DYNAMO TEAM BIENNIAL REPORT 2016-2017

Part of ReSoLVE Centre of Excellence

Maarit Käpylä (ed.)
DYNAMO team members
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DYNAMO TEAM in a nutshell

Personnel structure

Foreign employees (position, nationality, wherefrom joined ReSoLVE):
- Dr. Omer Anjum, Academy of Finland postdoctoral researchers, currently on extended research visit at University of Urbana-Illinois, US, Pakistani/Finnish, Nokia Networks (own funding)
- M.Sc. (tech.) Alexander Grigorevskiy, PhD student, Russian, Department of computer science, Aalto, Finland (own funding)
- M.Sc. Nigul Olspert, PhD student (computer science), Estonian, Tartu University.
- Dr. Frederick Gent, postdoctoral researcher, UK, Sheffield University, UK
- Dr. Matthias Rheinhardt, postdoctoral researcher, German, University of Helsinki, Finland

Finnish employees:
- Maarit Käpylä, team leader (adjoint independent group leader position (W2) position at Max Planck Institute for Solar System Research, Göttingen, Germany)
- Petri Käpylä, part-time research fellow (senior researcher at Leibniz Institute Potsdam, Germany)
- Sami Kivistö, M.Sc. student (jointly with MAGNETIC team and Metsähovi)
- Johannes Pekkilä, M.Sc. student
- Simo Tuomisto, M.Sc. student

Alumni (role in ReSoLVE, nationality, whereto moved from ReSoLVE)
- Dr. Elizabeth Cole, PhD degree in 2016, US, postdoc in Melbourne, Australia.
- Dr. Jyri Lehtinen, PhD degree in 2016, Finnish, postdoc at MPS, Germany.
- Dr. Marjaana Lindborg, PhD degree in 2014, Sanoma Pro, Heureka, the Finnish Science Centre, Finland, medical student at Karolinska Institutet, Stockholm, Sweden.
- Dr. Jan Snellman, PhD degree in 2015, postdoctoral research at Complex systems group, Aalto University, Finland.
- Dr. Miikka Väisälä, PhD degree in 2017, Finnish, postdoc at ASIAA SINICA, Taiwan.

Track record
- The DYNAMO-team is the resource-wise smallest team of the CoE with 16.1% funding shear from the Academy of Finland.
- During 2014-present, 40 publications in peer-reviewed journals (class A1) and computer science conferences (class A4). These publications have been cited roughly 440 times (NASA ADS), and the team leader has more than thousand citations over this time period (Google Scholar).
- Four PhD degrees (astronomy) and one BSc. (computer science) obtained
- Two PhD degree (computer science) in preparation, one MSc. (computational physics) and one MSc. (astronomy) in preparation
- Team leader nominated as an independent Max Planck group leader at MPS Göttingen and as an adjunct professor in astroinformatics in Aalto University.
- Foundations’ Postdoc pool grant to Dr. Omer Anjum for one year as a visiting postdoc in USA (University of Urbana-Illinois, US), for GPU solver development
● Academy of Finland three-year postdoctoral position for Dr. Omer Anjum “Solving GPU Assisted Exascale Computing Challenges with High-Order Finite Difference Methods”

● *Heisenberg fellowship* from German Research Foundation for Petri Käpylä for the project “Spot-forming dynamos”

● PhD grants to E. Cole (*Väisälä foundation*), M. Väisälä (*Wihuri foundation*), and N. Olspert (*Finnish Cultural Foundation*)

● Budget of 500k SEK for organising the Nordita Program “Solar helicities in theory and observations: implications for space weather and dynamo theory”, March 2019, in collaboration with the HELIOS and MAGNETIC teams

● HPC projects SOLDYN, SPOTDYN (*PRACE*) & NEOCON (*CSC Grand Challenge*)

**Used and developed infrastructures**

The dynamo team utilizes both supercomputing resources for its modelling efforts and observational infrastructures for investigating young solar-type stars. These include:

- CSC - IT Center for Science supercomputing facilities including the Finnish Cloud and Grid Infrastructure (FCGI; national roadmap initiative) and IDA storage services
- PRACE supercomputing facilities (national roadmap initiative)
- Science-IT Aalto supercomputing resources (part of the FCGI consortium)
- Nordic Optical Telescope (NOT) funded by the Academy of Finland through NOTSA, the Nordic Optical Telescope Scientific Association. The team has been operating and running the SOFIN instrument at NOT since 1991.
- European Southern Observatory (ESO) facilities, Finland a member country.

