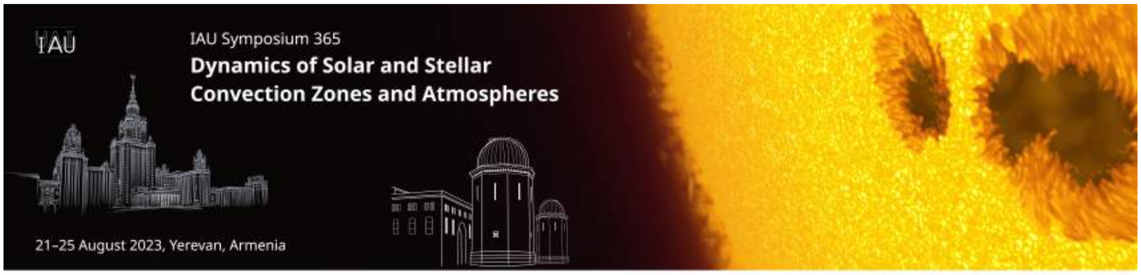
International Astronomical Union

Symposium 365



The Symposium will bring together solar and stellar physicists investigating the dynamics of convection zones and lower atmospheres. It will be dedicated to observational and theoretical aspects of the hydrodynamics and magnetohydrodynamics of the solar and stellar convection zones and lower atmospheres, both global and local, with the inclusion of numerical simulations as a particular branch of theoretical research. Specific subjects to be discussed are as follows:

- Convection (solar - on different scales - and stellar)
- Differential rotation and meridional circulation (both solar and stellar)
- Global dynamo (in the Sun and stars; solar-cycle observed patterns and predictions)
- Helioseismology and asteroseismology (both global and local; probing subsurface structure and dynamics)
- Local processes of magnetic-flux emergence, sunspot and starspot formation (observed patterns of sunspot evolution, small-scale motions, local dynamo)

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International Astronomical Union

Symposium 365

Dynamics of Solar and Stellar Convection Zones and Atmospheres

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Scientific Rationale

The Sun as a complex hydrodynamic and magnetohydrodynamic object has attracted much investigators' attention for a few past decades. Modern observational instrumentation onboard orbital observatories such as, e.g., Solar Dynamics Observatory (SDO) currently provide an invaluable abundance of diverse data. Substantial progress has been achieved in theoretical studies of solar convection, differential rotation, meridional circulation, global solar dynamo and local processes of interaction between plasma flows and magnetic fields in the upper convection zone and photosphere, which are responsible for the local phenomena of solar activity. On the other hand, the progress in the development of observational techniques stimulated investigations aimed at understanding the dynamics of stellar plasma. Hydrodynamic and magnetohydrodynamic studies of the Sun and stars demonstrate a remarkable convergence, approaching a unified description of all these objects. In the numerical simulations of convection and magnetoconvection, which have now greatly increased their coverage in the parameter space, the solar-convection regime plays the role of a "reference point" for the set of models. The theories of differential rotation and of global dynamo have now reached a level that allows considering both these constituents of the global dynamics in the framework of a single model. Helioseismology offers a previously unreachable insight into the dynamics of layers hidden from our eyes. The ideas of helioseismology are now being extended to stellar physics, which results in the successful development of asteroseismology.

A particular point of importance is related to magnetic-flux-emergence processes producing active regions and to the link between global and local magnetohydrodynamic processes. The extensive data from, e.g., SDO can be used for detailed analyses and investigations of the underlying physics on the basis of an adequate magnetohydrodynamic description, which is of paramount importance for the elaboration of techniques of active-phenomena predictions.

An important application field of the investigations of solar global-scale processes is related to the prediction of solar-activity cycles. Such predictions will be the more reliable, the more complete our understanding of the global solar dynamics, and the investigation of stellar dynamics may substantially contribute to the completeness of the general view of the physical processes.

Further progress in tackling this multifaceted complex of phenomena requires the coordination of efforts of investigators engaged in different problems, extensive discussions and exchange of views. It is important to pay particular attention to processes in the dense plasma of the solar and stellar convection zones and photospheres, where the complex of active phenomena originates. At the same time, since the photosphere is strongly dynamically coupled with the overlying layers and flows in the convection zone and photosphere may definitely have counterparts in the lower atmosphere, a strict separation between the photosphere and the layers situated immediately above it would not be warranted. For this reason, although the scope of the planned Symposium is mainly focussed on the dynamics of the convection zones and photospheres, it is also meant to encompass those processes in the lower atmospheres that can be regarded as a direct continuation of the processes in the underlying zones.

