Activity report based on time used on PDC, Kebnekaise, and C3SE of 2018 and 2019

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In this activity report, I describe and list some highlights of the 30 papers that all acknowledge SNAC. Out of those, 7 are submitted, 5 accepted, 9 published in 2019, and another 9 published in 2018. 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 3-digit numbering of the papers coincides with that of my full list of publications on `http://www.nordita.org/~brandenb/pub`. All the papers quoted below acknowledge SNAC.

1 Shocks and turbulence in collisionless astrophysical plasmas

Many astrophysical plasmas are extremely diluted and, hence, appear almost collisionless. In order to investigate such a 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]. Main focus of the code is to perform self-consistent fully-kinetic studies of non-thermal particle acceleration in collisionless plasmas.

Turbulence in astrophysical plasmas is ubiquitous appearing in systems such as solar wind all the way to galaxy cluster scales. By using massively-parallel PIC simulations, we have studied the formation and evolution of turbulence in magnetically-dominated diluted plasmas [1]. This work helped us, for the first time, understand how the large-scale energy in the plasma is transferred from one state (large magnetic field perturbations) to other forms (small turbulent motion and subsequently non-thermal particle populations).

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.

The kinetic turbulence is also known to depict a copious creation of intermittent, very energetic, and localized space regions with strong currents. By using our first-principles simulations, we are, for the first time, starting to trace the statistics and dynamics of these sheet-like structures (forthcoming paper [3]). Such understanding is important as it can be used to parameterize the efficiency of particle acceleration and dissipation strength of diluted plasmas.

1. Nättilä, J.: 2019, “Runko: Modern multi-physics toolbox for simulating plasma [arXiv:1906.06306]

There are currently two papers that are close to being submitted. We list those separately below.

2. Nättilä, J., & Belobodorov, A.: 2019, “Kinetic simulations of relativistic microturbulent flares with radiative losses”, in prep.

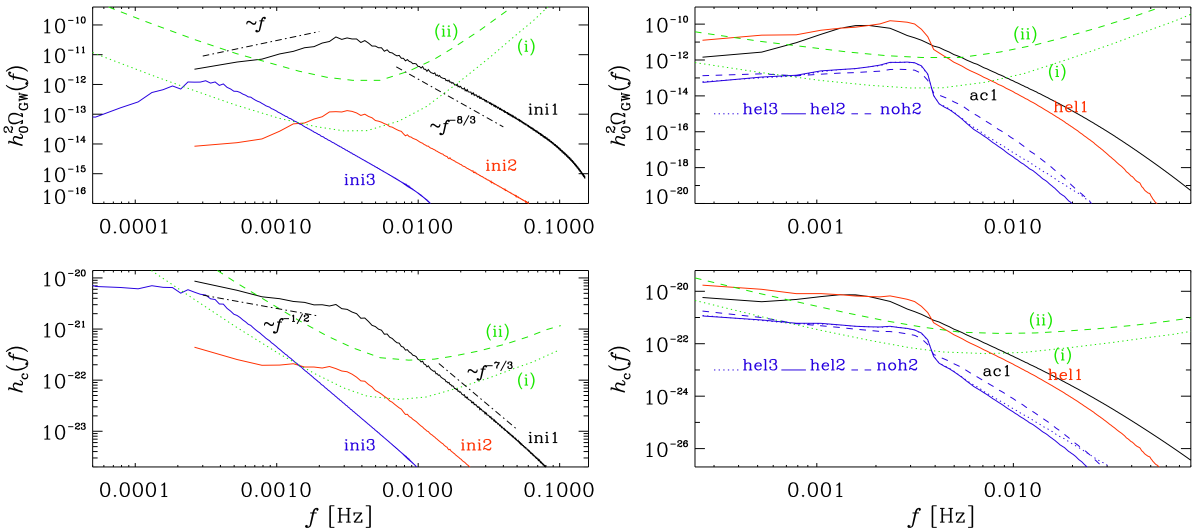

Figure 1: *Left*: spectra of $h_0^2\Omega_{\rm GW}(f)$ and $h_{\rm c}(f)$ along with the LISA sensitivity curves in (i) the 6-link configurations with 5×10^9 m arm length and (ii) the 4-link configurations with 2×10^9 m arm length after 5 years duration. The dash-dotted lines indicate the slopes 1 and $-8/3$ in the upper panel and $-1/2$ and $-7/3$ in the lower. *Right*: similar, but for Runs hel1–3, noh2, and ac1. Note the similarity in the low-frequency tail for $f < 3$ mHz. Adapted from Ref. [401].