**Relation to Aalto strategy**

“One of the core competence areas of Aalto University, with recognized excellence, is ICT and digitalization. The core fields of research serve as the excellence base for the multidisciplinary challenge-based and societally relevant themes. The PROF1 application concentrated, among other things, to strengthening research on core ICT focusing on mathematical and computational research, PROF12 on the application of the core competences to advance development on the multidisciplinary themes.”

The expertise and objectives of the DYNAMO team are within the core competences of Aalto University. The ReSoLVE overarching objective to use astro-, space-, and geophysics to advance the understanding of solar long-term variability and effects fulfills the Aalto criteria for multidisciplinarity and societal impact.

**SWOT analysis**

**Strengths**: The CoE project has significantly strengthened the research group, provided crucial resources to pursue this line of research, and leveraged the group to the world-leading position in the modelling of the solar dynamo. The CoE status has given the team members a unique chance to progress in their careers, and the team has been able to aggregate more resources. The Aalto support for the DYNAMO team has been excellent, and the presence of the team in the computer science department is leading to real multidisciplinary research efforts (between computer science and astrophysics). Thus,
a new field of science, namely astroinformatics, has emerged in Finland. The collaboration across team borders has significantly increased. One important factor in achieving this was the MAGNETIC team move from FMI to Aalto. On the other hand, such cross-disciplinary efforts simply take time to bear fruit, as also the collaboration in the Oulu-Helsinki axis is similarly enhanced.

**Weaknesses:** The DYNAMO team is still very loosely integrated to the host institute despite the support being otherwise excellent. The presence of the CoE has not lead to the establishment of new faculty positions that could ensure the continuation of this line of research after the CoE ends. This is especially surprising in the case of the DYNAMO team, where strong investments for astroinformatics are made elsewhere in the world (e.g. Georgia AstroInformatics Nexus (GAIN) cluster; AIN at Heidelberg Institute for Theoretical Studies), and such expertise is also needed for the EUCLID work that Aalto is participating.

**Opportunities:** More aggregate funding and knowledge exchange to and from other fields of science (computer science, engineering) are possible. One such opportunity has already been realised by the award of an Academy of Finland postdoc project for one of the team members in the realm of computer science.

**Threats:** The CoE term of 6 years is definitely too short to integrate well to the host institute, unless the CoE team is already established there earlier. Also, a CoE such as ReSoLVE with interdisciplinary goals (solar physics - space physics - geophysics), would have needed a significantly longer period of time to reach all its objectives. The decision to change the CoE terms from 6 to 8 years is definitely a good one, but threatens seriously the continuity of the CoEs that end in 2019. Unless there is at least a faculty position in Aalto opened in the research field of DYNAMO team, there is no continuity for this line of research after the CoE period in Finland.
Objective: Develop a solar dynamo model that reproduces the observed centennial evolution of the toroidal and poloidal magnetic fields

Effort leader: DYNAMO team, Aalto
Effort participants: MAGNETIC, HELIOS and COSMIC teams

During the years 2016-2017 the DYNAMO team has continued its efforts towards its main objective, namely to understand the long-term evolution of the solar dynamo, through direct numerical simulations of turbulent convection both in local, but dominantly in global spherical geometries. In addition to the scientific results, significant methodological advances, both in data analysis and numerical modeling, have been accomplished that have enabled some of the results presented here, but are also vital for making further progress in the imminent future.
1 Long-term evolution of the solar dynamo

The Sun, aside from its eleven year sunspot cycle, is additionally subject to long-term variations (such as the Gleissberg cycle which manifests itself as amplitude modulation of the basic cycle) and irregular disruptions (such as the Maunder minimum) in its activity. The DYNAMO team has made a huge computational effort to capture such behavior in global-scale convection dynamo simulations. The first ever solar-like solutions, covering a few magnetic cycles with the toroidal magnetic field showing clear equatorward migration in low latitudes and a poleward branch at higher latitudes, were obtained in wedges of compressible turbulent magnetoconvection by the group members in 2012 (Käpylä et al. 2012, ApJL, 775, 22). These models have since that time been extended considerably in time to be able to investigate the solutions on a scale of a millennium in solar time units (Käpylä et al. 2016a, the “Pencil-Millennium” simulation). Our longest model produced so far covers 200 magnetic cycles, and reveals extremely complex behavior, including multiple dynamo modes, strong short-term hemispherical asymmetries, and epochs of disturbed and even ceased surface activity. Surprisingly, the most prominent epoch with suppressed surface activity (see Figure 1, 25-50 yrs) is actually a global magnetic energy maximum; during this epoch it is particularly the bottom toroidal magnetic field, which reaches a maximum, demonstrating that during grand-minima-type events the magnetic field can be hidden in the deep parts of the convection zone, making the interpretation of such events non-trivial.

