Activity report based on time used on PDC, Kebnekaise, and C3SE of 2019 and 2020

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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 submitted, 17 published in 2020, and another 8 published in 2019. 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 submitted their effort to JOSS, the Journal of Open Source Software [417].

[417] The 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.: 2020, "The Pencil Code, a modular MPI code for partial differential equations and particles: multipurpose and multiuser-maintained," *Journal of Open Source Software* **5**, 2684 (arXiv:2009.08231)

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`. 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 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.

Turbulence in astrophysical plasmas is ubiquitous, appearing in systems such as the 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 [3]. 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 [4]). 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]

In recent years, particle-in-cell simulations have allowed to study particle acceleration in relativistic shocks from first principles. They showed, notably, that relativistic shocks with no or low magnetizations lead to efficient particle acceleration through Fermi acceleration while for highly magnetized shocks, no substantial particle energization was reported.

However, 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 are in preparation:

[2] Demidem, C., Nättilä, J., & Veledina, A.: 2020, ”Particle acceleration in corrugated relativistic collisionless shocks”, in prep.

[3] Nättilä, J., & Belobodorov, A.: 2020, “Kinetic simulations of relativistic microturbulent flares with radiative losses”, in prep.

[4] Kruuse, M., & Nättilä, J.: 2020, “Statistics and dynamics of current sheets in relativistic kinetic turbulence”, in prep.

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. Our first paper on the numerical method is described in Ref. [394]. In [410], we compare the resulting primordial gravitational wave signal with the sensitivity curves for LISA.

We have continued studying the chiral magnetic effect [384,393]. We have also studied new aspects of decaying turbulence in the early universe with magnetic helicity [383,405]; see Figure 1.

[410] Roper Pol, A., Mandal, S., Brandenburg, A., Kahniashvili, T., & Kosowsky, A.: 2020, “Numerical Simulations of Gravitational Waves from Early-Universe Turbulence,” *Phys. Rev. D* **102**, 083512

[405] Brandenburg, A., Durrer, R., Huang, Y., Kahniashvili, T., Mandal, S., & Mukohyama S.: 2020, “Primordial magnetic helicity evolution with a homogeneous magnetic field from inflation,” *Phys. Rev. D* **102**, 02353