The Symposium will be dedicated to observational and theoretical aspects of solar and stellar hydrodynamics and magnetohydrodynamics, both global and local, with the inclusion of numerical studies as a particular branch of theoretical research. With this scope assumed, the meeting will hopefully stimulate the origin of new ideas and development of new techniques in this topical field of research.

1 Solar and Stellar Convection

Spectra of large-scales flows on the Sun
(Invited talk)

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There are significant differences between observational inferences and models of the large-scale flows in the upper layers of the convection zone of the Sun. Consistent comparison of different inferences and models is crucial. Here we present an updated comparison of models and observations of large-scale flows. There remain significant difference between different observations and also between observations and models.

Applying the Kuhfuss Convection Theory to Convective Envelopes

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In 1D stellar evolution models, the process of convection is often described using the mixing length theory (MLT). However, MLT does not account for the non-locality of convection, and an ad hoc implementation of overshooting is needed. The Kuhfuss theory is one of the theories that attempts to derive a more complete picture of turbulent convection. In this theory, non-locality is not implemented artificially, but is included in the theory.

Both versions of the Kuhfuss theory, the 1-equation model as well as the 3-equation model, are implemented in the stellar evolution code GARSTEC and have already been tested on convective cores on the main sequence before [1]. Following these promising results for convection in stellar cores, we tested the Kuhfuss theory for convective envelopes.

We applied the 1-equation model of the Kuhfuss convection theory to a stellar model calibrated to the Sun. Using helioseismic measurements of quantities of the convective envelope and interior structure, we quantified the differences and improvements from the Kuhfuss theory compared to MLT. We furthermore followed the evolution of stars to the red giant branch to study the influence of the Kuhfuss theory on the location of the red giant branch bump, which is known to be sensitive to the description and depth of convective overshooting.

In the future, these cases will also be studied using the full 3-equation Kuhfuss model.

[1] F. Ahlborn et al., *Astronomy & Astrophysics*, 2022, **667**, A97.

Probing the superadiabaticity of the solar convection zone with inertial modes

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Numerical simulations of global-scale solar convection cannot explain the transport of thermal energy and angular momentum in the convection zone, nor the spatial power spectrum of convective velocities. This problem is known as the 'convective conundrum' and is one of the important problems in solar physics. The solution to this problem relies on a knowledge of the superadiabatic temperature gradient. The recently observed global modes of solar oscillation in the inertial frequency range are known to be sensitive to the superadiabaticity and thus constitute a new tool to probe the solar convection [1].

In this work, we study the properties of the solar inertial modes by solving the 2.5D eigenvalue problem for the linearized equations of momentum, mass, and energy conservation [2]. The background solar model includes realistic stratification, differential rotation (from global helioseismology) and a corresponding latitudinal entropy variation. We consider several profiles of superadiabaticity $\delta(r) = \nabla - \nabla_{\rm ad}$ in the convection zone to study how the solar inertial modes depend on $\delta(r)$ (their complex eigenfrequencies and surface eigenfunctions). We show that a number of well-identified inertial modes (such as the equatorial Rossby and high-latitude modes) provide observational constraints on $\delta(r)$.

[1] L. Gizon, R. Cameron, Y. Bekki et al *Astronomy* & *Astrophysics*, 2021, **22**, 652.

[2] Y . Bekki, R. Cameron, L. Gizon *Astronomy* & *Astrophysics*, 2022, **23**, 662.

Helioseismic imaging of supergranules reveals new insight into solar convection

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Supergranules (30,000 - 40,000 km, ∼24 hrs) appear prominently in averaged images of the solar surface but their internal flows are unknown. Constraints on the opaque solar interior, possible only through the use of helioseismology, have the potential to reveal the origin of supergranules. Analyzing measurements of 23,000 supergranules, we find that (1) the depth of the peak upflow occurs at ∼10 Mm, (2) contrary to predictions from numerical simulations, this depth is roughly invariant over the range of horizontal supergranular scales, and (3) within the seismic resolution, we infer a mass-flux imbalance, downflows being ∼40% weaker than upflows. We argue that (3) implies a rain of descending narrow plumes, at scales too small for seismic waves to resolve, in mass balance with a weak large-scale upflow.

