FINAL REPORT

for the NKFI project no. K128384
"Feedback vs. fluctuations in solar activity variations"
2018–2022

1. Introduction

The intensity of solar activity is known to vary cyclically with a period of about 11 years. These cycles are, however, only semi-regular: the amplitude and length of successive solar cycles shows quite large variations. This leads to long-term variations in our planet's cosmic environment, with an increasing impact on diverse facets of our technology-based civilisation. Understanding and forecasting solar actvity cycles is therefore of prime importance.

Experience has shown that the best candidate for a physical precursor of the amplitude of an upcoming cycle is the peak strength of the solar polar magnetic fields (or alternatively, the solar dipole moment), reached typically around the time of solar minimum. Observations show that these polar fields, in turn, are built up during the previous solar cycle by the poleward transport of magnetic flux emerging in the form of active regions (magnetic flux bundle emerging from the subsurface layers and portruding into the solar atmosphere). This transport process is phenomenologically modelled as a combination of diffusion and flow advection in the highly successful surface flux transport (SFT) model; the flows in question are the differential rotation and an effective meridional flow. The polar fields, in turn, are amplified into a strong toroidal field by differential rotation which emerges under the action of buoyancy and convective flows. To model also these subsurface processes full dynamo models are needed, of which the SFT is just one component.

2. Research objectives and methods

The objective of the research project, as set out in the proposal, was to clarify the influence of parameters and other choices in SFT and dynamo models on the general characteristics of the solar magnetic cycle, on nonlinear feedback effects and on the dynamo effectivity of individual active regions, as well as to improve solar cycle forecasting by assimilating individual active regions into the source term of optimalized flux transport and dynamo models.

The approach taken consisted in a combination of axisymmetric SFT models, axisymmetric dynamo models and non-axisymmetric models with observational data analysis and algebraic methods.

3. Results

3.1 Algebraic method

Perhaps the most significant individual achievement of the project has been the development of an algebraic method for the reconstruction and potentially prediction of the solar dipole moment value at sunspot minimum (known to be a good predictor of the amplitude of the next solar cycle). The method consists of summing up the ultimate contributions of individual active regions to the solar axial dipole moment at the end of the cycle. A potential limitation of the approach is its dependence on the underlying surface flux transport (SFT) model details. We demonstrated by both analytical and numerical methods that the factor relating the initial and ultimate dipole moment contributions of an active region displays a Gaussian dependence on latitude with parameters (in particular, half width λ_R called the *dynamo effectyivity range*) that only depend on

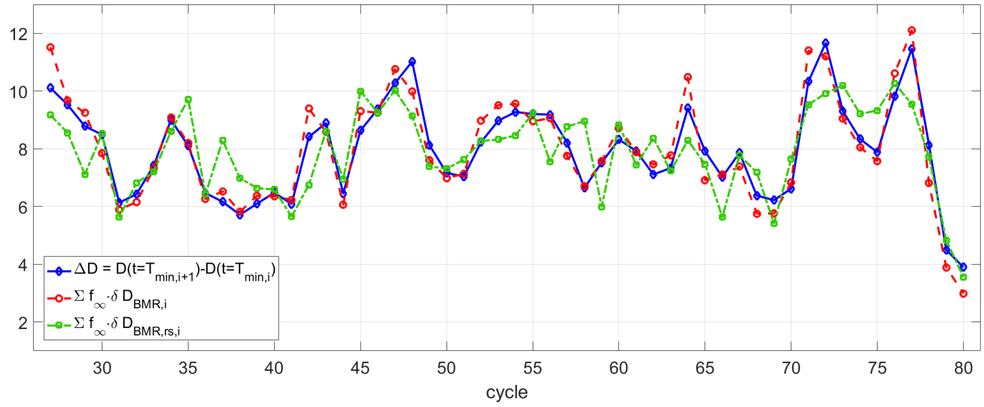

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Figure 1: *Comparison of the change in the solar dipole moment during each solar cycle in a series of about sixty cycles simulated with the 2×2D dynamo model (blue solid) with the prediction of the algebraic method (red dashed).*

details of the SFT model through the parameter η/D_u where η is supergranular diffusivity and D_u is the divergence of the meridional flow on the equator. In a comparison with cycles simulated in the 2×2D dynamo model we further demonstrated that the inaccuracies associated with the algebraic method are minor and the method may be able to reproduce the dipole moment values in a large majority of cycles (Fig. 1)[4].