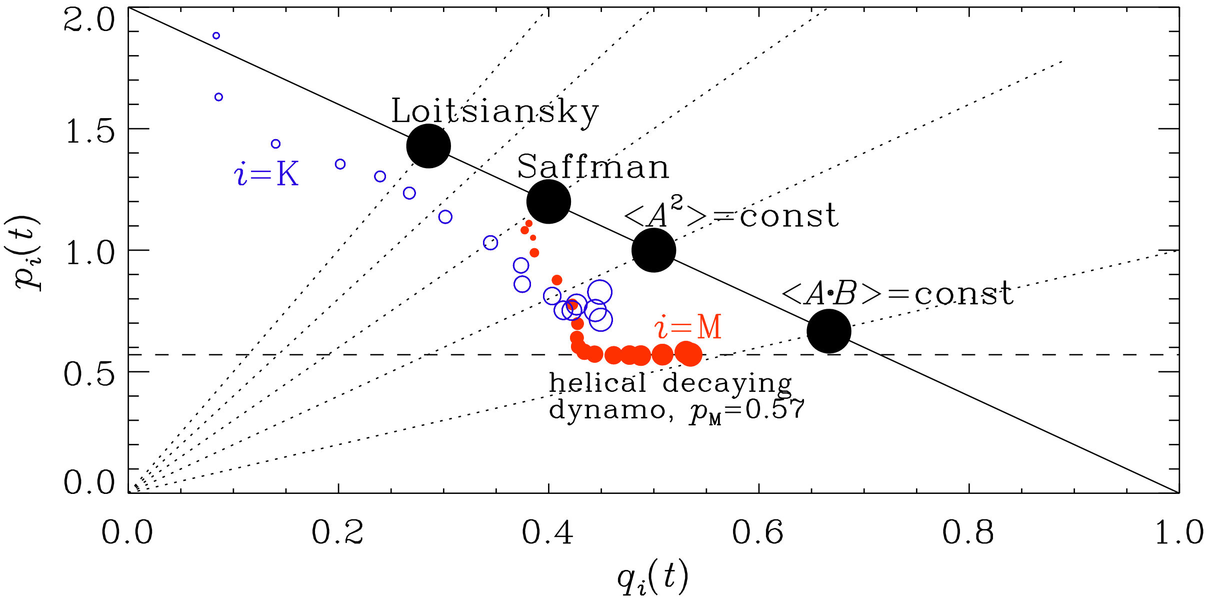

Figure 1: Decaying helical turbulence amplifies a weak magnetic field, which then itself becomes helical. However, it displays a transient behavior different from any other helical or nonhelical magnetic decaying field in a parametric representation between the temporal scaling exponents $p(t)$ and $q(t)$. Adapted from [383].

[394] Roper Pol, A., Brandenburg, A., Kahniashvili, T., Kosowsky, A., & Mandal, S.: 2020, "The timestep constraint in solving the gravitational wave equations sourced by hydromagnetic turbulence," *Geophys. Astrophys. Fluid Dyn.* **114**, 130–161

[393] Schober, J., Brandenburg, A., & Rogachevskii, I.: 2020, "Chiral fermion asymmetry in high-energy plasma simulations," *Geophys. Astrophys. Fluid Dyn.* **114**, 106–129

[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

3 Sunspot formation, 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 [418]. In an earlier study of this type, we have determined the time step constraint for radiation hydrodynamics [395]. We have also now combined a solar dynamo with a Parker wind [414]. Moreover, we have studied the formation of magnetic bipoles in rotating turbulence with coronal envelope [379].

[418] Brandenburg, A., & Das, U.: 2020, "Turbulent radiative diffusion and turbulent Newtonian cooling," *Phys. Fluids*, submitted (arXiv:2010.07046)

[414] Jakab, P., & Brandenburg, A.: 2020, "The effect of a dynamo-generated field on the Parker wind," *Astron. Astrophys.*, submitted (arXiv:2006.02971)

[395] Brandenburg, A., & Das, U.: 2020, "The time step constraint in radiation hydrodynamics," *Geophys. Astrophys. Fluid Dyn.* **114**, 162–195

[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

4 Dynamo action in the Sun and Galaxies

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 [396]. We have now extended these studies to our Galaxy [402] and to edge-on galaxies [404]; see Figure 2.

[404] Brandenburg, A., & Furuya, R. S.: 2020, "Application of a helicity proxy to edge-on galaxies," *Mon. Not. Roy. Astron. Soc.* **496**, 4749–4759

[402] Brandenburg, A., & Brüggen, M.: 2020, "Hemispheric handedness in the Galactic synchrotron polarization foreground," *Astrophys. J. Lett.* **896**, L14

[396] Singh, N. K., Raichur, H., Käpylä, M. J., Rheinhardt, M., Brandenburg, A., & Käpylä, P. J.: 2020, "f-mode strengthening from a localized bipolar subsurface magnetic field," *Geophys. Astrophys. Fluid Dyn.* **114**, 196–212

[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

5 Particles in Turbulence

We have now completed several papers on the subject of multi-dimensional condensation and coagulation. 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 [397]. 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].

[5] Li, X.-Y., & Mattsson, L.: 2020, "Dust growth by accretion of molecules in supersonic interstellar turbulence," *Mon. Not. Roy. Astron. Soc.*, submitted (arXiv:2009.00151)

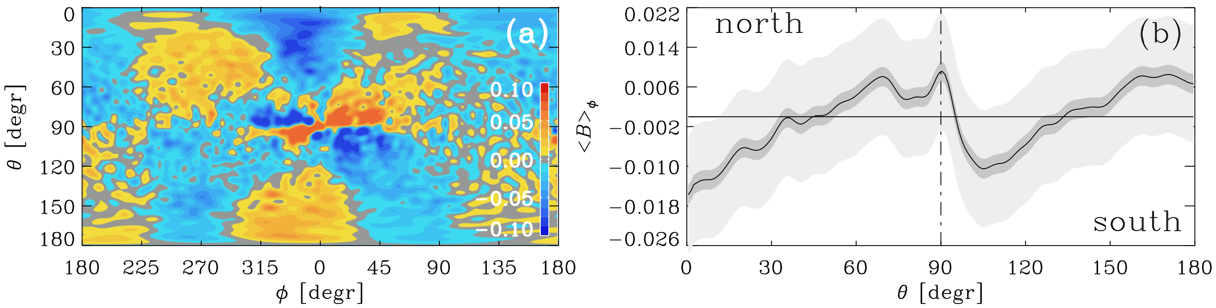

Figure 2: B polarizations for the Galaxy (left) and its azimuthal average (right). Adapted from Ref. [402].

