Activity report based on CPU time and storage used on PDC and NSC of 2021/2022

Axel Brandenburg (Nordita)

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In this activity report, we describe and list some highlights of the 44 papers that all acknowledge SNAC. Out of those, 4 are in press, 13 are published in 2021, and another 17 are published in 2020. For the calculations, we use the code Runko and the Pencil Code, both of which are hosted on github (`https://github.com/natj/runko` and `https://github.com/pencil-code`). The Pencil Code Collaboration consists of currently 38 developers who have published their effort in JOSS, the Journal of Open Source Software [412].

412. Pencil Code Collaboration: Brandenburg, A., Johansen, A., Bourdin, P. A., Dobler, W., Lyra, W., Rheinhardt, M., Bingert, S., Haugen, N. E. L., Mee, A., Gent, F., Babkovskaia, N., Yang, C.-C., Heinemann, T., Dintrans, B., Mitra, D., Candelaresi, S., Warnecke, J., Käpylä, P. J., Schreiber, A., Chatterjee, P., Käpylä, M. J., Li, X.-Y., Krüger, J., Aarnes, J. R., Sarson, G. R., Oishi, J. S., Schober, J., Plasson, R., Sandin, C., Karchniwy, E., Rodrigues, L. F. S., Hubbard, A., Guerrero, G., Snodin, A., Losada, I. R., Pekkilä, J., & Qian, C.: 2021, "The Pencil Code, a modular MPI code for partial differential equations and particles: multipurpose and multiuser-maintained," *J. Open Source Softw.* **6**, 2807

Here and below, the 3-digit numbering of the papers coincides with that of Brandenburg's full list of publications on `http://www.nordita.org/~brandenb/pub`. Those preceded by the letter B are also in that list, but under invited conference proceedings. All the papers quoted below acknowledge SNIC, PDC, and/or NSC.

1 Shocks and turbulence in collisionless astrophysical plasmas

Many astrophysical plasmas are extremely diluted and, hence, appear almost collisionless. In order to investigate such plasmas that are beyond the validity regime of MHD, we in Nordita have developed a new open-source particle-in-cell (PIC) simulation code Runko [1]. The main focus of the code is to perform self-consistent fully-kinetic studies of non-thermal particle acceleration in collisionless plasmas.

Under a strong radiation field (such as close to black holes) the turbulence dynamics is altered due to strong radiative cooling. In order to understand the non-linear behavior of turbulent plasma in such a strong radiation environment, we have performed pioneering radiative kinetic turbulence simulations [2]. This in turn, will help us understand, for example, particle acceleration and heating of diluted plasmas near black holes and neutron stars.

In realistic astrophysical environments, one can expect the upstream plasma not to be homogeneous as assumed in these studies but, to present perturbations or even to be turbulent. How upstream turbulence affects the shock properties and particle acceleration is to date an open question. Using the Runko code, we have studied how a relativistic magnetized shock responds to upstream density perturbations and found, unlike previous works, evidence of particle acceleration [2].

The following papers presenting our results have appeared:

[1] Nättilä, J.: 2022, "Runko: Modern multiphysics toolbox for plasma simulations," *Astron. & Astrophys.*, **664**, A68.

[2] Nättilä, J., & Belobodorov, A.: 2021, "Radiative turbulent flares in magnetically-dominated plasmas," *Astrophys. J.*, **921**, 87.

2 Gravitational waves and early universe magnetic fields

An important activity involves the computation of the stochastic gravitational wave background from the Big Bang. Those can be measured in future with LISA and the pulsar timing array. We have continued studying the chiral magnetic effect and have now calculated the resulting GW production [416]. We have also studied in more detail the circular polarization of gravitational waves from early-universe helical turbulence [413]. We have also studied gravitational waves from the chiral magnetic effect [416], which is also fully helical. The scalar, vector, and tensor modes of gravitational wave turbulence simulations are studied in [417]. In [418], we computed the effects of a finite graviton mass on the spectrum of turbulence-sourced gravitational waves. We also show that QCD phase transition-generated gravitational waves can we observed the through pulsar timing arrays [419]. We have also studied relic gravitational waves from inflationary magnetogenesis without helicity [421] and with helicity [422], along with detailed observational aspects [426]. We have now also studied in more detail the low frequency tail of gravitational wave spectra from hydromagnetic turbulence [433]; see also Figure 1, where we show spectra of the magnetic field, the traceless-transverse-projected stress, the strain derivative, and the strain for suddenly initiated turbulence with magnetic helicity.