As the method sums up the ultimate dipole moment contributions of individual active regions in a solar cycle, for this detailed and reliable input data would in principle be needed for thousands of active regions in a solar cycle. To reduce the need for detailed input data, we proposed a new active region descriptor called ARDoR (Active Region Degree of Rogueness). In a detailed statistical analysis of a large number of activity cycles simulated with the 2x2D dynamo model we demonstrate that ranking active regions by decreasing ARDoR, for a good reproduction of the solar dipole moment at the end of the cycle it is sufficient to consider the top N regions on this list explicitly, where N is a relatively low number, while for the other regions the ARDoR value may be set to zero. E.g., with $N = 5$ the fraction of cycles where the dipole moment is reproduced with an error exceeding 30% is only 12%, significantly reduced with respect to the case $N = 0$, i.e. ARDoR set to zero for all active regions, where this fraction is 26%. This indicates that stochastic effects on the intercycle variations of solar activity are dominated by the effect of a low number of large "rogue" active regions, rather than the combined effect of numerous small ARs. The method has a potential for future use in solar cycle prediction.[5]

3.2 Rogue ARs and their effects

Through a systematic analysis using the state-of-the-art 2×2D solar dynamo model, we found that active regions with atypical characteristics, so-called rogue active regions, can significantly modify the strength of the next cycle via their impact on the buildup of the dipole moment as a sunspot cycle unfolds.

Rogue active regions also have the ability to generate hemispheric asymmetry in the subsequent sunspot cycle, since they modify the polar cap flux asymmetry of the ongoing cycle. In a study based on the 2×2D dynamo model we found a strong correlation between the polar cap flux asymmetry of cycle i and the total sunspot number asymmetry of cycle $i + 1$. Good correlation also appears in the case of the time lag of the hemispheres of cycle $i + 1$.[1]

In a study related to the identification and of rogue active region candidates [10] and their assimilation into SFT models we investigated the temporal evolution of the areas of sunspot groups in a large sample composed of various databases spanning over 130 years. While we found a significant asymmetry, described by a skew parameter of fitted curves, between the growing and decaying phases of analysed sunspot groups, we found a weak correlation between the values of skew parameters and the maximum area of sunspot groups and their hemispherical latitude.[7]

3.3 SFT parameter study

The choice of free parameters in SFT is critical for the correct reproduction of the polar magnetic flux. We performed a large-scale systematic study of the parameter space in an SFT model where the source term representing the net effect of tilted flux emergence was chosen to represent a typical, average solar cycle as described by observations. Comparing the results with observational constraints on the spatiotemporal variation of the polar magnetic field, we marked allowed and excluded regions in the 3D parameter space defined by the flow amplitude u_0, the magnetic diffusivity η and the decay time scale τ, for three different assumed meridional flow profiles. Without a significant decay term in the SFT equation (i.e., for $\tau > 10$ yr) the global dipole moment reverses too late in the cycle for all flow profiles and parameters, providing independent supporting evidence for the need of a decay term, even in the case of identical cycles. An allowed domain is found to exist for tau values in the 5–10 yr range for all flow profiles considered. Generally higher values of η (500–800 km^2/s) are preferred though some solutions with lower η are still allowed.[2]

3.4 Role of different nonlinearities

Following our research plan we also studied of the respective importance of nonlinear and stochastic effects in solar cycle variations in dynamo and surface flux transport of various dimensionality. Two candidate mechanisms have recently been considered for the nonlinear modulation of solar cycle amplitudes. Tilt quenching (TQ) is a negative feedback between cycle amplitude and the mean tilt angle of bipolar active regions relative to the azimuthal direction; latitude quenching (LQ) consists in a positive correlation between cycle amplitude and average emergence latitude of active regions. We have explored the relative importance of and the determining factors behind the LQ and TQ effects. The degree of nonlinearity induced by TQ, LQ and their combination is systematically probed in a grid of surface flux transport (SFT) models. The role of TQ and LQ is also explored in the successful 2x2D dynamo model optimized to reproduce the statistical behaviour of real solar cycles. The relative importance of LQ vs TQ is found to correlate with the ratio u_0/η in the SFT model grid, where u_0 is the meridional flow amplitude and eta is diffusivity. An analytical interpretation of this result has also been given, further showing that the main underlying parameter is the dynamo effectivity range which in turn is determined by the ratio of equatorial flow divergence to diffusivity (Fig. 2). The presence of latitude quenching is demonstrated in the 2×2D dynamo, even though this model operates in a parameter range where TQ dominates the nonlinear modulation of cycle amplitudes.[9]

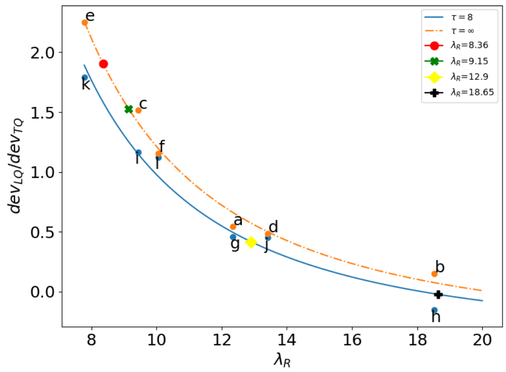

Figure 2: *Relative importance of latitude quenching vs. tilt quenching, as measured by the ration of the deviations from the linear case, plotted against the dynamo effectivity range in SFT simulations (dots) and analytic prediction based on the lagenraic method (curves). Coloured symbols mark the position of some recent dynamo models.*