3. Kruuse, M., & Nättilä, J.: 2019, "Statistics and dynamics of current sheets in relativistic kinetic turbulence", in prep.

2 Gravitational waves and early universe magnetic fields

An important upcoming 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. Our first paper on the numerical method is described in Ref. [393]. In [401], we compare the resulting primordial gravitational wave signal with the sensitivity curves for LISA; see also Figure 1.

We have continued studying the chiral magnetic effect [364,384] as well as the chiral vortical effect [392]. We have also studied new aspects of decaying turbulence in the early universe with magnetic helicity [383] and with cross helicity [377].

401. Roper Pol, A., Mandal, S., Brandenburg, A., Kahniashvili, T., & Kosowsky, A.: 2019, "Numerical Simulations of Gravitational Waves from Early-Universe Turbulence," *Phys. Rev. Lett.*, submitted (arXiv:1903.08585)

393. Roper Pol, A., Brandenburg, A., Kahniashvili, T., Kosowsky, A., & Mandal, S.: 2019, "The timestep constraint in solving the gravitational wave equations sourced by hydromagnetic turbulence," *Geophys. Astrophys. Fluid Dyn.*, DOI: 10.1080/03091929.2019.1653460 (arXiv:1807.05479)

392. Schober, J., Brandenburg, A., & Rogachevskii, I.: 2019, "Chiral fermion asymmetry in high-energy plasma simulations," *Geophys. Astrophys. Fluid Dyn.*, DOI: 10.1080/03091929.2019.1591393 (arXiv:1808.06624)

384. Schober, J., Brandenburg, A., Rogachevskii, I., & Kleeorin, N.: 2019, "Energetics of turbulence generated by chiral MHD dynamos," *Geophys. Astrophys. Fluid Dyn.* **113**, 107–130

383. Brandenburg, A., Kahniashvili, T., Mandal, S., Roper Pol, A., Tevzadze, A. G., & Vachaspati, T.: 2019, "Dynamo effect in decaying helical turbulence," *Phys. Rev. Fluids*, **4**, 024608

377. Brandenburg, A., & Oughton, S.: 2018, "Cross-helically forced and decaying hydromagnetic turbulence," *Astron. Nachr.* **339**, 641–646

364. Schober, J., Rogachevskii, I., Brandenburg, A., Boyarsky, A., Fröhlich, J., Ruchayskiy, O., & Kleeorin, N.: 2018, "Laminar and turbulent dynamos in chiral magnetohydrodynamics. II. Simulations," *Astrophys. J.* **858**, 124

3 Sunspot formation and radiation transport

Sunspots reveal properties of the underlying magnetic field through their geometrical arrangement in three- and four-spot configurations. This was revealed through our work in Ref. [376]. We have now performed simulations showing the spontaneous flux concentrations from the negative effective magnetic pressure instability beneath a radiative stellar surface [361]. We have also studied the formation of magnetic bipoles in rotating turbulence with coronal envelope [379]. In a more general paper in a special issue describing the Pencil Code, we have also studied the time step constraint in radiation hydrodynamics [396].

396. Brandenburg, A., & Das, U.: 2019, "The time step constraint in radiation hydrodynamics," *Geophys. Astrophys. Fluid Dyn.*, DOI: 10.1080/03091929.2019.1676894 (arXiv:1901.06385)

379. Losada, I. R., Warnecke, J., Brandenburg, A., Kleeorin, N., & Rogachevskii, I.: 2019, "Magnetic bipoles in rotating turbulence with coronal envelope," *Astron. Astrophys.* **621**, A61

376. Bourdin, Ph.-A., & Brandenburg, A.: 2018, "Magnetic helicity from multipolar regions on the solar surface," *Astrophys. J.* **869**, 3

361. Perri, B., & Brandenburg, A.: 2018, "Spontaneous flux concentrations from the negative effective magnetic pressure instability beneath a radiative stellar surface," *Astron. Astrophys.* **609**, A99

4 Dynamo action in the Sun

Linear polarization, as characterized by the Stokes Q and U parameters, is coordinate-dependent. A coordinate-independent characterization is provided by the parity-even and parity-odd E and B mode polarizations that are routinely used in cosmology. Their cross-correlation can also reveal information about magnetic helicity, but only if the system is inhomogeneous. This was shown in our new work of Ref. [380] using data of local numerical simulations. More recent work has extended this now to global simulations [390].

