Ideas for graduate student projects (2015-2018)

to be supervised by Axel Brandenburg during his time at CU

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1 Coronal mass ejections from a spherical dynamo

Purpose. To improve current modeling of coronal mass ejections (CMEs) for space weather prediction.

Background. Dynamos in spherical geometry have displayed recurrent CME-like ejection phenomena [1,2]. They have also displayed unusual magnetic helicity reversals with distance from the stellar surface that agree qualitatively with solar wind measurements [3].

Project. Repeat earlier isothermal models, but with larger latitudinal and longitudinal extents. Next, improve those models to include thermodynamics and allow for a significant temperature and density jump at the surface. Search for similarities with actual CMEs, study the relation with actual surface magnetic fields, and explore possibilities to utilize such models in space weather prediction.

Comments. This project is designed to connect with people at the Space Weather Prediction Center (SWPC); see `http://www.swpc.noaa.gov/`.

[1] Warnecke, J., Brandenburg, A., & Mitra, D.: 2011, "Dynamo-driven plasmoid ejections above a spherical surface," *Astron. Astrophys.* **534**, A11

[2] Warnecke, J., Brandenburg, A., & Mitra, D.: 2012, "Magnetic twist: a source and property of space weather," *J. Spa. Weather Spa. Clim.* **2**, A11

[3] Brandenburg, A., Subramanian, K., Balogh, A., & Goldstein, M. L.: 2011, "Scale-dependence of magnetic helicity in the solar wind," *Astrophys. J.* **734**, 9

2 Solar magnetic helicity

Purpose. To learn about the physics of the underlying magnetic field generation process, the topological complexity of the field, and the use of magnetic helicity (or twist) in space weather prediction.

Background. Magnetic helicity is a topological invariant in magnetohydrodynamics (MHD) and has therefore been used for a long time to characterize the solar magnetic field's complexity. Being a conserved quantity, the underlying dynamo can only produce equal amounts of positive and negative magnetic helicities separated in space (north and south) and/or in scale (large and small wavenumbers) [1]. In addition to using solar surface vector magnetograms, one can use the strong wavelength dependence of Faraday rotation to infer magnetic twist in the corona at long wavelengths (infrared to sub-millimeter radio wavelengths), where Faraday depolarization becomes significant [2].

Project. Use vector magnetograms of the solar surface to compute the wavenumber dependence of solar magnetic helicity, verify that its integral value is compatible with that from independent measurement techniques, and study its variation with the solar cycle and solar latitude [3,4]. Assess the feasibility of using infrared and radio measurements to infer the magnetic helicity of coronal magnetic fields. Compare with alternative techniques (related to Project 1 and related references).

Comments. This work is related to recent work by Alexei Pevtsov from NSO, see also Ref. [4], and collaboration with other people at NSO is expected.

[1] Brandenburg, A., & Subramanian, K.: 2005, "Astrophysical magnetic fields and nonlinear dynamo theory," *Phys. Rep.* **417**, 1–209

[2] Brandenburg, A., & Stepanov, R.: 2014, "Faraday signature of magnetic helicity from reduced depolarization," *Astrophys. J.* **786**, 91

[3] Zhang, H., Brandenburg, A., & Sokoloff, D. D.: 2014, "Magnetic helicity and energy spectra of a solar active region," *Astrophys. J. Lett.* **784**, L45

[4] Pipin, V. V., & Pevtsov, A. A.: 2014, "Magnetic Helicity of the Global Field in Solar Cycles 23 and 24," *Astrophys. J.* **789**, 21

3 Deep convection from intense surface cooling

Purpose. To resolve the apparent puzzle of low turbulent velocities found in time-distance local helioseismology [1] and the possible absence of giant cells in the Sun [2].

Background. The convective flux depends not just on the local negative mean entropy gradient, but also on the degree of entropy fluctuations that might have other origins. This second contribution is the Deardorff flux, which has been found in the meteorological context [3]. Mixing length models with such a flux included reproduce qualitatively important aspects: marginally stable stratification, but still with a sudden change of entropy gradient at the bottom of the convection zone [4].

Project. Use high-resolution two- and three-dimensional direct numerical simulations with reduced idealized opacity [5] to study the dependence of the depth, speed, and thickness of downdrafts as one increases the scaling parameter toward solar values. Separate the actual convective flux into contributions from gradient and Deardorff terms. Alternatively, if giant cell convection does exist, their visible effects at the surface may be screened more than theoretically expected [6].

Comments. Related efforts [7,8] are being pursued on campus and at HAO (Rast, Toomre, Rempel) and collaboration is encouraged.