433. Sharma, R., & Brandenburg, A.: 2022, "Low frequency tail of gravitational wave spectra from hydromagnetic turbulence," *Phys. Rev. D*, in press (arXiv:2206.00055)

426. Roper Pol, A., Mandal, A., Brandenburg, A., & Kahniashvili, T.: 2022, "Polarization of gravitational waves from helical MHD turbulent sources," *J. Cosmol. Astropart. Phys.* **04**, 019

422. Brandenburg, A., He, Y., & Sharma, R.: 2021, "Simulations of helical inflationary magnetogenesis and gravitational waves," *Astrophys. J.*, in press (arXiv:2107.12333)

421. Brandenburg, A., & Sharma, R.: 2021, "Simulating relic gravitational waves from inflationary magnetogenesis," *Astrophys. J.* **920**, 26

419. Brandenburg, A., Clarke, E., He, Y., & Kahniashvili, T.: 2021, "Can we observe the QCD phase transition-generated gravitational waves through pulsar timing arrays?" *Phys. Rev. D* **104**, 043513

418. He, Y., Brandenburg, A., & Sinha, A.: 2021, "Spectrum of turbulence-sourced gravitational waves as a constraint on graviton mass," *J. Cosmol. Astropart. Phys.* **07**, 015

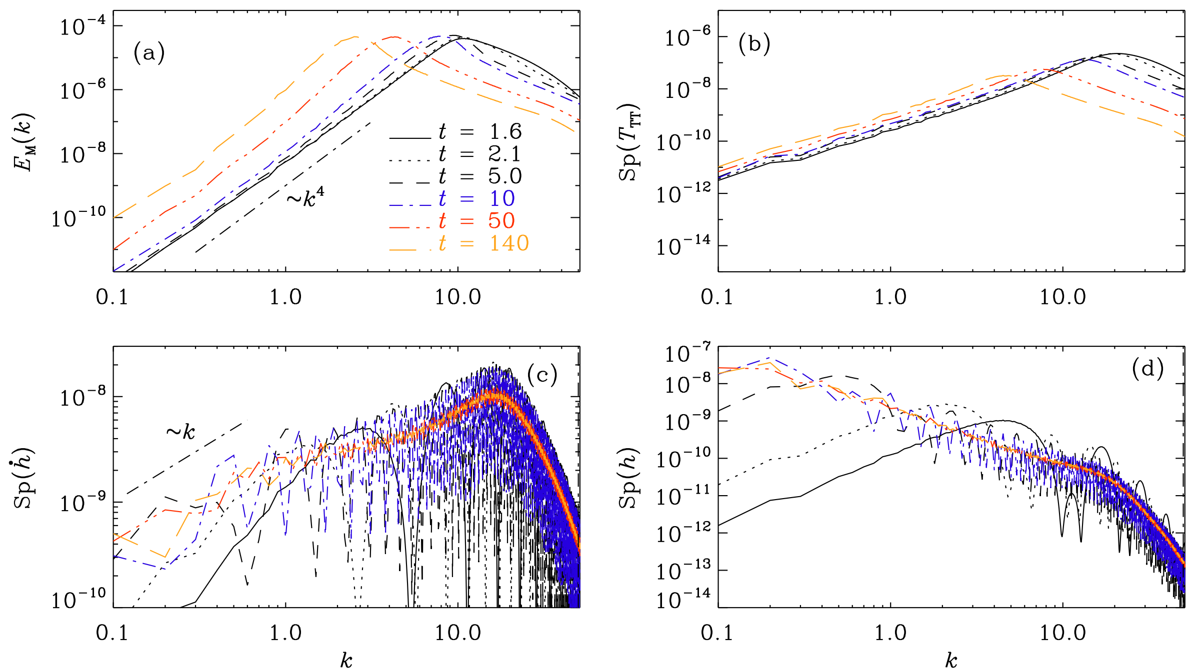

Figure 1: Spectra of the magnetic field, the TT-projected stress, the strain derivative, and the strain for suddenly initiated turbulence with magnetic helicity.

