Activity report based on time used on PDC and HPC2N since October 2014

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During the reporting period, Ms Illa R. Losada has submitted and successfully defended her licentiate thesis with the title "Effects of rotation and stratification on magnetic flux concentrations" (December 5, 2014), in addition to Ms Sarah Jabbari, who defended her licentiate thesis on May 19, 2014. Both thesis projects are based on calculations that have been done on Lindgren and Beskow.

We have continued investigating helioseismic signatures from our simulations. This is the work of one of our post-docs hired on the *VR breakthrough research grant*, "Formation of active regions in the Sun" (2012-5797, January 2013 – December 2016, 4.2 MSEK). Bidya Karak (former post-doc at Nordita) has been doing spherical shell simulations of convection with magnetic fields. Xiang-Yu Li has been doing simulations of condensation and coagulation processes in the meteorological context. Sarah Jabbari has been doing large-scale simulations of turbulence in spherical shells and found the spontaneous formation of magnetic spots. Together with Master Students and visitors, Axel Brandenburg has been doing simulations with radiative transfer and ionization included. He has also been doing hydromagnetic simulations in the cosmological context.

For all calculations, we use the Pencil Code, which is hosted by Google Code[1] The code has now been moved to `https://github.com/pencil-code`. Below, I describe the research outcome by quoting published papers since October 2014 in refereed journals. The 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 and none of those papers were mentioned in the activity report of the previous period.

1 Helioseismology

In addition to our 2014 discovery paper of the fanning out of the solar f-mode, we have now published a more extensive work; see Figure 1.

321. Singh, N. K., Brandenburg, A., Chitre, S. M., & Rheinhardt, M.: 2015, "Properties of p- and f-modes in hydromagnetic turbulence," *Mon. Not. Roy. Astron. Soc.* **447**, 3708–3722

We have been continuing this work and are proposing a new precursor to solar active region formation, which has relevance to space weather prediction.

[1]The Pencil Code was written by Brandenburg & Dobler (2002) as a public domain code.

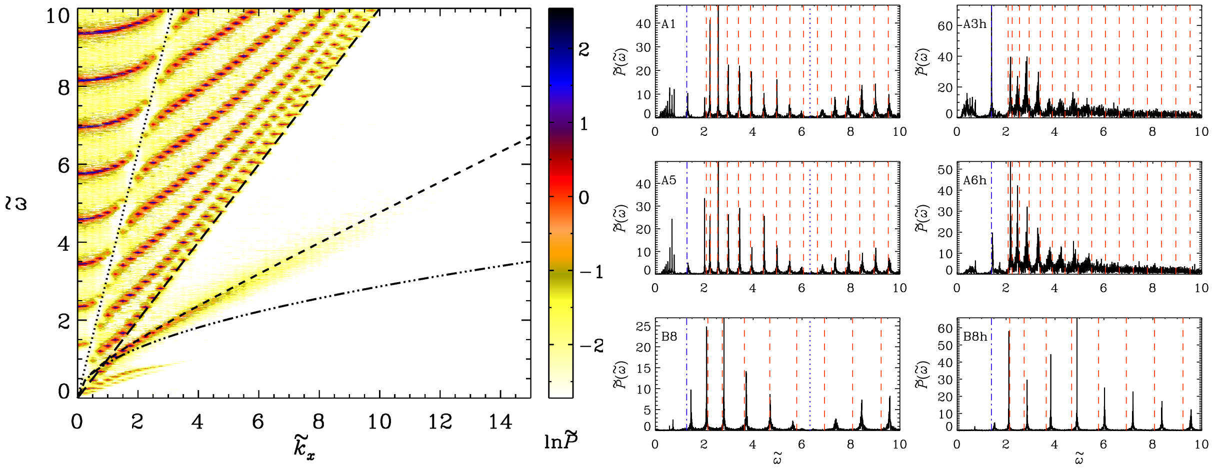

Figure 1: Left: $k\omega$ diagram for an isothermal domain with a moderately strong magnetic field. Right: Mode power as function of frequency $\tilde{\omega}$ with horizontal magnetic field for different runs. Dash-dotted (blue) and dashed (red) lines: theoretically expected locations of the f- and p-modes, respectively. Blue dotted lines: position of the $\omega = c_{\rm s}k_x$ line, shown dotted in the $k\omega$ diagrams.

2 Radiation hydrodynamics simulations

We have engaged in radiation hydrodynamics simulations and discovered that the local stability properties of hydrostatically stratified layers are solely determined by the coefficients in the opacity law [319]. The deeper layers are therefore a priori stably stratified. These effects are modified further by ionization effects [328].

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

328. Bhat, P., & Brandenburg, A.: 2015, "Hydraulic effects in a radiative atmosphere with ionization," *Astron. Astrophys.*, in press (arXiv:1411.6610)

This work is in preparation of doing realistic simulations of sunspot formation, which are also the subject of two of the three PhD thesis subjects at Nordita.

3 Sunspot formation and NEMPI

The discovery of remarkably strong magnetic spots reported in our 2014 report have now been verified in global spherical shell simulations [325].