Imaging stellar surface features with optical interferometry

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Albeit their masses are very different, Red Supergiants (RSG) and Asymptotic Giant Branch (AGB) stars share a few characteristics. They both lose a non-negligible fraction of their mass in a still only partially understood way. They are both surrounded by molecular shells at a fraction of stellar radius or at a few stellar radii distance above their photosphere. They both have dusty shells starting at the condensation radius or further and extending to very large distances.

One major difference though between the two classes of stars is that the AGB stars undergo a stable pulsation regime for a good fraction of the time spent on the branch that provides the mechanical energy required to levitate mass up to distances where dust can condensate and drag the shell away thanks to radiation pressure [7, 5]. This mechanism does not apply to RSG stars and another source of energy needs to be invoked to explain how huge masses of material can reach the dust condensation radius. Magnetic fields produced by convective cells are a good candidate. After images of the surface of the prototypical RSG Betelgeuse were obtained in the H-band with the IOTA interferometer [3] and found compatible with hydro-radiative simluations of surface convection [2], a 1-Gauss magnetic field was detected by [1]. Convection may also play a role for mass loss through a different mechanism proposed by [6]: it could decrease the effective gravity and ease the escaping of outbound material.

In this contribution, I will present a selected overview of insights on stellar convection that were brought by optical interferometry. Finally, I will present an overview of the STELLIM project [4] that aims to characterize stellar surfaces and circumstellar environments by producing fast and reliable interferometric images.

[1] Aurière, M., Donati, J.-F., Konstantinova-Antova, R., et al. 2010, *A&A*, 516, L2

[2] Chiavassa, A., Haubois, X., Young, J. S., et al. 2010, *A&A*,515, A12

[3] Haubois, X., Perrin, G., Lacour, S., et al. 2009, *A&A*, 508, 923

[4] Haubois, X., Schuhler, N., Bourget, P., et al. 2022, *Proceedings of the SPIE conference*, 12183, 121831T.

[5] Höfner, S. 2008, *A&A*, 491, L1

[6] Josselin, E. & Plez, B. 2007, *A&A*, 469, 671

[7] Woitke, P. 2006,*A&A*, 452, 537

Subadiabatic convection and overshooting in deep convection zones
(Invited talk)

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The overall understanding of solar and stellar convection has been questioned during the last decade or so with helioseismic results suggesting that the convective amplitudes at large horizontal scales in the Sun might be much lower than indicated by current simulations or mixing length estimates; see e.g. [1]. Another manifestation of this "convective conundrum" is that global simulations struggle to reproduce a solar-like differential rotation with a fast equator and slow poles for solar luminosity and rotation rate [2]. A major contributor to this is that giant cell convection, with characteristic length scale comparable to the depth of the convection zone, is excited in simulations but appears to be much weaker in the Sun.

A possible solution to this conundrum is that a large fraction of the solar convection zone is in fact stably stratified, such that giant cell convection is not excited. This has been suggested to occur if convection is driven by cooling at the surface which launches strong downflow plumes piercing the whole convection zone and penetrating deep into the stably stratified layer below [3, 4]. Non-rotating numerical simulations lend support to this highly non-local scenario of convection and lead to sizeable Schwarzschild-stable, yet convecting, layers in deep convection zones [5].

New results from rotating convection simulations are presented that seek to capture the rotationally constrained convection near the base of the solar convection zone. The current results indicate significantly shallower subadiabatic and overshoot layers in the rotationally constrained regime. On the other hand, for Prandtl numbers $\mathrm{Pr} = \nu/\chi < 1$, where ν is the viscosity and χ the thermal diffusion, the subadiabatic but fully mixed layers are again deeper [6]. The implications of these results are discussed in the contexts of the convective conundrum and the design of future numerical simulations.