Figure 1: Time-latitude diagram of the azimuthally averaged toroidal magnetic field near the surface (upper panel) and at the bottom of the convection zone (lower panel), from Käpylä et al., 2016a.

The models are extremely demanding in terms of computational resources (e.g. the Pencil-Millennium was run for nine months in real time, consuming over 400,000 CPU hours), requiring the utilization of the most efficient supercomputers nation- and Europe-wide (see Section 2.7 for the measures we are currently undertaking to improve the efficiency of our solver), but even the post-processing data analysis tasks constitute a major challenge. One of them is posed by the large size of the data, but also

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1 Our main computational tool is the Pencil Code, available from: https://github.com/pencil-code
the non-periodic (but cyclic) and incoherent nature of the dynamo solutions requires special techniques to be dealt with properly (Olspert et al., 2017). The huge amount of data stored from the simulation can be used to search for the physical mechanisms behind the detected phenomena - even though the models yet represent only ‘tar Suns’ with much too low Reynolds numbers, and thereby emulating, in comparison to reality, a much more viscous plasma. In any case they provide laboratories to investigate the complex nonlinear dynamo-active system.

*Figure 2: Zoom into the time-latitude evolution of the azimuthal magnetic field (top), the $\alpha_{\phi\phi}$ tensor component (middle), and the time-radius evolution of the radial turbulent pumping vector component during a ceased surface activity epoch.*

We were especially interested in finding a physical cause for the Maunder-minimum-type ceased surface activity epochs. In Käpylä et al. (2016a) we studied whether variations in the large-scale flows could drive them: neither differential rotation nor meridional circulation, however, showed any marked differences between different states of activity, suggesting the turbulent transport coefficients to play a crucial role in causing the long-term variations in the magnetic field. Therefore, we applied the test-field analysis tool, the spherical extension of which was inaugurated during the first biennial (2015-2016) of ReSoLVE efforts, to measure and quantify the effects of turbulence in the generation and evolution of the large-scale magnetic field (Gent et al., 2017).

The test-field analysis provides an explanation of the missing surface magnetic cycle in terms of the reduction of part of the alpha effect, one of the key ingredients for dynamo action. Furthermore, we found an enhancement of downward turbulent pumping during the event to confine some of the magnetic field at the bottom of the convection zone, where a local maximum of magnetic energy is observed during the event (see Figure 2, Gent et al., 2017). At least in the parameter regime attainable by these models, the turbulent effects play a crucial role in producing Maunder-minimum-type epochs.
In a multi-decade study of the photometric variability of 21 young solar-type stars we found systematic
tendencies in the behavior of the spot cycles and active longitudes of active stars (Lehtinen et al., 2016, A&A, 588, 38). We found that active longitudes, or persistent non-axisymmetric spot distributions, are common on the fast rotating, strongly active stars, but absent on the slow rotating, moderately active ones. This is indicative of a transition from axisymmetric to non-axisymmetric dynamo modes between slow and fast rotating stars. In many cases we observed a significant difference between the active longitude rotation periods and the stellar bulk rotation, which may suggest the presence of longitudinally (azimuthally) travelling dynamo waves in these stars.

We set out to find an explanation for the observed behavior by using our semi-global convection
dynamo simulations, where we relaxed the wedge assumption in the longitudinal direction. This was necessary to capture non-axisymmetric dynamo modes, posing even greater computational challenges than the solar models that are normally produced in narrower wedges. Hence, we modelled solar-like stars over the full longitudinal extent, but still missing a polar cap, with variable rotation rates (see Figure 3, adapted from Viviani et al., 2018). These runs were partially produced using special DEISA/DECI project allocations. As a result, we indeed found a transition from axisymmetric to non-axisymmetric dynamo modes: the solar-like low-latitude axisymmetric toroidal rings were observed to change into high-latitude non-axisymmetric structures, that were most often symmetric with respect to the equator. The most typical configuration is shown in Figure 3, where the azimuthal Fourier mode with $m = 1$ is dominating the solution. The point of the axis- to non-axisymmetric transition in terms of rotation rate was, however, very close to the solar one, in disagreement with observations (see Figure 5). Also, the non-axisymmetric solutions exhibited azimuthal dynamo waves almost as a rule, but so far the models prefer retrograde (slower than the rotation rate of the star) waves whereas observations very often indicated prograde (faster) ones. In almost every case we obtained an oscillatory magnetic field solution, and could study the relation between cycle period and rotation rate, a quantity also measurable from observations (see Figure 5). Our modelled points are in fair agreement with the active and superactive branches, while forming a scattered cloud of points in the regime of the inactive branch (see discussion in Sect 3 and gray symbols in Figure 5).
Figure 4: Radial magnetic field from a Yin-Yang convection run. Colour scaling as in Figure 3.