325. Jabbari, S., Brandenburg, A., Kleeorin, N., Mitra, D., & Rogachevskii, I.: 2015, "Bipolar magnetic spots from dynamos in stratified spherical shell turbulence," *Astrophys. J.* **805**, 166

To understand the significance of this work, it should be emphasized that it is generally believed that the solar dynamo operates in the shear layer beneath the convection zone. This idea faces several difficulties that might be avoided in distributed solar dynamos shaped by near-surface shear. In that scenario, active regions would form due to large-scale (mean-field)

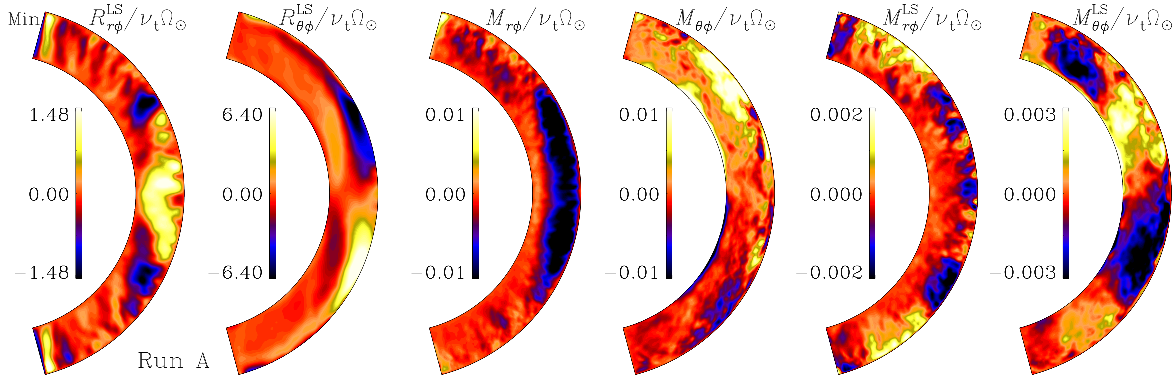

Figure 2: $R^{LS}_{r\phi} = \overline{u}_r(\overline{u}_\phi + \Omega_0 r \sin\theta)$, $R^{LS}_{\theta\phi} = \overline{u}_\theta(\overline{u}_\phi + \Omega_0 r \sin\theta)$ (left two panels), $M_{r\phi} = \overline{B'_r B'_\phi}/\rho\mu_0$, $M_{\theta\phi} = \overline{B'_\theta B'_\phi}/\rho\mu_0$ (middle two), $M^{LS}_{r\phi} = \overline{B}_r\overline{B}_\phi/\rho\mu_0$ and $M^{LS}_{\theta\phi} = \overline{B}_\theta\overline{B}_\phi/\rho\mu_0$ (right two), normalized by $\nu_t\Omega_\odot$.

instabilities in the near-surface shear layer. One candidate has been NEMPI. Until recently, this possibility remained uncertain, because it was based on results from mean-field calculations using turbulent transport coefficients determined from direct numerical simulations (DNS). An important result was the direct detection of NEMPI in direct numerical simulations; see my activity report of 2011. The recent discovery of magnetic spots (Summer 2013) has been followed up with more realistic simulations to see whether real sunspots can be produced this way (see previous section).

4 Dynamo action in spherical shells

Differential rotation in stars is caused by anisotropic convection, and the solution can be either such that the equator is faster or slower than the poles. It now turns out that this depends on wether or not one allows for magnetic fields to be generated [323]. We have computed the radial and latitudinal components to the angular momentum transport by the meridional circulation, $R^{LS}_{r\phi} = \overline{u}_r(\overline{u}_\phi + \Omega_0 r \sin\theta)$ and $R^{LS}_{\theta\phi} = \overline{u}_\theta(\overline{u}_\phi + \Omega_0 r \sin\theta)$; see Figure 2. We see that these stresses, particularly the latitudinal component, are the most dominating stresses for transporting angular momentum. This is because here we have strong meridional circulation, mostly poleward near surface and equatorward near the bottom. We also observe temporal modulations of transport due to meridional circulation, which become stronger during magnetic minimum. Therefore this temporal variation could lead to a variation in the differential rotation.

323. Karak, B. B., Käpylä, M. J., Käpylä, P. J., Brandenburg, A., Olspert, N., & Pelt, J.: 2015, "Magnetically controlled stellar differential rotation near the transition from solar to antisolar profiles," *Astron. Astrophys.* **576**, A26

5 Dynamo action, helicity, and vorticity in Cartesian domains

We have demonstrated for the first time that inverse transfer is possible even in the absence of magnetic helicity [322]. This work has significance for cosmological applications and used high spatial resolution of 2304^3 meshpoints.

322. Brandenburg, A., Kahniashvili, T., & Tevzadze, A. G.: 2015, "Nonhelical inverse transfer of a decaying turbulent magnetic field," *Phys. Rev. Lett.* **114**, 075001

6 Turbulent transport coefficients and dynamos

The so-called test-field method has been developed and applied in many of our recent papers. We have now verified that this test-field method gives results that are equivalent to those obtained using an alternative (albeit less powerful) method called multiscale stability theory [326]. We have continued studying turbulent dynamos in the presence of shear and have now found hysteresis behavior between distinct modes of activity [324]. This result has direct applications to understanding grand minima and grand maxima in the Sun. We have now for the first time shown that traces of large-scale dynamo action can be identified even in the kinematic stage [317].

326. Andrievsky, A., Brandenburg, A., Noullez, A., & Zheligovsky, V.: 2015, "Negative magnetic eddy diffusivities from the test-field method and multiscale stability theory," *Astrophys. J.* **811**, 135

324. Karak, B. B., Kitchatinov, L. L., & Brandenburg, A.: 2015, "Hysteresis between distinct modes of turbulent dynamos," *Astrophys. J.* **803**, 95

317. Subramanian, K., & Brandenburg, A.: 2014, "Traces of large-scale dynamo action in the kinematic stage," *Mon. Not. Roy. Astron. Soc.* **445**, 2930–2940

Follow-up work has been submitted and will be discussed in the report next year.