[1] J. Schumacher, K. R. Sreenivasan, *Reviews of Modern Physics*, 2020, **92**, 041001

[2] P. J. Käpylä, *Astronomy & Astrophysics*, 2023, **669**, A98

[3] H. Spruit, *Mem. Soc. Astron. It.*, 1997, **68**, 397

[4] A. Brandenburg, *Astrophys. J.*, 2016, **832**, 6

[5] P. J. Käpylä, *Astronomy & Astrophysics*, 2019, **631**, A122

[6] P. J. Käpylä, *Astronomy & Astrophysics*, 2021, **655**, A78

3D Radiative Hydrodynamic Modeling of Shallow Convection Zones of Main-Sequence Moderate-Mass Stars

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Investigating the thermodynamic and dynamical structure of stars with 3D modeling based on first physics principles is an important tool for understanding how various stellar properties influence on properties of convection and turbulence. To perform these studies, we use the StellarBox code to model stars of different masses and metallicity and study the coupling between rotation and convection as well as their influence on the thermodynamic structure of the stellar envelopes. We use the MESA stellar evolution code to obtain realistic initial conditions of the internal structure and the stellar absolute abundances to regenerate the corresponding equation-of-state and opacity tables used in our 3D radiative hydrodynamics simulations. The size of the computation domain is adjusted for each model to resolve small and large-scale granulation patterns over the stellar photospheres. In the radial direction, each stellar model includes layers from the upper radiative zone, the whole convection zone, and the lower atmosphere. The models reveal the formation of multi-scale granulation patterns that correlate with the thermodynamical structure of the convection and acoustic waves excitation primarily in the near-surface layers and the interface between the convection and radiative zones, as well as with high-speed turbulent downdrafts. The stellar rotation causes a slight decrease in the stellar radius at high latitudes and the development of differential rotation and meridional flows.

This work is supported by NASA Astrophysical Theory Program.

On the nature of turbulent convection in the sun and stars: laboratory experiments, theory and mean-field simulations

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We discuss the new mean-field theory for turbulent convection [1, 2], the mean-field simulations [3] and the results of experiments conducted at the Laboratory of Multiphase Turbulent Flows of Ben-Gurion University of the Negev. The following results have been obtained:

1) The large-scale structures observed on the Sun, probably, are not turbulence, rather than a low-mode system resulting to dynamic chaos.

2) The large-scale structures formed by the new instability require, for their maintenance, a separation of scales between large-scale structures and energy-containing scale of turbulent eddies. The ratio of these scales should be at least 5-7 as follows from both theoretical predictions and experiments. Instability is also possible at zero Rayleigh number.

3) The derived nonlinear mean-field equations was solved numerically. It was confirmed that the optimal ratio between the horizontal and vertical scale of the structure is close to 2, in contrast to the Rayleigh mode, where this ratio is close to unity.

4) The transition from the Rayleigh to the new mode occurs with a decrease in the Rayleigh number. The new mode at the nonlinear stage is accompanied by the appearance of nonlinear oscillations. An analysis of the numerical results and experiments shows that the appearance of the oscillations is associated with the formation of regions with stably stratified turbulence.

5) The relations between the mixing length theory and the newly developed theory of the formation of structures under conditions of stellar convection are discussed.

The project is supported by Russian Science Foundation, grant 21-72-20067.

[1] T. Elperin, N. Kleeorin, I. Rogachevskii, S. Zilitinkevich, *Physical Review E*, 2002, **66**, 066305.

[2] T. Elperin, N. Kleeorin, I. Rogachevskii, S. Zilitinkevich, *Boundary-Layer Meteorology*, 2006, **119**, 449-472.

[3] G. Orian, A. Asulin, E. Tkachenko, N. Kleeorin, A. Levy, I. Rogachevskii, *Physics of Fluids*, 2022, **34**, 105121.

