Activity report based on time used on HPC2N, PDC, and Nordic HPC since October 2012

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October 23, 2013

One of the major breakthroughs is the emergence of strong super-equipartition magnetic flux concentrations in the form of magnetic spots; see Figure 1. This work is the first one within a new effort supported though a *VR breakthrough research grant*, "Formation of active regions in the Sun" (2012-5797, January 2013 – December 2016, 4.2 MSEK) and led to paper now published in the Astrophysical Journal Letters; see Ref. [294] below. The mechanism is based on the negative effective magnetic pressure instability (NEMPI), and has been studied intensively before using horizontal magnetic fields. However, it now turns out that for vertical magnetic fields the effect can be much stronger. We are now in the process of understanding the operation of this mechanism at larger magnetic Reynolds numbers, which requires huge computing resources on Lindgren.

The calculations have been carried out using the Pencil Code which is hosted by Google Code (`http://pencil-code.googlecode.com`)[1]. Below, I describe the research outcome by quoting published papers since October 2012 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 Sunspot formation and NEMPI

As mentioned above, the by far most important outcome within this project is the discovery of magnetic spots; see paper [294]. It is based on earlier work that led to the discovery of NEMPI, which, in turn, led to significant progress within the present period of the activity report and has produced 5 papers [279,288,290,291,292], in addition to [294], which was mentioned above.

279. Losada, I. R., Brandenburg, A., Kleeorin, N., Mitra, D., & Rogachevskii, I.: 2012, "Rotational effects on the negative magnetic pressure instability," *Astron. Astrophys.* **548**, A49

288. Kemel, K., Brandenburg, A., Kleeorin, N., & Rogachevskii, I.: 2013, "Non-uniformity effects in the negative effective magnetic pressure instability," *Phys. Scr.* **T155**, 014027

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

291. Jabbari, S., Brandenburg, A., Kleeorin, N., Mitra, D., & Rogachevskii, I.: 2013, "Surface flux concentrations in a spherical α^2 dynamo," *Astron. Astrophys.* **556**, A106

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[1] The Pencil Code was written by Brandenburg & Dobler (2002) as a public domain code. The current number of project members on the google page is 92.

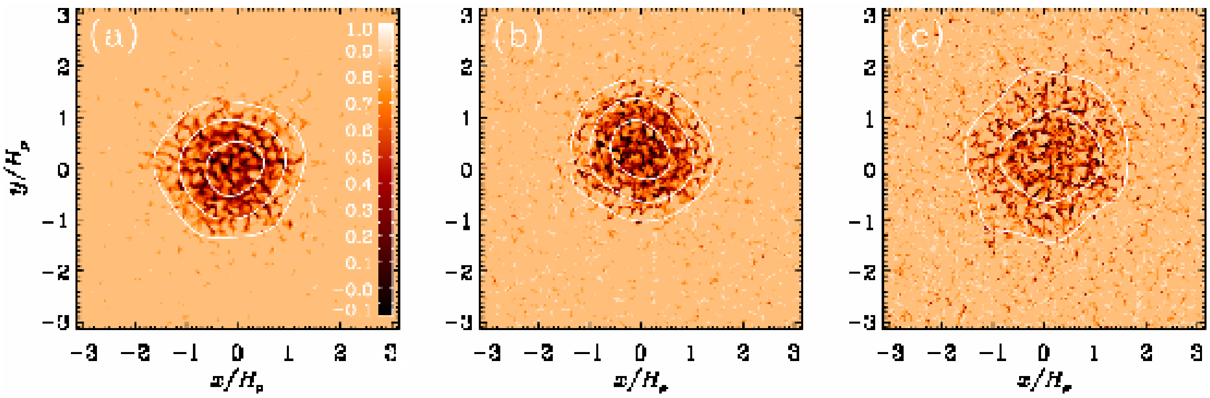

Figure 1: Magnetic field configuration at the upper surface for three values of the magnetic Reynolds number. The white contours represent the Fourier-filtered with $k_\perp \le k_\mathrm{f}/6$; their levels correspond to $\overline{B}_z^{\max}/B_\mathrm{eq}(z_\mathrm{top}) = 0.05$, 0.2, and 0.4.