417. Brandenburg, A., Gogoberidze, G., Kahniashvili, T., Mandal, S., & Roper Pol, A., & Shenoy, N.: 2021, "The scalar, vector, and tensor modes in gravitational wave turbulence simulations," *Class. Quantum Grav.* **38**, 145002

416. Brandenburg, A., He, Y., Kahniashvili, T., Rheinhardt, M., & Schober, J.: 2021, "Gravitational waves from the chiral magnetic effect," *Astrophys. J.* **911**, 110

413. Kahniashvili, T., Brandenburg, A., Gogoberidze, G., Mandal, S., & Roper Pol, A.: 2021, "Circular polarization of gravitational waves from early-universe helical turbulence," *Phys. Rev. Res.* **3**, 013193

3 Solar wind and radiation transport

We have studied turbulent radiative diffusion and the new concept of turbulent Newtonian cooling and found a surprisingly weak scale dependence [420]. We have also now combined a solar dynamo with a Parker wind [414].

420. Brandenburg, A., & Das, U.: 2021, "Turbulent radiative diffusion and turbulent Newtonian cooling," *Phys. Fluids* **33**, 095125

414. Jakab, P., & Brandenburg, A.: 2021, "The effect of a dynamo-generated field on the Parker wind," *Astron. Astrophys.* **647**, A18

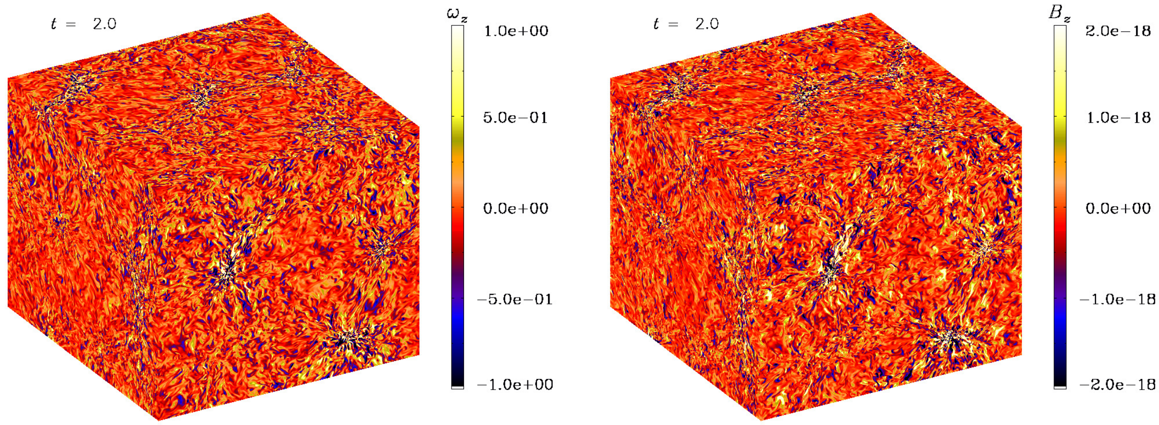

Figure 2: ω_z (upper left), B_z (upper right), $\boldsymbol{\nabla} \cdot \boldsymbol{u}$ (lower left), and $\ln \rho$ (lower right) near the end of the run. Note the close correlation of the magnetic field with the vorticity and their concentration toward regions of strong flow convergence ($\mathrm{div}\, \boldsymbol{u} < 0$) and high density.

4 Dynamo action in the Sun and Galaxies

To connect our early Universe simulations discussed above with the later cosmological evolution, we have now performed simulations of large-scale structure formation with realistic magnetic fields [427]. We have also studied the dynamo effect in self-gravitating turbulence [428], and found that most of the amplification comes from the vortical contribution that is amplified during the gravitational collapse.

428. Brandenburg, A., & Ntormousi, E.: 2022, "Dynamo effect in unstirred self-gravitating turbulence," *Mon. Not. Roy. Astron. Soc.* **513**, 2136–2151

427. Mtchedlidze, S., Domínguez-Fernández, P., Du, X., Brandenburg, A., Kahniashvili, T., O'Sullivan, S., Schmidt, W., & Brüggen, M.: 2022, "Evolution of primordial magnetic fields during large-scale structure formation," *Astrophys. J.* **929**, 127

5 Axionlike particle–photon conversion in MHD simulations

The conversion of axionlike particles (ALPs) and photons in magnetized astrophysical environments such as galaxy clusters provides a promising route to search for ALPs. We have presented the first systematic study of ALP–photon conversion in more realistic, turbulent fields from dedicated magnetohydrodynamic (MHD) simulations [440], which we compare with Gaussian random field (GRF) models. We find that the MHD models agree with the exponential law for typical, small-amplitude mixings but exhibit distinctly heavy tails for rare and large mixings; see Figure 3. We explain how non-Gaussian, local spikes in the MHD magnetic field are mainly responsible for the heavy tail. The results indicate that limits placed on ALPs using GRFs are conservative but that MHD models are necessary to reach the full potential of these searches.