We have also continued using simulations to reveal subsurface properties of the Sun's magnetic field using simulations [394]. Its small-scale [366] and large-scale [365] properties have been subjects of separate investigations of last year.

394. Singh, N. K., Raichur, H., Käpylä, M. J., Rheinhardt, M., Brandenburg, A., & Käpylä, P. J.: 2019, "f-mode strengthening from a localized bipolar subsurface magnetic field," *Geophys. Astrophys. Fluid Dyn.*, DOI: 10.1080/03091929.2019.1653461 (arXiv:1808.08904)

390. Brandenburg, A.: 2019, "A global two-scale helicity proxy from π-ambiguous solar magnetic fields," *Astrophys. J.* **883**, 119

380. Brandenburg, A., Bracco, A., Kahniashvili, T., Mandal, S., Roper Pol, A., Petrie, G. J. D., & Singh, N. K.: 2019, "E and B polarizations from inhomogeneous and solar surface turbulence," *Astrophys. J.* **870**, 87

378. Brandenburg, A.: 2018, "Magnetic helicity and fluxes in an inhomogeneous α^2 dynamo," *Astron. Nachr.* **339**, 631–640

366. Käpylä, P. J., Käpylä, M. J., & Brandenburg, A.: 2018, "Small-scale dynamos in simulations of stratified turbulent convection," *Astron. Nachr.* **339**, 127–133

365. Brandenburg, A., & Chatterjee, P.: 2018, "Strong nonlocality variations in a spherical mean-field dynamo," *Astron. Nachr.* **339**, 118–126

5 Particles in Turbulence

We have now completed 4 papers on the subject of multi-dimensional condensation and coagulation [373,382,398,399]. They show the importance of local energy dissipation in determining the speed of coagulation [373]. We have produced realistic models of cloud droplet growth due to supersaturation fluctuations in stratiform clouds [382]. We also have performed work that includes the effects of condensation, in addition to coagulation [398]. Finally, we have characterized the importance of fluctuations in dilute systems [399]. This led to the PhD thesis of Xiang-Yu Li, who finished in September 2018.

399. Li, X.-Y., Mehlig, B., Svensson, G., Brandenburg, A., & Haugen, N. E. L.: 2019, "Fluctuations and growth histories of cloud droplets: superparticle simulations of the collision-coalescence process," *Quart. J. Roy. Met. Soc.*, submitted (arXiv:1810.07475)

398. Li, X.-Y., Brandenburg, A., Svensson, G., Haugen, N. E. L., Mehlig, B., & Rogachevskii, I.: 2019, "Condensational and collisional growth of cloud droplets in a turbulent environment," *J. Atmosph. Sci.*, submitted (arXiv:1807.11859)

382. Li, X.-Y., Svensson, G., Brandenburg, A., & Haugen, N. E. L.: 2019, "Cloud droplet growth due to supersaturation fluctuations in stratiform clouds," *Atmosph. Chem. Phys.* **19**, 639–648

373. Li, X.-Y., Brandenburg, A., Svensson, G., Haugen, N. E. L., Mehlig, B., & Rogachevskii, I.: 2018, "Effect of turbulence on collisional growth of cloud droplets," *J. Atmosph. Sci.* **75**, 3469–3487

6 Small-scale dynamo turbulence and ambipolar diffusion

In an attempt to clarify the nature of large-scale dynamo action, we have discovered efficient quasi-kinematic large-scale dynamo growth as the small-scale dynamo saturates [402]. We have

