Detailed project description:
Astrophysical turbulence and dynamo action

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October 9, 2019

1 Overview

The microphysics of non-thermal plasmas 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 a macroscopic fluid. These kind of simulations are known as kinetic plasma simulations. As an new effort at Nordita, we have developed a novel high-performance computing framework to enable such simulations, called Runko. Most importantly, by being able to simulate the microphysics of astroplasmas, we can study the mechanisms behind particle acceleration, a physical phenomenon where kinetic plasma processes accelerate electrons and ions up to ultra-relativistic velocities.

Another astrophysics activity at Nordita focuses on the calculation of the stochastic gravitational wave (GW) background. For those calculations we use the Pencil Code. 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). We also compute decaying and forced hydromagnetic turbulence in the one- and two-fluid descriptions to study the dynamo effect, the chiral magnetic effect, and ambipolar diffusion.

2 Resource usage

Our kinetic simulations are preformed with Runko framework. The code is open source and is publicly available from GitHub[1]. On Beskow our typical kinetic turbulence production runs with Runko are 5120^2 meshpoints and 3×10^9 particles on 1024 cores. A typical run requires $30,000$ time steps. With a standard particle push time of 3μs/particle/processor, this translates to about 1 day of wallclock time at a cost of 30,000 CPU hours per run. For $3D$ runs we require about a minimum of 1024^3 meshpoints. This is a factor of 40 increase in the cost. With 8192 processors and 30,000 time steps, this translates to about 5 days of wallclock time and 1,000,000 CPU hours per production run. Reconnection runs (both in 2D and in 3D) are of similar cost. Smaller kinetic plasma test runs are planned for Kebnekaise with a typical cost of $\sim$ 30,000 CPUh.

We will also run simulations with the Pencil Code[2], which is hosted by Github[3]. 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 30,431 revisions since 2001 are publicly available through our repository. We have adapted and optimized this code for spherical polar

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

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

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

coordinate system (Mitra et al., 2009). This addition to the code is used in several of the problems discussed here. 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 $4.2\times10^{-4}\mu$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 $3.5\times10^{-3}\mu$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 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. 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.

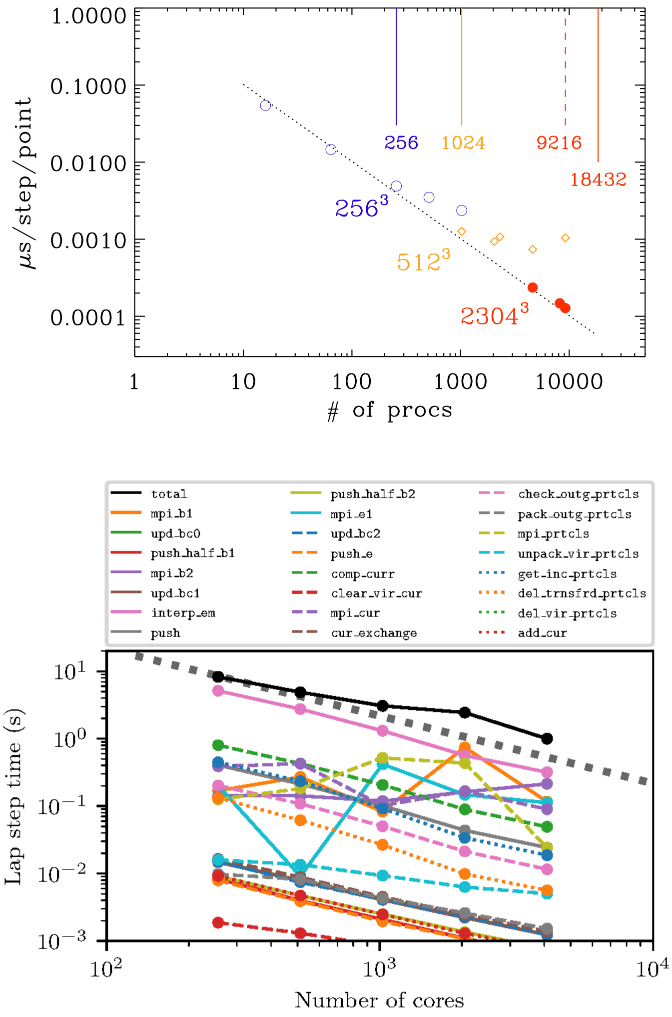

Figure 1: Strong scaling of Pencil Code on Triolith (top) and Runko on Beskow (bottom).