Analyzing supergranulation and its variations over solar cycles 23 and 24 based on magnetic power spectra

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The supergranulation, as a dynamical cellular flow pattern, is considered to have a close relationship to the magnetic network. Therefore, we expect to find relevant features of supergranulations in magnetic power spectra that could be obtained from high-resolution synoptic maps. The availability of SOHO/MDI and SDO/HMI synoptic maps covering solar cycles 23 and 24 allows us to explore its variations over solar cycles. For the first time, we find that the calibration factor r between SOHO/MDI and SDO/HMI varies with the spatial scale l of the magnetic field, where l is the degree of spherical harmonics. Specifically, the calibration factor can be expressed as $r(l) = \sqrt{-0.021 l^{0.64} + 2} \quad (5 < l \leq 539)$ [1]. With the calibration, the most contemporaneous SOHO/MDI and SDO/HMI magnetograms show consistent power spectra from about 8 Mm to the global scales over about 3 orders of magnitudes. Moreover, magnetic power spectra from SOHO/MDI and SDO/HMI maps show peaks/knees at $l \approx 120$ corresponding to the typical supergranular scale (about 35 Mm) constrained from direct velocimetric measurements [1, 3]. We identify and statistically analyze the spatial scales of peak/knee in power spectra over solar cycles 23 and 24 to study the variations in the size of supergranulations over solar cycles. We observe a partial correlation between the size of supergranulations and the solar cycle. This study of supergranulations via magnetic power spectra provides another way to reveal supergranulation properties and gives the solar-cycle dependence of supergranulations from the magnetic field.

[1] Luo, Y, Jiang, J, Wang, R, *The Sun's Magnetic Power Spectra Over Two Solar Cycles. I. Calibration Between SDO/HMI And SOHO/MDI Magnetograms*, to be submitted to ApJ

[2] Hathaway, D.H., Teil, T., Norton, A. A., & Kitiashvili, I. 2015, ApJ, 811, 105

[3] Williams, P. E., Pesnell, W. D., Beck, J. G., & Lee, S. 2014,SoPh, 289, 11

Modeling Convection and Transport in the Sun

(Invited talk)

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What physical processes primarily drive thermal convection in the interior of the Sun? Currently, two possible mechanisms are under discussion: locally-driven convection, which is fueled by a local (negative) entropy gradient, and cooling-driven convection, which is triggered by surface radiative cooling. The conventional understanding of solar interior physics is based on the mixing-length theory, assuming locally-driven convection as the dominant mechanism. However, in recent years, it has become evident that a significant disparity exists between the theory and observations of solar convection, known as the "convection conundrum". To address this inconsistency, the concept of cooling-driven convection, characterized by stochastically-generated downflow plumes, is being reevaluated. In this talk, we will discuss "recent progress in the study of thermal convection in the solar interior", the "convection conundrum and potential solutions", and the "impact of cooling-driven convection on the dynamo process". We will also share the findings from our recent theoretical and numerical studies on cooling-driven convection.

[1] Masada, Y., & Sano, T. *Arxiv*, 2022, (**arXiv:2206.06566**)

[2] Yokoi, N., Masada, Y., & Takiwaki, T. *MNRAS*, 2022, **516**, 2, pp.2718-2735.

[3] Ishikawa, R.T., Nakata, M., Katsukawa, Y., Masada, Y., & Riethmuller, T. *A&A*, 2022, **658**, A142, 9 pp.

Impact of the Nusselt number on the energy distribution among solar convection scales

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Global models of solar turbulent convection have recently been developed with some success, in order to explain the origin of the observed differential rotation (DR) and surface magnetic flux, at the origin of the 11 years activity cycle. However, the amplitude of giant convective cells needed to reproduce these solar patterns is currently too high when compared to observational constraints coming from helioseismology. This over-estimation of convective velocities especially results in a reversal of the DR profile when the turbulence of models is increased to reproduce the solar small convective scales, which is known as the Convective Conundrum.

In this talk, we will expose our current understanding of this paradox and its possible origin, by presenting a suite of high-performance numerical simulations. In particular, we propose a method to control the amplitude of convective transport, while maintaining the overall transport of solar luminosity and being closer to what is expected from current solar surface observations. We further study scale by scale force and energy balances in our series of model, showing how buoyancy, turbulence, geostrophy and diffusion processes compare to one another as we vary the Nusselt number of the simulation at fixed Reynolds number.