We also examined the impact of surface inflows into activity belts, introducing into the 2×2D dynamo model an axisymmetric inflow toward the activity belts with a speed depending on the magnetic flux present in the belts. For solar-like inflow speeds, our simulation results indicate a reduction of 10–20% in the strength of the global dipole building up at the end of an activity cycle. A significant stabilizing effect on cycle amplitude is also foundin parallel with an enhancement of cross-hemispheric coupling. Analysis of temporally extended simulations also indicate that the presence of inflows increases the probability of cycle shutdown (grand minimum onset) following an unfavorable sequence of emergence events.[3]

3.5 Extending the polar precursor method and Cycle 25 forecast

The polar precursor uses indicators of the magnetic field concentrated near the poles around sunspot minimum. In collaboration with Indian and Canadian researchers we performed an extensive performance analysis of various such predictors, based on both observational data (WSO magnetograms, MWO polar faculae counts and Pulkovo A(t) index) and outputs (polar cap magnetic flux and global dipole moment) of various existing flux transport dynamo models. We calculated correlation coefficients r of the predictors with the next cycle amplitude as a function of time measured from several solar cycle landmarks: setting $r > 0.8$ as a lower limit for acceptable predictions, we find that observations and models alike indicate that the earliest time when the polar predictor can be safely used is 4 years after polar field reversal. This is typically 2–3 years before solar minimum and about 7 years before the predicted maximum, considerably extending the temporal scope of the polar precursor method. Re-evaluating the predictors another 3 years later, at the time of solar minimum, further increases the correlation level to $r > 0.9$. As an illustration of the result, we determine the predicted amplitude of Cycle 25 from the WSO polar field at the now official minimum date, 2019.9. A forecast based on the value in early 2017, 4 years after polar reversal would have only differed from this final prediction by 2.4%. Our prediction is that Cycle 25 will peak at a monthly smoothed SSN value of 128, most probably in late 2024. [8]

4. Publications

Our results have been published in 1 D1 paper, 5 Q1 papers and 5 Q2 papers, with a cumulative impact factor of 56.2. The papers have received 110 citations.

5. Other achievements

Two team members have successfully defended their PhD thesis during the ogrant period (Melinda Nagy 2019, Mohammed Talafha 2022). Starting from 2021 the PI leads the Doctoral Program in Astronomy and Space Science in the Doctoral School of Physics at ELTE.

An international reseach team led by the PI studying issues related to the topic of the present project has been formed at the International Space Science Institute (ISSI) in Bern, Switzerland in 2019. This highly successful international collabrotaion has held two on-site meetings as well as about a dozen virtual meeting to date.[1]

From 2018 we joined in the efforts of the Astrophysics and particle physics area of the Excellence in Higher Education Program, led by Zsolt Frei. Our subproject entitled Space weather and space climate is led by the PI of the present project.

The support from NKFI has also helped us join an international consortium aimed at postgraduate training in the field of space weather and space climate. The H2020 MSCA ITN EJD project SWATNET, started in 2021, aims at the training of young researchers in the field. Each participating researcher will obtain a joint degree from two participating European universities.

Our research results have been presented at a number of international meetings, including two Space Climate symposia (SC7 2019 Orford, Canada and SC8 2022 Krakow, Poland), a Flux

[1] ISSI project link: `https://www.issibern.ch/teams/solactregars/`

Emergence Workshop (2019 Tokyo) and an invitation-only Dynamo workshop (2022 Bern). The PI was a SOC member at SC8 and chaired various sessions at the other aforementioned meetings.

In June 2021 the PI gave an invited online lecture in the SCOSTEP/PRESTO online seminar series with the title *The Sun making history. The mechanism behind the varying amplitude of the solar cycle.*[2] In September 2022 the PI also gave a talk in the seminar series of Konkoly Observatory.

8 October 2022

Kristóf Petrovay

principal investigator

Publications

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[2] Petrovay K., Talafha M.: Optimization of surface flux transport models for the solar polar magnetic field, Astron. Astrophys. 632, A87 (2019), 10pp

[3] Nagy M., Lemerle A., Charbonneau P.: Impact of nonlinear surface inflows into activity belts on the solar dynamo, J. Space W. Space Clim. 10, 62 (2020), 10pp

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[7] Forgács-Dajka E., Dobos L., Ballai I.: Time-dependent properties of sunspot groups. I. Lifetime and asymmetric evolution, Astron. Astrophys. 653, A50 (2021), 10pp

[8] Kumar P., Nagy M., Lemerle A., Karak B. B., Petrovay K.: The polar precursor method for solar cycle prediction: Comparison of predictors and their temporal range, Astrophys. J. 909, 87 (2021), 12pp

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[10] Quintero Noda C. and 280 coathors incl. K. Petrovay: The European Solar Telescope, Astron. Astrophys. 666, A21 (2022), 36pp

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Talk: http://astro.elte.hu/~kris/fileserv/PRESTO2021_Petrovay.mp4
Seminar series: https://scostep.org/online-seminar-series/