

Detailed project description: Astrophysical turbulence and dynamo action

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Abstract

Support for large-scale computing is being requested. In connection with my new VR breakthrough research grant on the “Formation of active regions in the Sun”, in addition to a regular VR project grant on “Turbulent dynamo simulation in a spherical shell segment”, a number of people are working on projects connected with this application. In addition to dynamos, we are also working on sunspots and helioseismology, and plan to make predictions about the magnetic influence of the so-called surface mode (or f-mode). Many of us use the PENCIL CODE (<http://pencil-code.googlecode.com>), which is a sixth order finite difference code with a third order time stepping scheme. The code uses MPI and is running on a range of different platforms around the world and is designed to work on large clusters. It is in the public domain and developed by an increasing number of project participants (currently 92 people of which 10 have project owner status). In the last year alone, since October 2012, Swedish computing resources are acknowledged in the 14 refereed papers of our last activity report; see <http://www.nordita.org/~brandenb/AstroDyn/progress/computing/report13.pdf>. This work is connected with two PhD theses to be continued in 2013 and three PhD thesis that will be completed later this year.

1 Background

In connection with a VR breakthrough research grant, “Formation of active regions in the Sun” 2012-5797 (January 2013 – December 2016, 4.2 MSEK) and a regular VR project grant, “Turbulent dynamo simulation in a spherical shell segment” 621-2011-5076 (January 2012 – December 2014, 1.65 MSEK) the group at Nordita will embark on trying to understand the origin of sunspots as a consequence of strong density stratification at the surface of a turbulent dynamo in the Sun. We also have now one post-doc dedicated to helioseismology (Nishant Singh). The following people will be involved:

Ms Sarah Jabbari (PhD student)
Ms Illa R. Losada (PhD student)
Dr Nishant Singh (Post-doc)
Dr Bidya B. Karak (Nordita fellow)
Dr Lars Mattsson (Nordita fellow)
Dr Mikhail Modestov (Nordita fellow)
Dr Anthony van Eysden (Nordita fellow)
Dr Dhruvadya Mitra (assistant professor)

2 Scientific content

Sunspots are visible surface manifestations of the Sun’s magnetic field. Current explanations are dominated by Parker’s idea that the magnetic field exists in the form of flux tubes that can become magnetically buoyant, rise to the surface, pierce it, and form a bipolar pair of spots (Parker, 1955). Since D’Silva & Choudhuri (1993), it is generally assumed that magnetic flux tubes of the toroidal field generated at ~ 200 Mm depth by differential rotation can reach the surface, but they need a highly super-equipartition strength and a considerable amount of twist (Fan, 2001). Simulations by Cheung et al. (2008, 2010) reproduce observations, but they release magnetic flux tubes close below the surface. Observationally, Stenflo & Kosovichev (2012) find that important aspects of the statistics of active regions are not compatible with the deeply rooted flux tube paradigm. Instead, turbulent dynamo theory predicts kG magnetic field generation distributed throughout the convection zone (Brandenburg, 2005). This poses difficulties for the standard scenario of sunspot formation.

A radically different idea is that sunspots are formed locally near the surface by the convective turbulence, as has been demonstrated recently by Brandenburg et al. (2013); see Figure 1. The formation of a bipolar spot through the same mechanism has also been found (Warnecke et al., 2013) and appears to reproduce magnetic field formations known as U-loops (van Driel-Gesztelyi et al., 2000).

Our research program proceeds in two parallel strands; one is connected with the development and exploitation of the spherical extension of the PENCIL CODE, and the other one is connected with important and unresolved problems that are to be addressed with the PENCIL CODE in its usual Cartesian configuration. The prime objective of the PENCIL CODE is to be efficient on massively parallel machines. The code uses the message passing interface and is made cache efficient by assembling the right hand side for all equations along one-dimensional pencils first. It has been run on up to 6144 cores without noticeable loss of scaling. Partial differential equations are being solved to third order in time and to sixth order in space. The code is most efficient in 3-D, but for test purposes it runs also well in 2-D, 1-D, and 0-D (corresponding to solving ordinary differential equations). The user can code up easily new equations, but the equations currently supplied are those of compressible magnetohydrodynamics, including the effects of radiation, self-gravity, dust particles with inertia and coagulation, chemistry, variable ionization, cosmic rays. For turbulence and dynamo studies it has been critical to be able to solve with the correct diffusion operators. Alternatively, however, shock diffusion and subgrid scale