These results are very encouraging, as it seems evident that the convection dynamo simulations are reaching the parameter regimes to be useful in understanding the Sun’s magnetic field evolution over time. Severe discrepancies in comparison to observations yet exist, indicating further needs for improvements both physically and numerically.

One such critical improvement is the inclusion of poles (see Figure 4). This important methodological step, namely the implementation of the Yin-Yang grid in the MHD solver, was undertaken since the end of 2015. During 2017, the setup has undergone rigorous testing, during which we had to solve many demanding methodological issues, such as how to minimize the inaccuracies caused by the interpolation on the grid interface, and how to mitigate the two solutions on the different grids to deviate from each other too strongly. We implemented and investigated several interpolation schemes of various spatial order, and converged on the necessity of having interpolation and differentiation schemes of roughly matching spatial accuracy. The implementation is now undergoing testing with demanding physical setups, such as turbulent convection. Our goal is to start full-scale runs, matching those of Viviani et al. (2018), during 2018.
3 Sun as a solar-like star
Contributing team members: Nigul Olspert, Maarit Käpylä, Alexander Grigorevskiy
Contributing resource persons: Jaan Pelt
International collaboration: Jyri Lehtinen, Max Planck Institute for Solar System Research

The solar dynamo models can be further constrained if we look at the Sun as a star among others. Especially the kinematic mean-field models, solving for the evolution of the large-scale magnetic field only, and hence having the need to parameterise the unresolved turbulent effects, are usually fine-tuned to reproduce the solar-like dynamo solutions by adjusting the many free parameters that are contained in the models. Therefore, even two conceptually very different approaches can successfully reproduce the main behavior of the global solar magnetic field: The flux-transport (or Babcock-Leighton) dynamo models consider turbulent convection largely unimportant, and assume dynamo action to take place in two separated field generation regions ($\Omega$ effect in the tachocline, $\alpha$ effect near the surface due to the decay of tilted active regions) connected by a one-cell meridional circulation pattern. Turbulent dynamo models assume convection to be important throughout the convection zone ($\alpha$ effect being distributed all over), complemented with shear layers both in the tachocline and near the surface, but consider meridional flow unimportant due to vigorous turbulent mixing. Without further constraints it is impossible to tell which model is more correct.

Figure 5: Stellar cycles from the Mount Wilson Ca H&K survey (red and blue symbols, Olspert et al. 2018b). Green/gray symbols show other observations/global convection model results for comparison. The observations are consistent with two continuously connected branches: inactive (I) stars with predominantly axisymmetric fields (AS) and active (A) rapid rotators with mostly non-axisymmetric (NAS) fields. The models yet fail to produce clear branches, and the AS-NAS transition points (vertical lines) do not match.

One way to obtain such constraints is to look for dependencies of the stellar magnetic cycle length on the rotation rate of the star, as these are the standard “output” and “input” quantities of the dynamo models of various kinds. As stellar cycles can be expected to be of decadal lengths, such observational studies are not easy due to the lack of long enough samples. Some exist, however, with the most often used one being the Mount Wilson Ca H&K chromospheric activity survey, which we recently analysed utilizing modern probabilistic methods (see Section 6 for details, Olspert et al., 2018a,b), while also checking the reliability of the derived cycles against different kinds of model assumptions (strict harmonicity, periodicity, quasi-periodicity, sensitivity to the removal of linear trends). Our results,
depicted in Figure 5 in a rotation-to-cycle-period ratio versus activity (RCRA) diagram with blue and red symbols, indicate that only one very robust, method-independent trend exists in the Mount Wilson survey: For stars with activity levels similar to the Sun (inactive (I), red symbols), the rotation-to-cycle-period ratio is an increasing function of magnetic activity, while for more active stars (A, blue symbols) the trend is inconclusive. They seem to behave like even more active stars studied through photometry by Lehtinen et al. (2016, A&A, 588, 38), that is to show a decreasing trend in this diagram.