292. Kemel, K., Brandenburg, A., Kleeorin, N., Mitra, D., & Rogachevskii, I.: 2013, "Active region formation through the negative effective magnetic pressure instability," *Solar Phys.* **287**, 293–313

294. Brandenburg, A., Kleeorin, N., & Rogachevskii, I.: 2013, "Self-assembly of shallow magnetic spots through strongly stratified turbulence," *Astrophys. J. Lett.* **776**, L23

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) 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 new discovery of magnetic spots (Summer 2013) needs to be followed up with more realistic simulations to see whether real sunspots can be produced this way.

For vertical magnetic fields, the effect can be dramatic. Although NEMPI itself only works for moderately strong magnetic fields, it sets up a downward flow in the tube, which leads to sideways inflow and further field concentration, as found from mean-field simulations; see the right panel of Figure 2. This has also been seen through local helioseismology (Zhao et al., 2010); see the left and middle panels of Figure 2. In the presence of a coronal outer layer, we have also been able to see the formation of bipolar regions; see Figure 3.

2 Dynamo action in spherical shells

Our simulations of astrophysical flow in spherical shells are now well developed and have led to detailed measurements of the resulting differential rotation in simulations driven by convection in rotating spherical shells. In the previous report we mentioned the development of what looks like coronal mass ejections above a spherical surface. We have now extended this work to flows driven by convection [297]. One of the unexpected results from this includes changes in the

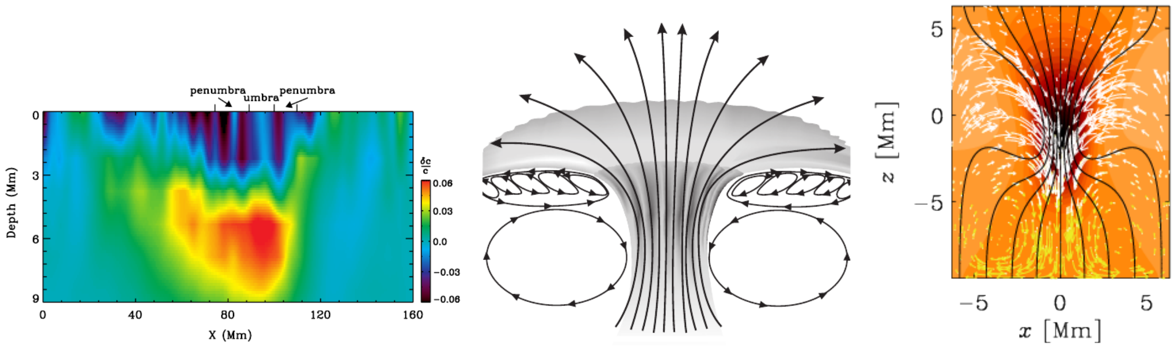

Figure 2: *Left:* sound speed perturbations near a sunspot (Zhao et al., 2010). *Middle:* sketch of their helioseismically inferred flow. *Right:* mean-field simulation of NEMPI from Brandenburg et al. (2013b).

differential rotation in the interior. This has to do with the baroclinic term, which balances the curl of the Coriolis force, and this baroclinic term is sensitive to details in the outer boundary conditions.

297. Warnecke, J., Käpylä, P. J., Mantere, M. J., & Brandenburg, A.: 2013, "Solar-like differential rotation in a convective dynamo with a coronal envelope," *Astrophys. J.*, in press (arXiv:1301.2248)

3 Dynamo action, helicity, and vorticity in Cartesian domains

We have continued our work on magnetic helicity fluxes. We find that the divergence of those fluxes begin to alleviate the so-called catastrophic quenching at magnetic Reynolds numbers on the order of around 1000 and above. We have now barely been able to reach this value [281]. This is important information, because we now know that most other models are not yet in this regime. We have also clarified controversial issues regarding the question how much kinetic helicity is needed to drive large-scale dynamos [284]. Finally, we have continued our work on decaying helical and non-helical magnetic fields in the early Universe [285,278].