[6] Li, X.-Y., & Mattsson, L.: 2020, "Coagulation of inertial particles in supersonic turbulence," *Mon. Not. Roy. Astron. Soc.*, submitted (arXiv:2002.12172)

[7] Sandin, C. & Mattsson, L.: 2020, "Three-component modelling of C-rich AGB star winds V. Effects of frequency-dependent radiative transfer including drift," *Mon. Not. Roy. Astron. Soc.*, submitted (arXiv:2006.11296)

[412] Li, X.-Y., Mehlig, B., Svensson, G., Brandenburg, A., & Haugen, N. E. L.: 2020, "Fluctuations and growth histories of cloud droplets: superparticle simulations of the collision-coalescence process," *Quart. J. Roy. Met. Soc]*, submitted (arXiv:1810.07475)

[397] Li, X.-Y., Brandenburg, A., Svensson, G., Haugen, N. E. L., Mehlig, B., & Rogachevskii, I.: 2020, "Condensational and collisional growth of cloud droplets in a turbulent environment," *J. Atmosph. Sci]* **77**, 337–353

[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

6 Small-scale dynamo turbulence, ambipolar diffusion, Hall cascade

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 [413]. We have studied the Hall cascade and applied it to neutron star crusts [408]. Using kinetic simulations, we have shown that the dynamo effect in weakly collisional nonmagnetized plasmas is strongly impeded by Landau damping of magnetic fields [403]. Our work on hydromagnetic turbulence has also led to the understanding that the spectrum of the resulting stress is the same as that of the underlying field, provided the spectrum is not bluer than white noise [400]. We have also discovered the existence of negative turbulent magnetic diffusion in three classes of optimal dynamos [399]. We have compared magnetic helicity conservation with the PENCIL CODE and with `FLASH` and found that the latter produces spurious magnetic helicity [398]. We have 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

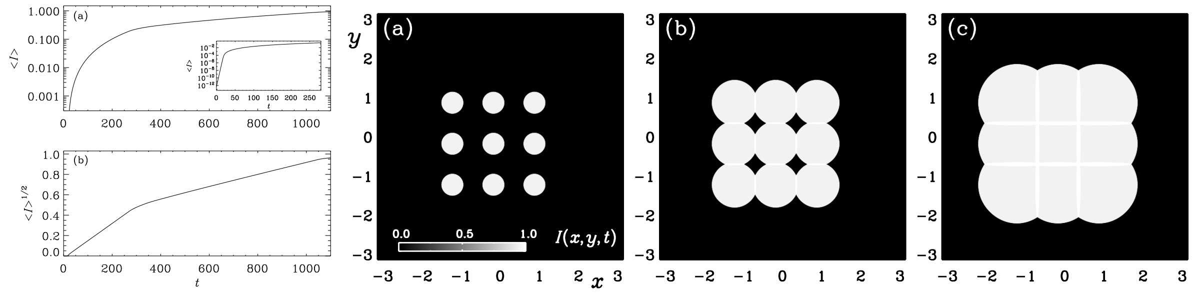

Figure 3: Left: Simulation with 9 hotspots that later merge and overlap. The local distribution of $I(x, y, t)$ is shown in the xy plane for three values of t. The length of the circumference determines the speed of growth. When several hotspots merge, the circumference shortens and the growth slows down. Right: Time series for simulation with 9 hotspots that later overlap. Note that $N^{1/2} \propto \langle I \rangle^{1/2}$ grows linearly with time t, which shows that $N \propto t^2$.

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.