Such an increasing trend for the I-branch stars is inexplicable by Babcock-Leighton-type dynamo models, which would predict a very steep linear decrease in the RCRA diagram. The simple $\alpha\Omega$ turbulent dynamo models do slightly better predicting a less steep decrease, but even when stretched to their very limits, they could only explain a flat behavior. Even the global convection dynamo models fail to reproduce this branch - instead we see a cloud of points (gray symbols) that show no clear trends. **Thus, the solar activity branch remains enigmatic to all dynamo paradigms and state-of-the-art models, and finding a solution to these inconsistencies poses the greatest challenge of modern solar and stellar dynamo theory.** Our path towards a solution, however, is clear. Our models, nor any other convection dynamo model on the market, do not yet reproduce realistically the solar, and hence not the stellar differential rotation profiles. In particular, they do not yet self-consistently generate the tachocline nor the near-surface shear layer, which necessarily affect the dynamo solutions, and the models must be improved in this respect.
The parameter regimes of current global convection dynamo simulations are still far distant from realistic conditions of stellar interiors. This is because the equations to be solved are discretized on a finite-sized grid, and orders of magnitude larger diffusion coefficients than those occurring in the real stars are needed to stabilize the solutions - hence the current models can be characterised as models of ‘tar stars’. The ways to alleviate the tar problem include increasing the resolution of the grid, using non-uniform or adaptive grids to enable higher resolution where needed and less where not, or using diffusion schemes that use the properties of the flow to enhance diffusion only in locations with strong gradients, while leaving the smooth parts unaffected. The real parameter regimes of the Sun or stars will remain out of the reach for the foreseeable future, but the realistic expectation is to reach an asymptotic regime where the solutions no longer depend on the diffusion coefficients, and where the large-scale results would likely be representative of real stars.

In Käpylä et al., (2017a) we made an attempt to reach to the asymptotic regime by performing progressively higher resolution simulations with explicit diffusivities. As we increased the resolution, in addition to the large-scale dynamo, an independent dynamo instability, the small-scale dynamo was excited in the simulations. The effect of it on the system was somewhat unexpected: it suppressed the differential rotation very strongly, and therefore also the large-scale dynamo efficiency was reduced; the clear cyclicity of the large-scale magnetic fields in more laminar parameter regimes disappeared or became highly irregular. **Our study showed that the effects of the small-scale dynamo on the global-scale one can be very diverse and go through many different paths; as the numerical models have only very recently reached the parameter range where these two dynamo types occur simultaneously in global models, these effects are all largely unexplored, and major discoveries can be expected in the imminent future. Our results, however, did not yet reach an asymptotic regime, and hence call for follow-up studies with even higher resolution.**
Another issue that differentiates the global convection dynamo simulations from real stars is that the latter are observed to form spots of various sizes and properties, whereas no global convection dynamo simulation has so far been able to produce them spontaneously (which we call as the spot-forming dynamo paradox). The current paradigm for spot formation assumes that strong toroidal magnetic fields are generated in the tachoclinic shear layer, which then de-stabilize, and release thin buoyant flux tubes that reach the surface very rapidly. The Coriolis force twists them during their rise, and therefore they can readily form tilted sunspot pairs after piercing the surface.

The problem with this scenario is that no convection model so far has been able to reproduce anything resembling a flux tube (unless put there by hand) that could survive its rise through the convection zone without being affected by the vigorous turbulence within it. Instead, two types of robust observations from numerical convection models have recently been obtained by several groups: 1) global simulations produce strongly helical torus structures that do not necessarily have anything to do with the tachocline (see Figure 6, adapted from Viviani et al., 2018), but can occur also rather near the surface, and 2) local simulations with even higher resolution (such as those produced during the SPOTDYN Prace project, see Figure 7, Singh et al., 2018, in prep.) generate magnetic field concentrations spontaneously. The exact physical mechanisms for this spontaneous structure formation still elude our understanding, but options include turbulent effects resulting into a negative effective magnetic pressure (NEMP instability, see e.g. Brandenburg et al., 2016, New Journal of Physics, 18, id. 125011), flux expulsion (Käpylä et al., 2016b), or cooling-induced instability (Kitchatinov & Mazur, 2000, A&A, 359, 531). The parameter regime where the spontaneous spot formation is seen is not dramatically far away from that where the current highest resolution global models work; therefore, the first spot-forming global convection dynamo models might become possible in the near future in the quest for reaching the asymptotic regimes.
5 Cracking the convection conundrum

Contributing team members: Petri Käpylä, Maarit Käpylä, Matthias Rheinhardt, Nigul Olspert
Contributing resource persons: Axel Brandenburg
International collaboration: Rainer Arlt, Leibniz Institute Potsdam, Germany; Andreas Lagg, Max Planck Institute for Solar System Research

The details of the differential rotation profiles in the solar models are not the only discrepancy with helioseismic results: the models also consistently produce too large convective velocities at supergranular and larger scales in comparison to the helioseismic inversions. This problem is dubbed the convection conundrum. It is likely that both observations and models need to be refined to fully resolve this issue. On the modelling side, however, it raises the question about the validity of the basic building blocks of the current convection models. For example, the heat conductivity profiles of the models are typically built on the assumption that the convection zone is convectively unstable throughout which is what mixing length theory (MLT) is telling us. However, this is unlikely to be a valid assumption, as a large fraction of the solar convection zone can actually be very close to marginal stability or even subcritical (Brandenburg 2016, ApJ, 832, 6). Models built on heat conductivity profiles, producing a supercritical convection zone throughout, excite convective modes at all scales from the smallest allowed by the grid to the thickness of the convection zone. Hence, excess convective power at large scales would be produced. This excess power in current simulations can also result from the relatively laminar parameter regimes which are too far away from the fully developed turbulence expected to occur in stellar convection zones.