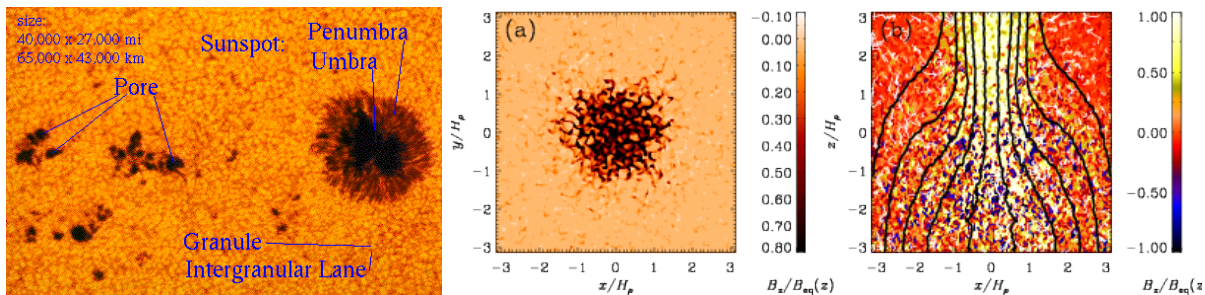


Figure 1: *Left*: white-light image of several pores and a sunspot on the turbulent solar surface consisting of many granules, which are much smaller than the magnetic structures. *Middle*: self-assembly of a magnetic spot from strongly stratified small-scale turbulence (Brandenburg et al., 2013). *Right*: vertical slice of the magnetic field of the same simulation. Black: magnetic field lines averaged about spot axis.

modeling can be included. The PENCIL CODE comes with an infrastructure where the code's integrity is tested each night on several machines on currently 50 test problems. Therefore everybody uses normally always the latest version, which is made public every morning. The number of people having downloaded the code is well over 1000 since its initial development in 2001.

There is a multitude of tasks to be performed. In the following we list detailed steps of our research program. Background and technical details of each of the steps in this synopsis are explained in Section 2 of this proposal.

- Determine the role of a radiative surface and hydrogen ionization for NEMPI. What is the size of structures, can they form fast enough and how is their time scale determined by the subsurface magnetic field evolution of the global dynamo? Compare with observations using the Swedish 1-m Solar Telescope.
- Reproduce the variety of magnetic phenomena including Ω - and U-loops, as well as δ spots (opposite polarity within a single penumbra). Study their twist and cross helicity. Determine coronal signatures for various spot configurations.
- Determine detailed features of subsurface magnetic fields. Which aspects of the field can be captured by observing the f-mode? Apply local helioseismology to NEMPI.
- Compute superflare statistics from a dynamo with shallow spot origin. Study relation to starspots using dynamo simulations. Reconsider the possibility of solar superflares.
- Using our global simulations of convectively driven dynamos, we shall study the origin of the different branches in stellar dynamo diagrams. Can discrepancies between the Sun and solar dynamo simulations be understood as shifts in parameter space, e.g., are shortcomings in turbulence modeling compensated for by faster rotation?
- Isolate starspots and the associated time-dependent global nonaxisymmetric field structure in rapidly rotating convective shells. Is the flip/flop phenomenon common?
- Simulate magnetic activity of young stars undergoing accretion. Determine effects on convective instability and the resulting dynamo.
- Understand magnetic braking and the role of magnetic fields in the radiative interior using well controlled simulations of possible dynamo action in cylindrical geometry.

3 Requested resources

Almost all the problems described above will principally use the PENCIL CODE¹, which is hosted by Google-Code since 2008². This is an open-source code developed by myself, my current and former coworkers, some of whom are part of this project, as well as others that have been invited to join the effort. The performance of this code has been discussed at several international conferences; see, e.g., <http://www.nordita.org/~brandenb/talks/misc/PencilCode09.ppt>. The code has been optimized over the years and is still being improved in terms of performance and new features are also being added. All of the 21,209 revisions since 2001 are publicly available through our svn repository. We have adapted and optimized this code for spherical polar coordinate system (Mitra et al., 2009). This addition to the code is used in several of the problems listed in the previous section. The code runs well on all the different platforms. This time we are applying for resources in the four machines Lindgren, Abisko, Gardar, and Triolith.