278. Kahniashvili, T., Brandenburg, A., Campanelli, L., Ratra, B., & Tevzadze, A. G.: 2012, "Evolution of inflation-generated magnetic field through phase transitions," *Phys. Rev. D* **86**, 103005

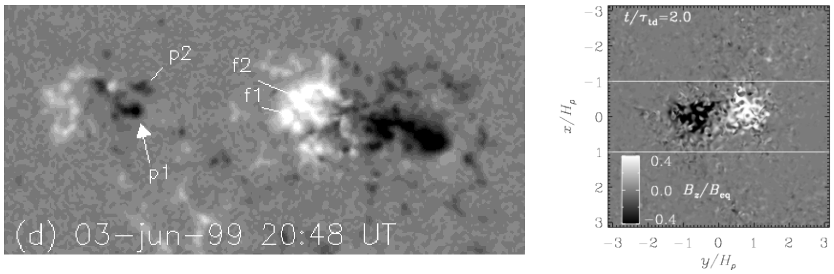

Figure 3: *Left:* magnetogram showing bipolar regions (van Driel-Gesztelyi et al., 2000). *Right:* self-assembly of a bipolar spot in a simulation with outer coronal layer (Warnecke et al., 2013).

281. Del Sordo, F., Guerrero, G., & Brandenburg, A.: 2013, "Turbulent dynamo with advective magnetic helicity flux," *Mon. Not. Roy. Astron. Soc.* **429**, 1686–1694

284. Candelaresi, S., & Brandenburg, A.: 2013, "How much helicity is needed to drive large-scale dynamos?" *Phys. Rev. E* **87**, 043104

285. Kahniashvili, T., Tevzadze., A. G., Brandenburg, A., & Neronov, A.: 2013, "Evolution of primordial magnetic fields from phase transitions," *Phys. Rev. D* **87**, 083007

4 Turbulent transport coefficients

Dynamo action based on negative magnetic eddy diffusivity has been speculated upon before, but we have now for the first time been able to show that some of those claims were wrong, and at the same time we have found a very simple example where it actually works [286]. We have also determined an α dynamo effect from just rotation (Yoshizawa's cross-helicity effect) and have measured its quenching with the magnetic field. Finally, we have addressed the long-standing question whether the α effect in dynamo theory is proportional to the gradient of $\rho u_{\rm rms}$, as was previously thought, or of $\rho u_{\rm rms}^2$. We now find evidence for the latter, and at larger Mach numbers even $\rho u_{\rm rms}^3$ [280].

280. Brandenburg, A., Gressel, O., Käpylä, P. J., Kleeorin, N., Mantere, M. J., Rogachevskii, I.: 2013, "New scaling for the alpha effect in slowly rotating turbulence," *Astrophys. J.* **762**, 127

282. Brandenburg, A., & Rädler, K.-H.: 2013, "Yoshizawa's cross-helicity effect and its quenching," *Geophys. Astrophys. Fluid Dyn.* **107**, 207–217

286. Devlen, E., Brandenburg, A., & Mitra, D.: 2013, "A mean field dynamo from negative eddy diffusivity," *Mon. Not. Roy. Astron. Soc.* **432**, 1651–1657

References

Brandenburg, A., Gressel, O., Jabbari, S., Kleeorin, N., Rogachevskii, I. 2013, A&A, submitted, arXiv:1309.3547

van Driel-Gesztelyi, L., Malherbe, J.-M., Démoulin, P. 2000, A&A, 364, 845

Warnecke, J., Losada, I. R., Brandenburg, A., Kleeorin, N., Rogachevskii, I.: 2013a, "1308.1080," *Astrophys. J. Lett.*, submitted

Zhao, J., Kosovichev, A. G., Sekii, T. 2010, ApJ, 708, 304