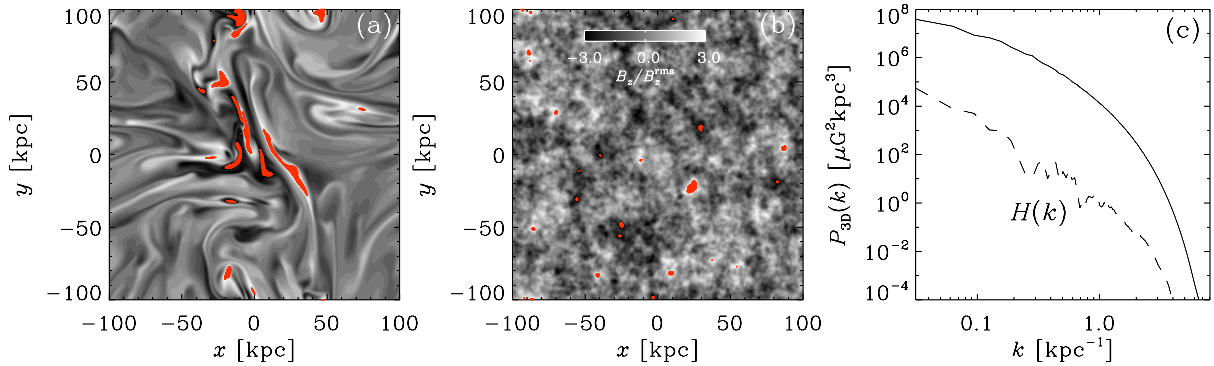

Figure 3: Cross-section of the magnetic field for (a) Run S and (b) the case of GRF with same the power spectrum. The red regions highlight the locations with $|B| > 3B_{\rm rms}$. (c) Power and helicity spectra for Run S.

440. Carenza, P., Sharma, R., Marsh, M. C. D., Brandenburg, A., Müller, E.: 2022, "Magnetohydrodynamics predicts heavy-tailed distributions of axion-photon conversion," *Phys. Rev. Lett.*, submitted (arXiv:2208.04333)

6 Small-scale dynamo turbulence

We have continued to study small scale dynamos both in forced and decaying non-helical turbulence and have shown that the Hosking integral, describing the correlation of magnetic helicity fluctuations, this gauge-invariant and conserved in non-helical turbulence [434]. In driven turbulence, the small-scale dynamo develops a $k^{3/2}$ Kazantsev spectrum, which is well known. We have now shown that in the kinematic regime of the dynamo, it connects to a very steep k^4 Batchelor spectrum, which turns to a shallower k^2 Saffman spectrum as the dynamos saturates. The turning point is the integral of scale of turbulence. We have studied its diagnostics properties in terms of the rotational invariant E and B polarizations [439]. To our surprise, the two are very different from each other, especially at large magnetic Prandtl numbers Pr_M, which is 30 in Figure 4. In [441], we also show that the ratio of wavenumber of dissipative to viscous structures is $k_\eta/k_\nu = (\mathrm{Pr}_M/\mathrm{Pr}_M^{\rm crit})^{1/2}$, where $\mathrm{Pr}_M^{\rm crit} \approx 0.27$.

441. Brandenburg, A., Rogachevskii, I., & Schober, J.: 2022, "Dissipative magnetic structures and scales in small-scale dynamos," *Mon. Not. Roy. Astron. Soc.*, submitted (arXiv:2209.08717)

439. Brandenburg, A., Zhou, H., & Sharma, R.: 2022, "Batchelor, Saffman, and Kazantsev spectra in galactic small-scale dynamos," *Mon. Not. Roy. Astron. Soc.*, submitted (arXiv:2207.09414)

434. Zhou, H., Sharma, R., & Brandenburg, A.: 2022, "Scaling of the Hosking integral in decaying magnetically-dominated turbulence," *J. Plasma Phys.*, in press (arXiv:2206.07513)

