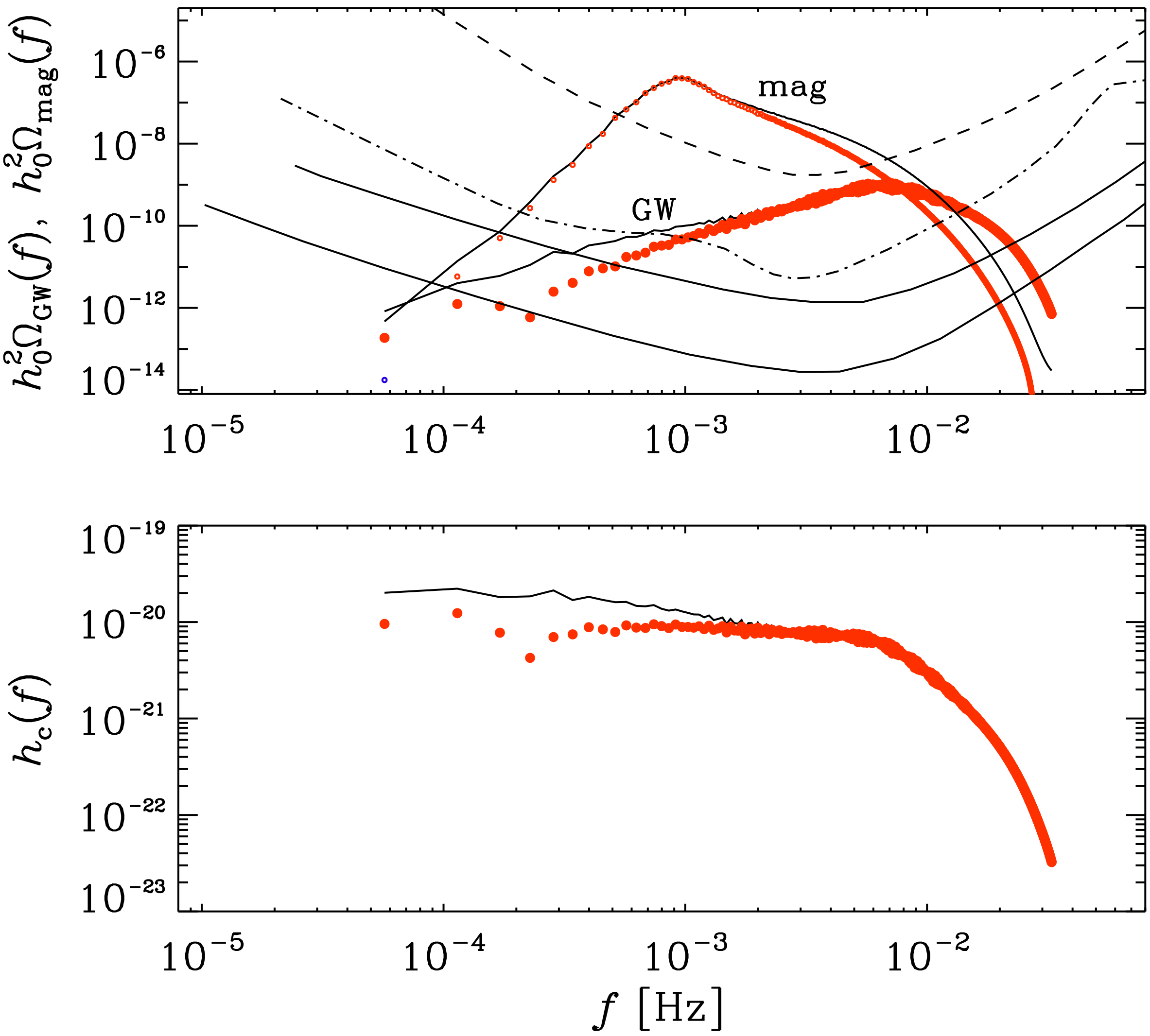

Figure 1: Simulation results for $h^2\Omega_{\rm GW}(f)$ and $h_{\rm rms}$. The upper and lower straight lines denote the eLISA sensitivity curves in the 4-link configurations with 2×10^9 m arm length and the 6-link configurations with 6×10^9 m arm length after 5 years duration. (Unpublished results.)

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

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

where a tilde denotes the Fourier transform and the hats denote components of the unit vector of $\boldsymbol{k}$ 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.

Kinetic plasmaphysics. The microphysics of non-thermal plasma can only be captured by kinetic simulations. This requires evolving the location and momentum of electrons and ions separately as individual computational particles instead of describing the system as macroscopic fluid. Solving the full six-dimensional Vlasov equation is, however, computationally an enormous obstacle as it requires evolving 6D simulation domains. As a new effort at Nordita, we have begun developing a computational framework to enable such simulations, called PlasmaBox framework. Most importantly, by being able to simulate the microphysics of astroplasmas, we can study the mechanisms behind particle acceleration, a physical phenomenon where kinetic small-scale plasma processes accelerate electrons and ions up to ultra-relativistic velocities.

Collisionless shocks are one possible particle energization engine thought to be powering many astrophysical systems such as supernova remnants and gamma-ray bursts. As our first application, we will focus on simulating these relativistic colliding plasma flows with the so-called Vlasov method where local momentum distribution of particles is presented with an adaptive 3D mesh. Collisionless shock setups can be studied, as a first approximation, in one spatial dimension. This enables us to start applying the code from early on to real astrophysical problems. Applying the Vlasov method to such systems would mark the first high-resolution study of the plasma processes powering these shocks.

