

Detailed project description: Astrophysical turbulence and dynamo action

(Nordita, Stockholm)

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1 Overview

Earlier this year, we received significant funding from the European Research Council for a Synergy Grant (COSMOMAG) under grant No. 101224803, together with Franco Vazza (Bologna), Chiara Caprini (CERN), and Andrii Neronov (Paris and Lausanne). Additional funding comes now from VR under grant No. 2025-05957. Arrhenius is already our main production platform for the COSMOMAG work on primordial magnetic fields from electroweak-scale $SU(2)$ configurations.

In the astrophysics group at Nordita, we are routinely using the PENCIL CODE¹, which is hosted by Github². Over the past few years, this code has been extended to be accelerated by GPUs. The PENCIL CODE group in Finland has been developing it on LUMI, and more recently, we also have benchmarked the code on Dardel. The speedup is up to a factor 16 for problems of practical interest. For a subset of our research, the GPU acceleration has not yet been implemented. Therefore, we also request standard CPU-based time. Also, at least on Dardel, the total problem size that we can simulate with GPU acceleration may not yet be large enough, which is another reason why we also need time on CPU nodes.

The PENCIL CODE is an open-source code developed by Brandenburg, his 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. 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 44,607 revisions since 2001 are publicly available through our repository. We have adapted and optimized this code for spherical polar coordinate system. This addition to the code is used in several of the problems discussed here. The code runs well on all the different platforms.

For our work on primordial magnetic fields from electroweak-scale $SU(2)$ configurations, we use 3D lattice simulations (up to 400^3) of dumbbell/sphaleron-like decays in an axion background, run with our own Julia $SU(2)$ lattice code as reproducible Slurm jobs (more than 150 runs so far, scanning separation, lattice spacing, twist and noise). We also run Pencil Code (chiral MHD + GWs, 512^3 on 512 ranks) to follow the resulting helical magnetic fields and their gravitational wave signal. In the next period we will complete the finite-box and resolution tests and the Pencil Code scans needed for the two papers in preparation. We also plan to extend the $SU(2)$ code beyond the present zero-temperature setup, to include thermal effects (thermal noise and friction, and a finite-temperature Higgs potential), a time-dependent and spatially varying axion background, and larger populations of interacting dumbbells. This will let us connect the lattice results to realistic electroweak-era conditions and to the magnetic-field and LISA-band GW signals expected today, and will require substantially more computing time than the present zero-temperature runs.

2 Resource usage

We begin by reviewing the performance of the GPU-accelerated simulations with the PENCIL CODE using both LUMI and Dardel.

¹<http://www.nordita.org/software/pencil-code> (The Pencil Code Collaboration, 2021)

²<https://github.com/pencil-code>

2.1 GPU-acceleration on the PENCIL CODE

All the scaling results reported here are based on three-dimensional simulations of decaying hydromagnetic turbulence, just as in the recent paper by Brandenburg et al. (2024). Here, we compare the PENCIL CODE (PC) on CPUs against the PC with Astaroth embedded (PC-A), where Astaroth³ (Puro et al., 2026) integrates the partial differential equations of magnetohydrodynamics while the PC performs all peripheral tasks (diagnostics & I/O). On Dardel, we build with `gfortran/gcc` and `nvcc` using the modules:

```
gcc/12.2.0   craype-accel-amd-gfx90a   PDC/23.12
PrgEnv-gnu/8.5.0   cray-mpich/8.1.27   rocm/5.7.0
```

For the timing results, we routinely output with the PC both the wallclock and normalized times per time step and mesh point. *On Dardel*, we performed the following set of tests: PC-A, 8GPUs = 1 node, grid size 512^3 , three repetitions:

```
Wall clock time/timestep/meshpoint [microsec] = 1.9076658E-03
Wall clock time/timestep/meshpoint [microsec] = 2.3275883E-03
Wall clock time/timestep/meshpoint [microsec] = 1.9224858E-03
```