¹ <http://www.nordita.org/software/pencil-code>

² <http://pencil-code.googlecode.com>

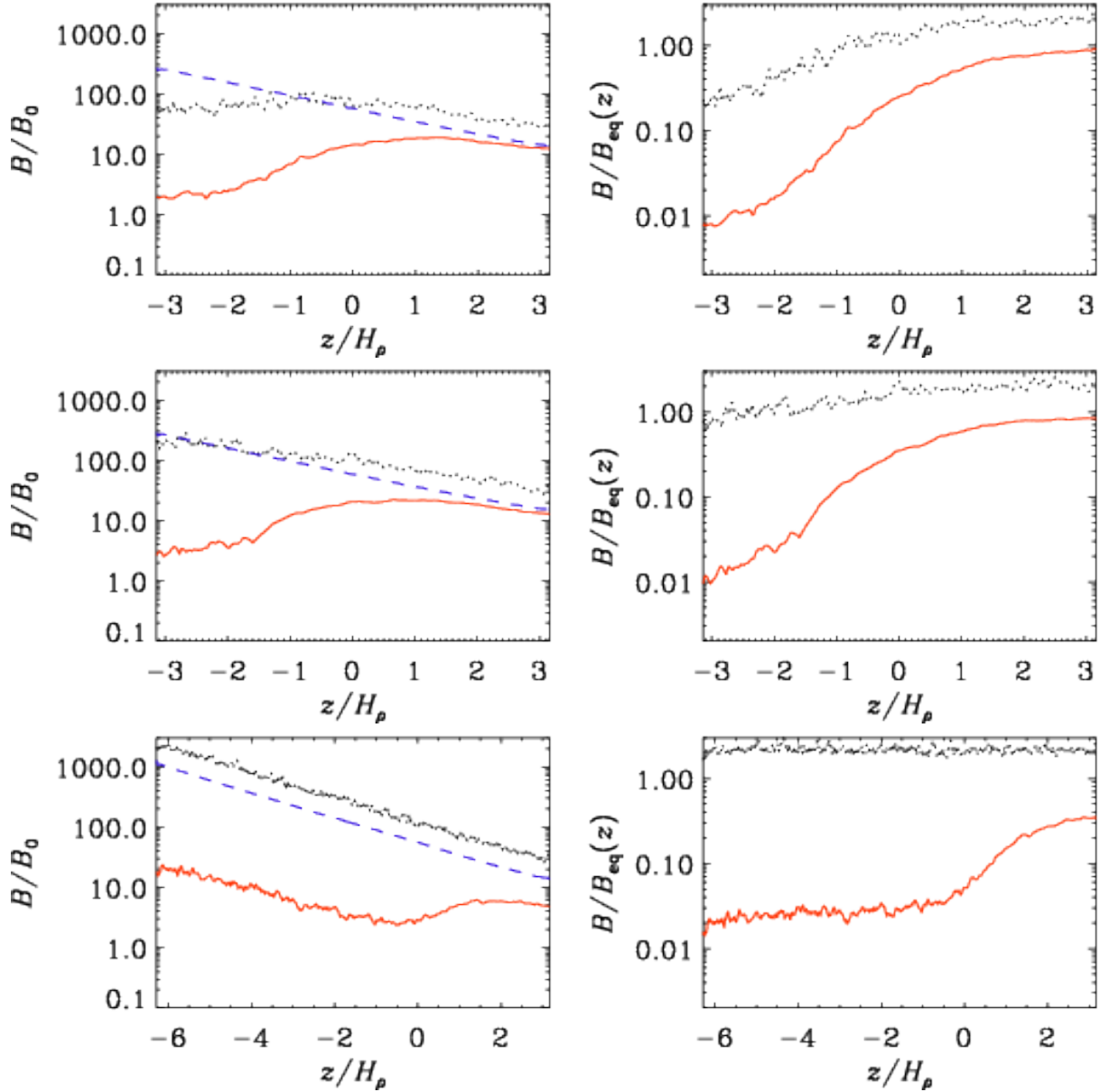


Figure 2: Top to bottom: runs with 256^3 , 512^3 , and $1024^2 \times 1536$ mesh points. *Left*: vertical dependencies of the mean vertical magnetic field in units of the background field (red), compared with total magnetic energy (black dotted line), and the equipartition field strength (blue dashed line). *Right*: vertical dependencies of the mean vertical magnetic field in units of the equipartition field strength (red), compared with total magnetic energy (black dotted line).

On Lindgren, we run production runs with $1024^2 \times 1536$ meshpoints on 6144 cores, while on Abisko, Gardar, and Triolith, most of our production runs tend to have 512^3 meshpoints and can require typically 512 processors. A typical run requires at least 500,000 time steps, but it can sometimes be much more, depending on circumstances. With $4.2 \times 10^{-4} \mu\text{s}$ per meshpoint and per timestep on Lindgren, this means 4 days of wallclock time at a cost of 600,000 CPU hours, while with $3.5 \times 10^{-3} \mu\text{s}$ per meshpoint and per timestep on Abisko, Gardar, or Lindgren, this means 3 days of wallclock time at a cost of 30,000 CPU hours per run.

To address properly the critical question of the dependence on the magnetic Reynolds number we have to use high resolution runs. As we move from 256^3 and 512^3 to $1024^2 \times 1536$ mesh points (and correspondingly higher magnetic Reynolds numbers), we see the emergence of small-scale dynamo action at all depth; see Figure 2. This does not yet affect the 512^3 runs, where the red line shows still a well-developed maximum of $\bar{B}/B_{\text{eq}} \approx 1$, but for the $1024^2 \times 1536$ the maximum is now only one third of that. We expect that this value will not decrease further, and that it will actually become bigger at larger stratification, but this needs to be shown. Note that the last of these runs is for a deeper domain, so as to include more safely the deep parts where it is important to reach values of \bar{B}/B_{eq} below 0.01, but this appears not to be possible due to small-scale dynamo action.

To confirm our ideas and to understand the effects of small-scale dynamo action, we plan to perform about 2 big runs per month on Lindgren, which requires at least 1000 kCPU hours, and about 5 intermediate ones on the other 3 machines, which requires 150 kCPU hours on each of them.

Computationally, all machines are comparable, but there can be unpredictable changes that hamper scientific progress. Most important is the waiting time in the queue and occasional opportunities when jobs start immediately. On Abisko and Triolith, the disk quotas restrict the ease with which we can run, while on Gardar there have been several periods when the machine was not functioning properly.

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