7 Particles in Turbulence

We have started a new project on the spectral characterization of inertial particle clustering in turbulence. We have found spectra to be an excellent tool to identify *different* and *new* mechanisms of particle clustering in supersonic turbulence [426]. We have also now completed

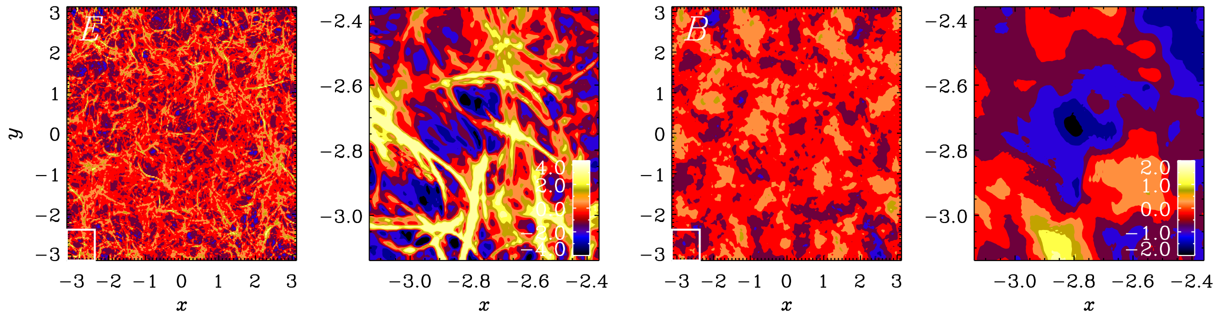

Figure 4: Diagnostic slices of E (left 2 panels), and B (right two panels), for a run with $\mathrm{Pr}_M = 30$ during the kinematic stage. The small white squares on the left column mark the part that is shown enlarged on the right column. All quantities are normalized by their rms value and the color bars for the enlarged frames are clipped at ± 2 times the rms value, while those for the full frames are clipped at ± 4 times the rms value.

several papers on the subject of multi-dimensional condensation and coagulation. We also have performed work that includes the effects of condensation, in addition to coagulation [424]. Finally, we have characterized the importance of fluctuations in dilute systems [412]. This work has now been extended to the astrophysical context [5,6] and applied to stellar wind [7].

431. Li, X.-Y., Mehlig, B., Svensson, G., Brandenburg, A., & Haugen, N. E. L.: 2022, "Collision fluctuations of lucky droplets with superdroplets," *J. Atmos. Sci.* **79**, 1821–1835

423. Haugen, N. E. L., Brandenburg, A., Sandin, C., & Mattsson, L.: 2022, "Spectral characterisation of inertial particle clustering in turbulence," *J. Fluid Mech.* **934**, A37

8 Astrobiology and chemical reactions

With the Pencil Code, we can perform simulations of chemical reactions. The spreading of COVID-19 is in principle one such example. This led us to understand why the spreading of COVID-19 follows a piecewise quadratic growth [409,B.42]. One important application is hydrogen combustion which can lead to detonation. Chemical reactions also play a role in origin-of-life studies. In [B.41], we have studied the effect of fluctuations in accomplishing reactions that drive the system toward a homochiral state without the explicit effects of autocatalysis or enantiomeric cross-inhibition.

438. Brandenburg, A.: 2022, "Quadratic growth during the COVID-19 pandemic: merging hotspots and reinfections," *J. Phys. A: Math. Theor.*, submitted (arXiv:2206.15459)

B.42 Brandenburg, A.: 2022, "Chirality in Astrophysics" in *Proceedings to Nobel Symposium 167: Chiral Matter*, ed. E. Babaev, D. Kharzeev, M. Larsson, A. Molochkov, & V. Zhaunerchyk, World Scientific, in press (arXiv:2110.08117)

B.41. Brandenburg, A.: 2021, "Homochirality: a prerequisite or consequence of life?" in *Prebiotic Chemistry and the Origin of Life*, ed. A. Neubeck, & S. McMahon, Springer, pp. 87–115

In [B.42], we have reviewed chirality in various fields of astrophysics, but biological homochirality is one aspect. The spatial spreading of COVID, which was already discussed in previous

PDC and NSC reports, is also covered there and in a new paper [438], where we investigate the effects of reinfections on the spreading in a spatially extended two-dimensional model.

Academic achievements

PhD student Yutong He has now reached the second stage and will defend his Licentiate thesis on 16 December 2022.