Thus, the normalized times per time step and mesh point are between 1.9 and 2.3 nanoseconds. For completeness, we also indicate here the actual wallclock times for the same three runs:

```
Wall clock time [hours] = 7.119E-02 (+/- 5.5556E-12)
Wall clock time [hours] = 8.687E-02 (+/- 5.5556E-12)
Wall clock time [hours] = 7.175E-02 (+/- 8.3333E-12)
```

PC, 64 CPUs = 1 node, grid size 512^3 , two repetitions:

```
Wall clock time/timestep/meshpoint [microsec] = 2.2191811E-02
Wall clock time/timestep/meshpoint [microsec] = 2.2515382E-02
```

Thus, without GPU acceleration, the normalized times per time step and mesh point are between 22 and 23 nanoseconds, so the comparison reveals a *speedup of about 11*. For testing weak scaling, we also performed a problem that is 8 times larger using 8 nodes instead of 1:

PC-A, 64GPUs = 8 nodes, grid size 1024^3

```
Wall clock time [hours] = 7.786E-02 (+/- 5.5556E-12)
Wall clock time/timestep/meshpoint [microsec] = 2.6079823E-04
```

Thus, the normalized time per time step and mesh point is 0.26 nanoseconds. Here we only did one such test. Therefore, the comparison reveals roughly the same wall-clock time as with PC-A on one node and the same grid size per process. This is therefore very satisfactory.

On LUMI, we performed an analogous comparison:

PC-A, 1 node, 8 GPUs, grid size 380^3 ,

```
Wall clock time [hours] = 1.522E-02 (+/- 8.3333E-12)
Wall clock time/timestep/meshpoint [microsec] = 1.1079179E-03
```

Thus, the normalized time per time step and mesh point is 1.1 nanoseconds.
PC, 1 node, 64 CPUs, grid size 352^3

```
Wall clock time [hours] = 0.192      (+/- 5.5556E-12)
Wall clock time/timestep/meshpoint [microsec] = 1.7558866E-02
```

Thus, the normalized time per time step and mesh point is 18 nanoseconds, so the *speedup is about 16*.

Next, we report weak scaling results:

PC-A, 1 node, 8 GPUs, grid size 512^3 ,

³<https://bitbucket.org/jpekkila/astaroth/>

Wall clock time [hours] = 4.535E-02 (+/- 5.5556E-12)
Wall clock time/timestep/meshpoint [microsec] = 1.2150889E-03

PC-A, 8 nodes, 64 GPUs, grid size 1024^3 ,

Wall clock time [hours] = 1.261E-02 (+/- 5.5556E-12)
Wall clock time/timestep/meshpoint [microsec] = 4.2233689E-05

PC-A, 2048^3 , 64 nodes, 512 GPUs

Wall clock time [hours] = 1.510E-02 (+/- 5.5556E-12)
Wall clock time/timestep/meshpoint [microsec] = 6.3206880E-06

The last two runs show roughly equal wallclock time. The longer time for the smallest grid size remains unclear.

2.2 CPU simulations with the PENCIL CODE

On Dardel, we run production runs with up to 2048^3 mesh points on up to 32768 cores. A typical run requires at least 500,000 time steps, but it can sometimes be much more, depending on circumstances. With $4.2 \times 10^{-4} \mu\text{s}$ per meshpoint and per timestep on Dardel. We anticipate that the time will be about 4 days of wall clock time at a cost of 600,000 CPU hours, while with $3.5 \times 10^{-3} \mu\text{s}$ per meshpoint and per timestep, this means less than 3 days of wall clock 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 2048^3 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 512^3 runs, but for the 2048^3 run, small-scale dynamo action becomes critical. 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 the mean field normalized to the equipartition value 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 Dardel, which requires at least 1,000,000 CPU hours, and about 4 intermediate ones, which requires 150,000 CPU hours on each of them. To shed light on some of the observational features of accretion disks, particularly those related to interactions between the inflow stream and the accretion disk, we must run high-resolution global simulations with radiation. This is a new activity, where each run takes about 300,000 CPU hours. We plan to run three of those. Our total time requirement is therefore 2,500,000 CPU hours on Dardel and Tetralith combined.