2 Differential Rotation and Meridional Circulation

The Transition from Solar-like to Antisolar Differential Rotation: A Geometric Interpretation

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The solar convection zone rotates differentially, with its equatorial region rotating faster than the polar regions. This type of differential rotation, also reported in many other low-mass stars, is thought to take place when Coriolis effects are stronger than those associated with buoyant driving of the convection. When buoyancy dominates, a state of differential rotation known as "anti-solar" is expected to arise, exhibiting rapidly-rotating poles and a slow equator. The transition between these two states has been shown to occur when the intensity of these two forces is roughly equal or, equivalently, when the convective Rossby number of the system is unity. In this study we propose an alternative view of the transition that relates this transition to the length of the convective structure and the convective-zone depth. On the basis of 3-D rotating convection-zone simulations, we show that the solar/antisolar transition occurs roughly when the columnar convective structures characteristic of rotating convection have a lengthscale roughly equivalent to the shell depth. We find that when the characteristic convective lengthscale exceeds the shell depth, the coherent convective structures necessary to sustain an equatorward Reynolds stress are lost, resulting in an antisolar state. Finally, we present a force-balance analysis that establishes a connection between our geometric interpretation of the transition and the previously identified convective-Rossby-number criteria.

Frequency-dependent Measurements of the Sun's Interior Meridional Circulation

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The Sun's meridional circulation is a crucial component for understanding the Sun's dynamo and its interior dynamics. However, the determination of meridional circulation is affected by from a systematic center-to-limb (CtoL) effect, which introduces systematic errors 5-10 times stronger than the meridional-flow-induced travel-time shifts in deep-flow measurements. Recently, it was found that the CtoL effect has a significant acoustic-frequency dependence, while flow-induced travel-time shifts show little frequency dependence [1] , which gives extra information in removing the CtoL effect. We therefore develop a frequency-dependent approach to disentangle the CtoL effect and the flow-induced signals in the Fourier domain. In this work, we compare the time-distance measurements in different frequencies and analyze their respective systematic effects. The frequency-dependent travel-time shifts are then inverted for the meridional flow profiles using a set of wave-based frequency-dependent sensitivity kernels [2]. We show preliminary results of comparing and reconciling the results of the meridional circulation derived using multiple frequency bands.

[1] R. Chen, J. Zhao, *Astrophys. J.*, 2018, **853**, 161.

[2] T. Hartlep, J. Zhao, *Astrophys. J.*, 2021, **909**, 66.

A theoretical model of the near-surface shear layer of the Sun

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Within the near-surface shear layer (NSSL) of the Sun, the angular velocity decreases rapidly with radius. We provide an explanation of this layer based on the thermal wind balance equation, the basic equation in the theory of the meridional circulation of the Sun. Since convective motions are not affected by solar rotation in the top layer of the convection zone, we argue that the temperature falls at the same rate at all latitudes in this layer. This makes the thermal wind term very large in this layer and the centrifugal term has also to become very large to balance it, giving rise to the NSSL [1]. From the values of differential rotation given by helioseismology at radii less than a radius r_c, we can calculate the temperature variation between the pole and the equator of the Sun by making use of the thermal wind balance equation. Assuming that the same latitudinal temperature variation in the top layer above r_c, we again use the thermal wind balance equation to calculate the angular velocity in the top layer just below the Sun's surface. We find that our theoretical results of the NSSL match the helioseismology data reasonably well for $r_c =\sim 0.96 R_\odot$, giving an estimate of the radius till which the convective motions are affected by the solar rotation [2].

[1] A.R. Choudhuri, *Solar Phys.*, 2021, **296**, 37.

[2] B.K. Jha, A.R. Choudhuri, *MNRAS*, 2021, **506**, 2189.

Rotational shear in the low photosphere of the Sun

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We present a new method to measure the rotational height-gradient in the solar photosphere. The method inspired from differential interferometric techniques is applied to spectroscopic observations in the FeI 630.15 nm obtained at the solar telescope THEMIS equipped with an efficient adaptative optics system.

At the center of the solar disk, we measured systematic retrograde shifts between images of the large-scale photospheric structures obtained at different depths in the line. The shift varies linearly with height. We interprete this as the signature of a steep decrease of the rotational velocity in the low photosphere. We derive an estimate of the angular velocity gradient $\partial \ln \Omega / \partial \ln r$ close to -3.