We set out to break free from heat conductivity profiles, constructed according to the MLT predictions, by computing them from the Kramers opacity law instead, in which case the heat conductivity is a strongly non-linear function of density and temperature. In such setups, we obtain dynamical, smoothly varying, heat conductivity profiles instead of a sharp, predefined gradient at the interface between the radiative and convective zones. Our setups are also not preconditioned to lead to superadiabatic layers of fixed depth. As a consequence, in local three-dimensional boxes, we found solutions where a substantial fraction of the lower part of the convection zone is stably stratified according to the Schwarzschild criterion (Käpylä et al., 2017b). If these results carry over to the Sun, roughly 40 per cent of the lower part of the convection zone is stably stratified.

We investigated the reason why such subadiabatic layers, beyond the scope of MLT, arise in the models. We found out that convection is driven by cooling near the surface, creating downward diving plumes that bring low entropy material from the surface to the stably stratified layers below (called entropy rain) giving rise to subadiabatic convection. At the same time, the topological structure of convection
changes from a tree-like (merging downflows) structure to a forest-like (constant number of downflows) one in the deep parts of the convection zone (Figure 8). The existence of such subadiabatic layers has possibly wide-ranging ramification in the theory of differential rotation and dynamos. These will be studied in detail in the global setups during the remaining two years to ReSoLVE.
6 Milestones in method development

6.1 Multi-GPU MHD library for Pencil Code and beyond

*Contributing team members: Johannes Pekkilä, Omer Anjum, Mikka Väisälä, Matthias Rheinhardt, Maarit Käpylä, Petri Käpylä*

*International collaboration: Liwen Chang, Carl Pearson, Wen-Mei Hwu, University of Urbana-Illinois, US*

Efficient and robust computational methods are the indispensable basis for generating useful science with high-performance computers. Physical simulations have traditionally been run on CPUs, which are relatively easy to program for and offer well-established application programming frameworks for scaling from single to multiple compute nodes. Graphics processing units (GPUs) on the other hand are designed for solving data-parallel problems efficiently and to this end, offer much higher memory bandwidth and larger number of parallel processing units than their CPU counterparts. The differences in GPU architecture do not come without a cost: latency for memory accesses is much higher, there are no large multi-level caches and problems which cannot be solved in a data-parallel fashion will exhibit abysmal performance.

Partial differential equations, discretized by finite differences, are excellent problems to be solved on GPUs, since at each discrete point in the computational domain the same set of equations can be processed in parallel. During the first biennial of ReSoLVE, we completed a proof-of-concept hydrodynamics solver for a single GPU, which provided a speedup of 6.8 with a Tesla K40c GPU over a highly optimized CPU solver run on all 12 cores of a comparable Intel Xeon processor (Pekkilä et al. 2017a, Pekkilä et al. 2017b).

During the past two years, work has continued towards a highly efficient multi-GPU library for magnetohydrodynamics (MHD), called *Astaroth*, which we will interface with the Pencil Code as a GPU module. The core of the library is the GPU layer, which is usable via a high-level interface with functions like *GPUReduce()* and *GPUIntegrate()* . These functions abstract away much of the implementation details, such as managing memory allocations, spawning threads and distributing the problem among an arbitrary number of GPUs in the node. We have also developed a reference implementation of the host layer, which can be used to benchmark, autotest and run the GPU-solver as a standalone application (see *Figure 9*).

*Figure 9: Structure of the Astaroth GPU-solver. To ensure continuous development, great care has been taken to divide the project into clearly defined modules and layers which enable us to write modular, performant and automatically verifiable code. Adapted from Pekkilä et al. (2018).*
The groundwork for the library has been done and will be presented in NVIDIA's GPU Technology Conference in Pekkilä et al., (2018). Currently, our GPU-solver supports the basic set of MHD equations and scales to 4x K80 GPUs with 95% efficiency, which was achieved by hiding inter-GPU communication completely by concurrent memory operations and computing. Our single-GPU implementation has been improved over our the earlier version (Pekkilä et al. 2017a) and it now uses two novel cache blocking schemes and a reformulation of the equations, which we seek to publish later this year. Work also continues towards generalizing our algorithms for solving arbitrary 55-point stencils, which would allow us to add new equations to the solver with little effort.