Computationally, all machines are comparable, but there can be unexpected future changes or outages on some machines that hamper scientific progress. Important is also the waiting time in the queue and occasional opportunities when jobs start immediately. Most of our activity will reside on Dardel. However, to maximize our scientific productivity, and not to be affected too much by outages and long waiting times, we also apply for time on Tetralith.

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.

Performancewise, Cray with O2 optimization is equivalent to gnu with O3. While gnu-O3 is able to handle memory or whatever compiler problems much better, it is otherwise not better than Cray-O2, and often some 10–20% slows, but this is within the measurement accuracy; see <https://github.com/pencil-code/website/blob/master/NewsLetters/2021/newsletter3.pdf>. More details can be found on <https://github.com/pencil-code/pencil-code/tree/master/doc/timings>.

3 Data management plan

Computer-generated data need to be stored for later analysis and for restarting new simulations. Those are kept on temporary storage. In all cases, simulation data could be reproduced, if needed, based on the

input files that, in turn, are maintained using CVS, the Concurrent Versioning System, and are published at the end of each project; see the references with DOI numbers for 15 examples of data sets published on Zenodo; see Brandenburg(2023), Brandenburg & Protiti(2023), Brandenburg et al. (2022a,b), (2023a,b,c), Carenza et al. (2022), Haugen et al. (2021), He et al. (2021,2022), Kahniashvili et al. (2022), Käpylä et al. (2022), Mizerski, et al.(2023), Roper Pol et al. (2022), Sarin et al.(2023), Sharma & Brandenburg(2022), Zhou et al. (2022). Also the PENCIL CODE has DOI numbers 10.5281/zenodo.2315093 and 3961647. The Pencil Code Collaboration consists of 37 coauthors on a publication to be published in the Journal of Open Source Software.

Data Format and Content We maintain records of our progress using laboratory notebooks. The notebooks document the development of new ideas and hypotheses, the records of their tests and execution, the results of data analysis and simulation, and the final results of the research. Notebooks could contain drawings, calculations, text, plots, and images. Laboratory notebooks will be legible and reasonably organized. Many ideas may be mentioned and the reasons for choices amongst alternatives will be articulated. Each laboratory notebook entry will normally be marked with the date, and sufficiently detailed and clear account of the hypotheses tried and the decisions made. Every single computer run will be done in a separate directory that is being maintained under CVS, SVN (subversion), and git (GitHub). The same applies to all secondary analysis tools that are being used for all the plots and table outputs. The computer code itself (the PENCIL CODE) is being maintained by GitHub (<http://github.com/pencil-code>), allowing every older version to be retrieved both by the researcher and members of the public.

Results of the research will be made available in digital form using formatted or unformatted data, as well as idl save files. Images will be saved in standard image formats. The main research products will be available online in digital form. Manuscripts will appear in PDF format, and will contain text, calculations, drawings, plots, and images. The targeted journals for the results of this research project, such as, The Astrophysical Journal, Phys. Rev. Letters, Phys. Rev. D and E, and Physics of Plasmas, all provide a downloadable PDF copy of the manuscript on the web. In addition, the PIs and co-PIs will link to these journal publications from their respective research websites.

Data Access and Sharing All participants in the project will publish the results of their work. Papers will primarily be published in peer-reviewed journals and/or conference proceedings. The results may also appear in books. Primary data and other supporting materials created or simulated in the course of the work will be shared with other researchers upon reasonable request and within a reasonable time of the request. In many cases, documented data sets will also be made available on the website <https://www.nordita.org/~brandenb/projects/>.

Data Archiving and Preservation of Access Products of the research will be made available immediately. Preprints of manuscripts submitted to peer-review journals will be available online through the arXiv e-print service prior to publication. After the actual publication in journals, papers will be available online from the respective journal websites and linked to by the PI's research website. All data generated as a result of this project will be backed up daily to protect from loss of data from hardware failures, fire, theft, and other unforeseen events.