[413] Bhat, P., Subramanian, K., & Brandenburg, A.: 2020, "Efficient quasi-kinematic large-scale dynamo as the small-scale dynamo saturates," *Phys. Rev. Lett.*, submitted (arXiv:1905.08278)

[408] Brandenburg, A.: 2020, "Hall cascade with fractional magnetic helicity in neutron star crusts," *Astrophys. J.* **901**, 18

[403] Pusztai, I., Juno, J., Brandenburg, A., TenBarge, J. M., Hakim, A., Francisquez, M., & Sundström, A.: 2020, "Dynamo in weakly collisional nonmagnetized plasmas impeded by Landau damping of magnetic fields," *Phys. Rev. Lett.* **124**, 255102

[400] Brandenburg, A., & Boldyrev, S.: 2020, "The turbulent stress spectrum in the inertial and subinertial ranges," *Astrophys. J.* **892**, 80

[399] Brandenburg, A., & Chen, L.: 2020, "The nature of mean-field generation in three classes of optimal dynamos," *J. Plasma Phys.* **86**, 905860110

[398] Brandenburg, A., & Scannapieco, E.: 2020, "Magnetic helicity dissipation and production in an ideal MHD code," *Astrophys. J.* **889**, 55

[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

7 COVID-19, 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; see Figure 3. This led us to understand why

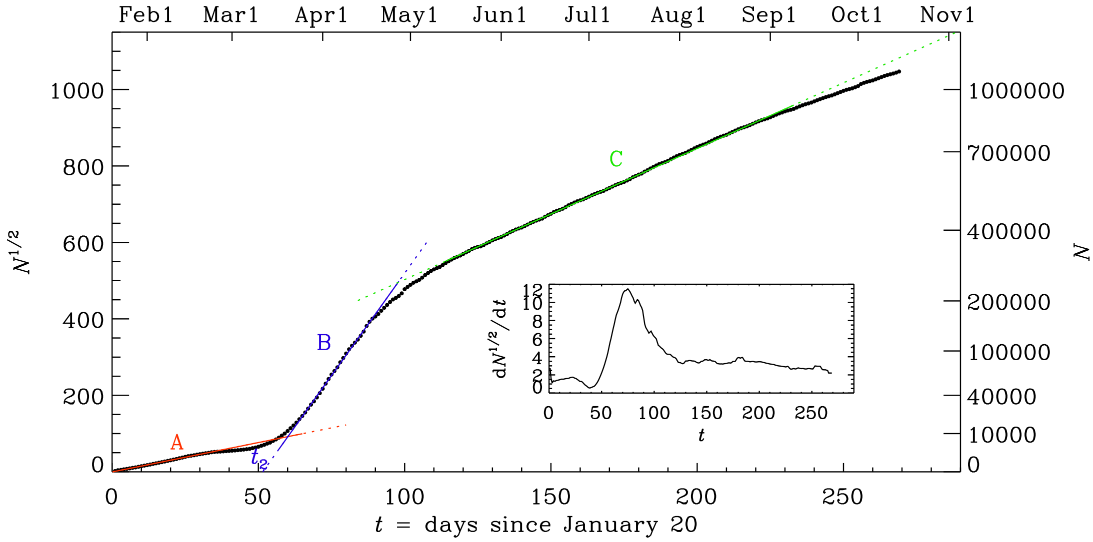

Figure 4: Square root of the number of COVID-19 fatalities N (black dots) versus time since January 20, 2020. The actual date is given on the upper axis and the actual values of N are given on the right-hand axis. The inset shows the time derivative of $N^{1/2}$ versus time.

the spreading of COVID-19 follows a piecewise quadratic growth [409]; see Figure 4. One important application is hydrogen combustion which can lead to detonation. In [392], 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.

[409] Brandenburg, A.: 2020, "Piecewise quadratic growth during the 2019 novel coronavirus epidemic," *Infectious Disease Modelling* **5**, 681–690

[392] Qian, C., Wang, C., Liu, J., Brandenburg, A., Haugen, N. E. L., & Liberman, M.: 2020, "Convergence properties of detonation simulations," *Geophys. Astrophys. Fluid Dyn.* **114**, 58–76

[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 July 2020, Dr Alberto Roper Pol successfully defended his PhD thesis at the University of Colorado with Axel Brandenburg as the main supervisor. This project was supported by a grant from the National Science Foundation in the US, with Axel 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 Nättilä 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.