Our GPU library has been designed to be run on a single node and the implementation details of inter-node communication are left to be decided by the host. The motivation for this is the very small difference between GPU and CPU implementations on the node level. Hence we can leverage the highly optimized MPI-implementation of the Pencil Code without having to develop our own. Work on integrating Astaroth in the Pencil Code is ongoing, and testing of the multi-node implementation and the recently added physical modules are the next steps of this project.

6.2 Time series analysis methods

*Contributing team members: Nigul Olspert, Alexander Grigorevskiy, Maarit Käpylä*

*Contributing resource persons: Jaan Pelt*

*International collaboration: Jyri Lehtinen, Max Planck Institute for Solar System Research*

To put solar dynamo models into the context of other late-type stars one needs to make comparison to observed quantities. There are not many ways to do it as on one hand, for real stars only a limited number of quantities are actually observable or directly derivable from observations and on the other hand, the convection simulations usually do not include photosphere and chromosphere, so that the direct link to observable quantities is often missing. One useful observable dimensionless quantity is the ratio of rotational and cycle period of the star. From the point of view of the simplest dynamo model, it can also be interpreted as a measure of the dynamo efficiency. Calculating this ratio, however, is challenging as neither the rotation of the star nor the magnetic cycles are manifested through fully periodic signals. In the former case one can understand the origin of the amplitude and phase modulations in the signal as due to dark spots simultaneously appearing and disappearing at different latitudes and longitudes of the star. In the latter case non-periodicity is the result of nonlinearities in the dynamo process. We will refer to both of these phenomena as quasi-periodic processes.

During the starting years of ReSoLVE we primarily focused on developing an effective method for quasi-periodic signal processing. This method, called D^2 statistics, we first applied to a photometric time series of the young solar analogue LQ Hya to determine the mean rotation (or Carrington) period of the star (Olspert et al., 2015). Using this period in turn enabled us to build a continuous light curve model for the star. We later generalized the D^2 method to multiple dimensions to allow easier handling of MHD simulation data. Using this approach we continued with the cycle analysis of the Pencil-Millennium simulation, where we eventually detected four different cycles with different coherence times and regional locations/spans in the convection zone (Olspert et al., 2017). In an earlier study of the same simulation, but over a shorter time range, where we used the Ensemble Empirical Mode Decomposition method for cycle detection, the shortest cycle around half a year was quantitatively left undetected due to it’s very short coherence time causing mode mixing (Käpylä et al, 2016a).
More recently we have turned to probabilistic time series analysis methods, such as Gaussian Processes (GP). One reason for that is the ease of adding and removing model components or changing their functional form, which in turn allows better model selection. For instance in the Mount Wilson (MW) Ca H&K dataset the presence of linear trends is evident and it is straightforward to include it into the GP model. Likewise we can easily try out models from different families (eg. periodic, quasiperiodic). We applied GP methods in Olspert et al., 2018b to obtain cycle length estimates for the MW stars and found significant differences to the previous studies. Examples of the GP models fitted to the solar data can be seen in Figure 10. Furthermore, we statistically confirmed the existence of two separate populations of stars in the activity (RCRA) diagram (see Figure 5 in Sect 3). Contrary to previous studies, however, we only detected a significant correlation between the activity index and the rotation-to-cycle-period ratio in the inactive population, but not in the active one.

Sometimes including the linear trend component directly into the model is not only beneficial, but even crucial as without doing it one can obtain biased period/cycle length estimates. To illustrate the importance of this aspect we extended the well known Generalized Lomb-Scargle Periodogram with the linear trend component and applied it to the MW dataset (Olspert et al., 2018a). In this study we pointed out some examples where significant deviations from the previously obtained estimates were detected.

Figure 10: Comparison of the periodic GP (top) and quasi-periodic GP (bottom) models fitted to the MW data of the Sun. Black crosses are observational data and red lines the predicted mean curves. The shaded areas around the means correspond to 2σ confidence intervals of the unobserved data points.