4 Sensitive data handling

Does not apply; all our data are public.

5 Scientific challenges

Inverse cascading in non-helical MHD. Today, high resolution numerical turbulence simulations are feasible. They allow for fairly large turbulent inertial ranges, but not all the resources must be spent on a large inertial range. It is also important to allow for enough scale separation toward very long length scales to avoid artifacts from a finite domain size. To help optimizing the computational resources, various groups have employed numerical tools to approach the physically relevant regime: (i) reduce the viscous

and diffusive subranges by adopting hyperviscosity and magnetic hyperdiffusivity, and (ii) to make the viscous and magnetic diffusion coefficients time-dependent, or do use, for example, slope-limited diffusion to prevent the code from crashing at early times when the turbulence is extremely vigorous and to allow for the physical viscosity to be as small as possible at late times. All these tools imply small artifacts that we need to examine very carefully. The slope-limited diffusion technique has recently been used in some of our simulations of chiral MHD. To assess the role of artifacts in simulations, we now need to perform more detailed studies by monitoring the evolutionary tracks in a pq diagram for different combinations of such numerical tools. We will therefore perform divers surveys to extract physically meaningful results from artifacts. This part will mostly be carried out with GPU-acceleration. However, some of the calculations with radiation transport will use CPUs for now.

Inflationary magnetogenesis and gravitational wave production. In two recent papers with Ramkishor Sharma, a new Nordita postdoctoral researcher, we have performed new simulations of inflationary magnetogenesis and gravitational wave production. In those models, we solved the equations for electromagnetic waves during the post-inflationary phase (the reheating phase), and switched to magnetohydrodynamics at the beginning of the radiation-dominated phase. In future models, we will include equations describing the evolution of scalar potentials in cosmology. This will lead to more realistic models. All models are three-dimensional and typical resolutions are of the order of 1024^3 to 2048^3 mesh points. This part will mostly be carried out with GPU-acceleration, although we have not yet tested the gravitational wave module with GPUs yet.

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. Hindmarsh et al. (2017) have recently presented detailed numerical models of gravitational waves from phase transition nucleation bubbles produced during the electroweak phase transition. Our new work involves the calculation of gravitational waves using the PENCIL CODE, where a gravitational wave solver has already been successfully implemented. This part will mostly be carried out with GPU-acceleration, although we have not yet tested the gravitational wave module with GPUs yet.

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. This part will mostly be carried out with GPU-acceleration, although we have not yet tested the chiral MHD module with GPUs yet. We expect that this will not cause any problems.

Entropy rain convection. Convection is a highly nonlocal phenomenon where low entropy blobs can descent over large depths through the convection zone. This causes an extra contribution to the enthalpy flux that is not described by a local entropy gradient, but by the value of the mean squared entropy fluctuation relative to the background. This always transports energy outward. The resulting stratification may end up being slightly subadiabatic instead of being slightly superadiabatic and therefore host gravity modes that may be observationally detectable. Corresponding simulations were produced by Brandenburg (2016) and Käpylä et al. (2017), but the effect of rotation is not well understood. This will

be studied using upcoming simulations. The use of radiation transport precludes at the moment GPU acceleration and will therefore use CPUs.

Solar/stellar dynamo simulations. Local simulations will be used to develop what we call smart boundary conditions for application in the global simulations. The purpose of such boundary conditions 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 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 of 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 surface layer in one and the same model. A number of modules preclude GPU acceleration at the moment and we will therefore use CPUs.

6 Research group and management

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 Oksana Iarygina (Marie Curie fellow)

Dr Mattia Cielo

Dr Lars Mattsson (guest researcher)

Ms Elisa Mema (PhD student)

Dr Dhrubaditya Mitra (assistant professor)

Mr Patrik Tegnér (Master student)

The monthly usage within the group is monitored and discussed during our weekly group meetings.

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