[1] Hanasoge, S. M., Duvall, T. L., & Sreenivasan, K. R.: 2012, "Anomalously weak solar convection," *Proc. Natl. Acad. Sci.***109**, 11928–11932

[2] Woodard, M.: 2014, "Detectability of large-scale solar subsurface flows," *Solar Phys.* **289**, 1085–1100

[3] Deardorff, J. W.: 1972, "Theoretical expression for the countergradient vertical heat flux," *J. Geophys. Res.* **77**, 5900–5904

[4] Brandenburg A.: 2015, "Stellar mixing length theory with entropy rain," *Astrophys. J.*, submitted (arXiv:1504.03189)

[5] Barekat, A., & Brandenburg, A.: 2014, "Near-polytropic stellar simulations with a radiative surface," *Astron. Astrophys.* **571**, A68

[6] Stix, M.: 1981, "Screening effects in the solar convection zone," *Astron. Astrophys.* **93**, 339–340

[7] Lord, J. W., Cameron, R. H., Rast, M. P., Rempel, M., & Roudier, T.: 2014, "The role of subsurface flows in solar surface convection: modeling the spectrum of supergranular and larger scale flows," *Astrophys. J.* **793**, 24

[8] Greer, B. J., Hindman, B. W., Featherstone, N. A., & Toomre, J.: 2015, "Helioseismic Imaging of Fast Convective Flows Throughout the Near-Surface Shear Layer," *Astrophys. J. Lett.* **803**, L17

4 Density-stratified turbulent dynamos with a radiative surface

Purpose. To understand from first principles the formation of magnetic flux concentrations and sunspots from a dynamo process.

Background. In highly stratified hydromagnetic isothermal turbulence, a helicity-driven large-scale dynamo is able to produce super-equipartition magnetic field concentrations [1]. This is reminiscent of sunspot formation, but essential aspects of actual sunspots such as radiative transfer are missing.

Project. Use the Pencil Code [2] to simulate radiation magnetohydrodynamics of a convectively marginally stable bulk with a nearly isothermal atmosphere [3], and at a later stages also with hydrogen ionization included [4]. Helical turbulence is driven in the deeper parts by mechanical driving, leading to a large-scale magnetic dynamo process [5]. Determine the magnetic field appearance in the surface layers, compare with earlier models without radiation [6], study the thermal structure of flux concentrations and identify similarities and differences with actual sunspots.

[1] Mitra, D., Brandenburg, A., Kleeorin, N., Rogachevskii, I.: 2014, "Intense bipolar structures from stratified helical dynamos," *Mon. Not. Roy. Astron. Soc.* **445**, 761–769

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

[3] Barekat, A., & Brandenburg, A.: 2014, "Near-polytropic stellar simulations with a radiative surface," *Astron. Astrophys.* **571**, A68

[4] Bhat, P., & Brandenburg, A.: 2016, "Hydraulic effects in a radiative atmosphere with ionization," *Astron. Astrophys.* **587**, A90

[5] Brandenburg, A., & Subramanian, K.: 2005, "Astrophysical magnetic fields and nonlinear dynamo theory," *Phys. Rep.* **417**, 1–209

[6] Losada, I. R., Brandenburg, A., Kleeorin, N., & Rogachevskii, I.: 2013, "Competition of rotation and stratification in flux concentrations," *Astron. Astrophys.* **556**, A83

5 Solar convection velocities from Doppler shifts

Purpose. To assess the accuracy of different techniques [1] involving Fourier space (ring diagrams) and autocorrelation functions (travel time differences) to determine flow velocities at 3–30 megameters depths and the sensitivity to perturbations from flows just beneath the surface, where sound waves reside the longest.

Background. Using an assembly of many ray paths that cross the same deep focusing point, but through different patches at the solar surface, it has been possible to find convection velocities in the deeper convection zone that are far below those theoretically expected [2]. On the other hand, by assembling ring diagrams for different Fourier modes from different depths to maximize the sensitivity to a certain depth, one has found flow velocities compatible with conventional wisdom [3]. However, the sensitivity to perturbations from near-surface flows remains to be assessed.

Project. Use ring diagrams from synthetic flows with controlled depth dependence to assess the sharpness of kernels used in the deep flow measurements [4]. Compare with sound travel time measurements of rays traveling in opposite directions. Identify discrepancies between both measurements to resolve the question of low convection flows in the Sun.

Comments. This project is related to recent work of colleagues at CU [3], and collaboration is encouraged.

[1] Gizon, L., & Birch, A. C.: 2005, "Local Helioseismology," *Living Rev. Solar Phys.* **2**, 6

[2] Hanasoge, S. M., Duvall, T. L., & Sreenivasan, K. R.: 2012, "Anomalously weak solar convection," *Proc. Natl. Acad. Sci.***109**, 11928–11932

[3] Greer, B. J., Hindman, B. W., Featherstone, N. A., & Toomre, J.: 2015, "Helioseismic Imaging of Fast Convective Flows Throughout the Near-Surface Shear Layer," *Astrophys. J. Lett.* **803**, L17

[4] Singh, N. K., Brandenburg, A., & Rheinhardt, M.: 2014, "Fanning out of the solar f-mode in presence of nonuniform magnetic fields?," *Astrophys. J. Lett.* **795**, L8