The downside of the GP methods are their high computational costs, therefore other methods like D^2 are still very valuable in practice. However, in our future research we generally see more use in probabilistic methods as their advantages and limitations are well defined, and the uncertainties of the parameter estimates come as byproducts of the analysis. This also means that the results are usually easier to interpret. Amongst others methods we are interested in State Space methods, which are equally powerful to GPs, but also highly scalable.
6.3 Digitising historical solar radio intensity maps from Metsähovi Radio Observatory

Contributing team members: Sami Kivistö, Frederick Gent, Nigul Olspert, Matthias Rheinhardt, Maarit Käpylä, Juho Kannala
Collaboration within ReSoLVE: MAGNETIC team
National collaboration: Juha Kallunki, Joni Tammi, Metsähovi Radio Observatory

Metsähovi Radio Observatory has performed solar observations since 1976, using a Cassegrain type radio telescope with dish diameter 14 m. The solar intensity has been scanned on various radio frequencies ranging from 10 GHz to 100 GHz, of which the most common is 36.8 GHz. Early solar data were stored on magnetic tapes, and were printed offline using a mechanical XY-plotter (Helsinki University of Technology, Metsähovi Radio Research Station. Series A, Report 5, 1991). The magnetic tapes are lost, leaving the printed contour plots the only storage of this valuable data set. In this form, however, the maps are of limited use, and severely hinder the usage of the newer data in digital form, as such data are utilized best in the form of continuous long-term sets.

Figure 11: a) An example of a scanned historical solar intensity map. b) Contour detection from the digital image. c) Contour plot converted to a cosine-corrected heatmap. A circle is fitted to the visual disk and an effective beam size radius is subtracted from the visual radius. Both relatively active and quiet regions were identified through statistics. d) Visual heatmap transformed into a Carrington map. The north pole was visible from Earth at the time of the observation.

As a joint effort between Metsähovi, CS department (DYNAMO team), and the MAGNETIC team, Sami Kivistö was employed to undertake this major important “reverse engineering” task as his MSc project. Supervised by the professor of computer vision, Juho Kannala, an algorithm has been developed for transforming these scanned contour plots into heatmaps. The process is fully automated, and involves several steps, including pen path tracking, line and circle fitting for a suitable subset of points on a path, text recognition, and detection of variable layouts. Maps with different styles require different parameters in line tracking and interpreting the contours. There are currently 33 such adjustable parameters. To cope with such a high dimensionality and to avoid manual work, there is an evolutionary optimization scheme for finding good parameter combinations for selected maps. The process is tolerant for not
having all contours intact, and this involves a Poisson solver with adaptive dimensionality reduction. The program is able to detect areas with especially low or high intensity. These are mapped onto the Solar surface using Carrington coordinates (http://wso.stanford.edu/words/Coordinates.html), which takes into account the average rotation of the Sun. An example of this process is shown in Figure 11.
2.7 Publication list


Bushby, P. J.; Käpylä, P. J.; Masada, Y.; Brandenburg, A.; Favier, B.; Guervilly, C.; Käpylä, M. J. “Large-scale dynamos in rapidly rotating plane layer convection.” ASTRONOMY AND ASTROPHYSICS, 2018, in press


Käpylä, Maarit; Käpylä, Petri; Olspert, Nigul; Brandenburg, A.; Warnecke, J.; Karak, B. B.; Pelt, J. “Multiple dynamo modes as a mechanism for long-term solar activity variations.” ASTRONOMY AND ASTROPHYSICS, Vol. 589, 56, 05.2016. (Käpylä et al, 2016a)

Käpylä, Maarit; Gent, Frederick; Väisälä, Miikka; Sarson, Graeme. “The supernova-regulated ISM. III. Generation of vorticity, helicity and mean flows.” ASTRONOMY AND ASTROPHYSICS, 2018, in press, doi: 10.1051/0004-6361/201731228


Käpylä, P. J. “Magnetic and rotational quenching of the Λ effect” ASTRONOMY AND ASTROPHYSICS, 2018, submitted


Usoskin, Ilya G.; Arlt, Rainer; Asvestari, Eleanna; Hawkins, Ed; Käpylä, Maarit; Kovaltsov, Gennady A.; Krivova, Natalie; Lockwood, Michael; Mursula, Kalevi; "O'Reilly", Jezebel; Owens, Matthew; Scott, Chris J.; Sokoloff, Dmitry D.; Solanki, Sami K.; Soon, Willie; Vaquero, José M. “The Maunder minimum (1645-1715) was indeed a grand minimum: A reassessment of multiple datasets.” ASTRONOMY AND ASTROPHYSICS, No. 581, 2015, id.A95, 19 pp.


Two of the ReSoLVE Centre of Excellence teams operate in Aalto University, DYNAMO team in the School of Science, Department of Computer Science. During the years 2016-2017 the DYNAMO team has continued its efforts towards its main objective, namely to understand the long-term evolution of the solar dynamo, through direct numerical simulations of turbulent convection both in local but dominantly in global spherical geometries. In addition to the scientific results, significant methodological advances have been accomplished both in data analysis and numerical modeling, that have enabled some of the results presented here, but are also vital for making further progress in the imminent future.