Computationally, all machines are comparable, but there can be unexpected future changes or outages on some machines 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 of Pencil code 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.

3 Scientific challenges

Kinetic turbulence in plasma around black holes and neutron stars Kinetic turbulence has been our first application of the framework. Here we use massively parallel particle-in-cell simulations within the Runko framework to study decaying turbulent plasma motions. Our large 2D simulations during 2019 have enabled us to study the magnetohydrodynamical turbulence from a completely different angle with self-consistent fully-kinetic plasma simulations. At the moment there are only two other groups with a capability to perform such a massive supercomputer simulations. This puts us in a unique position to start exploring this new regime of turbulence even further. At the moment, our completed simulations have already reveled a new energy dissipation mechanism for the turbulent plasmas in a form of localized non-thermal particle production in the so-called current sheets. This pioneering computational work will help us in formulating a more self-consistent theory of relativistic turbulence from first principles, currently under construction. Our next efforts in this field is to start focusing on high-fidelity 3D simulations. This helps us to really confirm the validity of our previous 2D simulation results and opens up a whole new window into studying the dynamics of the different structures seen in the simulations.

Another particle energization mechanism, that has gained a lot of focus as a promising alternative to turbulence, is relativistic magnetic reconnection. In this microphysical plasma phenomena the magnetic field changes its topology and the magnetic field lines undergo a microphysical reconnection (Lyubarsky, 2005). The subsequent evolution of the system appears even more intriguing: the configuration is unstable for the plasmoid tearing instability where blobs of plasma are captured by the surrounding and reconnecting magnetic fields and are being accelerated by the dragging motion of the evolving field. 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 Runko. Coupling radiative processes to the plasma under reconnection would mark the first self-consistent study of radiative relativistic reconnection.

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.

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.

Solar/stellar dynamo simulations. Local simulations will be used to develop what we call smart boundary conditions (BC) for application in the global simulations. The purpose of such BCs is to compactify the small-scale physics of the surface-driving layer in order to control the global simulations, which cannot resolve these scales, in a physically realistic way. Here we assume that (i) stellar turbulence is essentially driven by cooling in the surface-driving layer and (ii) large-scale structures like giant cells or a global dynamo field would not markedly affect neither the SDL nor the overall properties of the convection. Then, local Cartesian boxes which extend vertically just deep enough so that the (non-physical) boundary conditions to be applied at their bottom have no significant effect on the near-surface convection (say, 30 Mm deep) and which are horizontally just wide enough to capture the essential topology and dynamics of the granulation will be employed to solve the full convection problem with the necessary high grid resolution (say, 100 Mm horizontal extent) and with physically meaningful boundary conditions at their top. Time series of the simulated physical quantities on a horizontal plane placed at the estimated bottom of the surface-driving layer inside the computational box will be employed to define the boundary conditions at the top of a global simulation model which extends from the bottom of the convection zone (say 200 Mm depth) with physically meaningful boundary conditions to the bottom of the surface-driving layer. A simple way of doing this consists in directly employing the quantities from the local-box simulations as Dirichlet boundary conditions of the global model. Due to its coarser resolution, the data have to be properly restricted. As the simulated model time interval of the global model will in general be much longer than the one of the local model, the problem arises how the boundary values should be repeatedly used without introducing a strict periodicity. This approach will allow incorporating the NSSL in the global simulations, without needing to resolve the SDL in one and the same model.

4 Research group

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

Dr Akshay Bhatnagar (post-doc)
Dr Mattia Bulla (Nordita fellow)
Dr Upasana Das (Nordita fellow)
Dr Illa R. Losada (visiting post-doc)
Dr Joonas Nättilä (Nordita fellow)
Dr Guðlaugur Jóhannesson (assistant professor, shared with University of Iceland)
Dr Lars Mattsson (assistant professor)
Dr Dhrubaditya Mitra (assistant professor)
Dr Alexandra Veledina (assistant professor, shared with University of Turku)

Note that part 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.

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