Another particle energization mechanism, that has gained a lot of attention lately, is relativistic magnetic reconnection. In this microphysical plasma phenomena the magnetic field changes its topology and the magnetic field lines undergo the microphysical reconnection (Lyubarsky, 2005). The subsequent evolution of the system appears even more intriguing: the configuration is unstable for the plasmoid instability where blobs of plasma are captured by the surrounding and changing magnetic fields and are being accelerated by the dragging motion of the evolving field. Simulating the nonlinear evolution of such systems requires two spatial dimensions (and three momentum dimensions). Therefore, the problem of magnetic reconnection appears as a natural continuation from the one-dimensional collisionless shocks. Understanding the late-time evolution and coupling of plasma and radiation in the reconnection phenomena is of paramount importance to astrophysics because it is thought to power many of nature's most powerful phenomena such as black hole accretion disks and jets. It is also physically interesting to study the coupling of radiation and plasma, made possible by the radiation module in PlasmaBox.

Coupling radiative processes to the plasma under reconnection would mark the first self-consistent study of radiative relativistic reconnection.

Code and test case. For the first set of 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.

For the plasma reconnection runs, PlasmaBox will be used. It is an open-source framework developed at Nordita, and publicly available from GitHub.[1] The code is still being actively developed, but already now has a fully functioning 1D3V relativistic Vlasov solver, first of its kind in astrophysics community. It also includes a 2D3V particle-in-cell module capable of solving the same Vlasov-Maxwell system of equation with particles instead of phase-space fluid representation. Full 3D capability is currently under development.

The code is written in modern C++-14 relying on polymorphism and template metaprogramming, that allow the code to be easily extended. It implements a three-level parallelization scheme that takes advantage of low-level processor instruction vectorization (single instruction, multiple data; SIMD), shared-memory parallelism (openMP threading), and distributed-memory parallelism (Message Passing Interface; MPI). The simulation framework is build on a novel, massively parallel open-source library CORGI[2] that uses patch-based super-decomposition for load balancing. This allows interleaved (non-blocking) communications and particle/fluid evolution to hide computational communication costs. In addition to the underlying numerically efficient C++ implementation, all of the classes also have a Python3 interface. This way, many of the simulation setups can be quickly prototyped in a local laptop and then scaled up to supercomputer platforms for the actual production runs.

3 Requested resources

Almost all the problems described above will principally use the Pencil Code[3], which is hosted by Github since 2015[4]. 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 28,995 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 up to 2304^3 meshpoints on 9216 cores. A typical run requires at least $500,000$ time steps, but it can sometimes be much more, depending on circumstances. With $4.2 \times 10^{-4} \mu\,\mathrm{s}$ per meshpoint and per timestep on Beskow, this means 4 days of wallclock time at a cost of 600,000 CPU hours, while with $3.5 \times 10^{-3} \mu\,\mathrm{s}$ 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 288^3 and 576^3 to 2304^3 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 576^3 runs, where the red line shows still a well-developed maximum of $\overline{B}/B_{\rm eq} \approx 1$, but for the 2304^3 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

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[1] `https://github.com/natj/plasmabox`

[2] `https://github.com/natj/corgi`

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

[4] `https://github.com/pencil-code`

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.

In its current form, one Vlasov fluid cell update takes about 12μs/cell/CPU using the PlasmaBox code. Typical 1D3V relativistic Vlasov simulations of the collisionless shocks are 20,000 spatial cells large with 1000 momentum space cells, and the system is evolved for 300,000 simulation timesteps. This translates to 3 days of wallclock time at a cost of 20 kCPU hours per run. To be able to do parameter sweeps we therefore estimate that 150 kCPU hours per month is enough to start testing the code on Kebnekaise cluster.

For the reconnection studies, more resources are needed. Here a typical particle update per simulation cycle is 4μs/particle/CPU. Final production runs consists of about 100,000 simulation steps and 10^9 particles, translating to 2 days of wallclock time with a cost of 130 kCPU hours. Occasionally larger resources are also needed for example to asses the weak and strong scalability of the code beyond few nodes.

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.

Strong scaling

Regarding scaling tests, we have previously determined strong scaling on Triolith for three mesh sizes. The time per time step and mesh point is given for different processor numbers and layouts. Generally, it is advantageous to keep the number of processors in the x direction small. The code is well adapted to modern computing platforms.

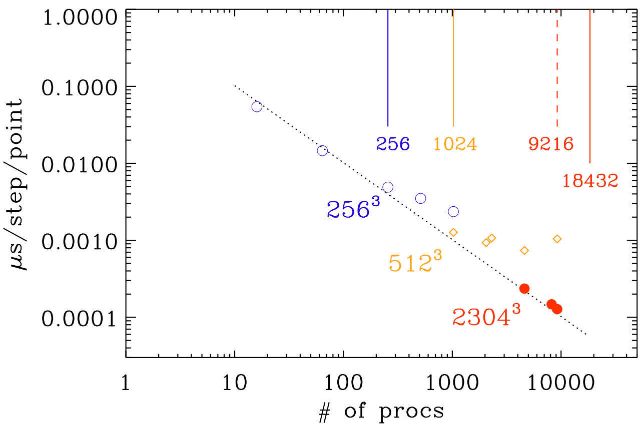

Figure 2: Strong scaling of Pencil Code on Triolith.

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