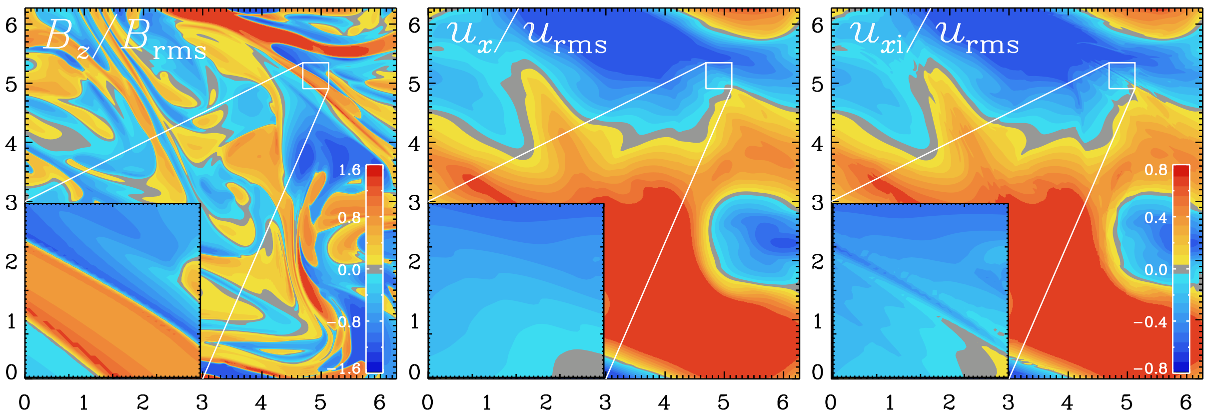

Figure 2: Visualizations of the magnetic field normal to the plane, $B_z/B_{\rm rms}$, as well as the x components of the neutral and ion flow speeds, $u_x/u_{\rm rms}$ and $u_{xi}/u_{\rm rms}$, respectively, for the two-fluid model. The insets show a blow-up near a magnetic structure. Adapted from Ref. [386].

conducted two investigations of dynamos and MHD systems at large magnetic Prandtl number: one that can be applied to galaxy clusters and the solar corona where we now argue that heating occurs not on current sheets, as usually believed, but viscously [387]. In the cooler interstellar medium, ambipolar diffusion becomes important and we have now conducted two-fluid simulations [386]. As an additional off-spring of earlier work, we have completed this year a detailed investigation on varying the forcing scale in low Prandtl number dynamos [367]. It will provide an important benchmark for future studies.

402. Bhat, P., Subramanian, K., & Brandenburg, A.: 2019, "Efficient quasi-kinematic large-scale dynamo as the small-scale dynamo saturates," *Phys. Rev. Lett.*, submitted (arXiv:1905.08278)

387. Brandenburg, A., & Rempel, M.: 2019, "Reversed dynamo at small scales and large magnetic Prandtl number," *Astrophys. J.* **879**, 57

386. Brandenburg, A.: 2019, "Ambipolar diffusion in large Prandtl number turbulence," *Mon. Not. Roy. Astron. Soc.* **487**, 2673–2684

367. Brandenburg, A., Haugen, N. E. L., Li, X.-Y., & Subramanian, K.: 2018, "Varying the forcing scale in low Prandtl number dynamos," *Mon. Not. Roy. Astron. Soc.* **479**, 2827–2833

7 Astrobiology and chemical reactions

With the Pencil Code, we can perform simulations of chemical reactions. One important application is hydrogen combustion which can lead to detonation. In [395], we have produced high-resolution studies of this process. Chemical reactions also play a role in origin-of-life studies. In [388], 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.

395. Qian, C., Wang, C., Liu, J., Brandenburg, A., Haugen, N. E. L., & Liberman, M.: 2019, "Convergence properties of detonation simulations," *Geophys. Astrophys. Fluid Dyn.*, DOI: 10.1080/03091929.2019.1668382 (arXiv:1902.03816)

388. Brandenburg, A.: 2019, “The limited roles of autocatalysis and enantiomeric cross-inhibition in achieving homochirality in dilute systems,” *Orig. Life Evol. Biosph.* **49**, 49–60

Academic achievements

In September 2018, Dr Xiang-Yu Li successfully defended his PhD thesis at the University of Stockholm in the Meteorology department with Gunilla Svensson as the main supervisor. This project was supported by a grant from the Norwegian Research Council to Nordita with Brandenburg as the PI. Furthermore, in January 2019, Dr Illa R. Losada successfully defended her PhD thesis at the University of Stockholm in the Astronomy department. This project was supported by a VR grant with Brandenburg as the PI.

From July to December 2019 Nordita was hosting John Hope (University of Bath, UK) as a master student intern to work on a Master’s thesis project on collisionless shock simulations with Joonas Nttil as a main supervisor. Additionally, Maarja Kruuse (Univ. Tarto; Estonia) has been a visiting PhD. fellow in the astrophysics group focusing on kinetic turbulence simulations as one part of her PhD. thesis with Joonas Nättilä as a host. Both projects have been heavily relying on computational resources by SNAC and will the acknowledge it in the forthcoming academic theses.