Superrotation of the pattern of convective structures at various depths in the solar subphotospheric zone

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Doppler measurements of the Sun's rotation rate reveal the superrotation effect of supergranules: the supergranulation pattern rotates faster than the solar plasma [1, 2]. This phenomenon was also found theoretically (e.g., [3, 4, 5]) but remains not completely understood as yet. Our previous work revealed the existence of convective structures substantially larger than supergranules at depths greater than 6 Mm [6].

In our new study, we investigate how the rotation rate of convective structures varies with depth and latitude, using horizontal velocity maps of subsurface flows from the time–distance helioseismology pipeline at the Joint Science Operations Center (JSOC) of the Solar Dynamics Observatory (SDO) [2]. These data refer to a period from March 2010 to September 2020. We determine the rotational velocities by applying a local-correlation-tracking (LCT) technique to the divergence field of the horizontal velocities. To suppress the noise component of the measured field, which increases with depth, we employ low-pass (long-wavelength) spectral filtering using a spherical-harmonic transform [6]. To estimate the errors of velocity determinations, we apply a tracking procedure superposing a given differential rotation onto the actual divergence fields. The systematic shifts determined for different windows are used to correct the LCT measurements. The latitudinal rotation-rate profiles for various depths are averaged annually.

Our results show that the rotation rate of the divergence field varies with depth and latitude. In the upper 6-Mm layer, the rotation rate describes the superrotation effects of supergranulation, but below 6 Mm, the latitudinal variation of the rotation rate substantially diminishes so that the rotation becomes solid-body-like. It can therefore be conjectured that the superrotation effect of large-scale convection in the layers below 6 Mm differs from that of supergranulation.

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Near-surface shear layer of solar rotation: Origin and significance

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Helioseismology discovered sharp downward increase in rotation rate with depth in the upper 30 Mm of the convection zone. Normalized surface shear is nearly constant with latitude. Differential rotation theory can explain the surface shear as a consequence of stress-free surface boundary and a short time-scale of near-surface convection compared to the rotation period. The fact that relative shear does not depend on latitude follows from dimensional arguments and does not depend on particular theoretical method of estimating the shear. The shear value does however depend on the estimation method. Quasi-linear theory of angular momentum transport can reproduce the observed value of -1 for the normalized shear only if the turbulent mixing possesses maximum possible anisotropy of radial type. The maximum anisotropy can result from anisotropic buoyancy forces pointing up or down in radius. The toroidal magnetic field which the surface shear can generate in course of the field diffusive or buoyant escape from the layer is too week for being significant for solar dynamo. However, the surface rotational shear influences the dynamo indirectly by exciting meridional flow for magnetic field transport.

Fine Structure of Differential Rotation and Meridional Flows in the Near-Surface Shear Layer of the Sun from 3D Radiative Hydrodynamics Simulations

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Spectropolarimetric observations of the solar surface and helioseismic inferences allow us to probe the dynamic, structure, and evolution of the Sun from the deep interiors to the photosphere. However, modeling and explaining the observed global dynamical properties of the Sun, such as the differential rotation, meridional circulation, and supergranulation, remains challenging. It has been suggested that a shallow, approximately 30-Mm deep layer of a strong radial gradient of the angular velocity (near-surface shear layer, or NSSL) may play a significant role in the global-Sun dynamics and dynamo. To shed light on the structure and dynamics of the NSSL, we perform 3D radiative hydrodynamics simulations in local cartesian domains located at various latitudes. In these simulations, we investigate the structure and dynamics of large-scale flows in the presence of rotation from the photosphere to 20Mm below. The simulation results reveal the formation of the fine structure of the near-surface shear layer (so-called 'leptocline'), self-formation of meridional flows, and supergranulation. In this presentation, we will discuss the thermodynamical structure of the upper layers of the convection zone and center-to-limb effects and present a comparison with surface observations and helioseismic inferences.

This work is supported by NASA Heliophysics Supporting Research program and NASA DRIVE Center Program (COFFIES project).

Properties of Inertial Oscillations and Rossby Waves in Solar and Stellar Convection Zones

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Recent helioseismology analyses of the long-term observational data from the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) have indicated the presence of large-scale flow patterns with enhanced sectorial harmonic power. These flows may correspond to the giant 'banana'-type convection cells [1], corresponding to convective thermal Rossby waves [2], and oscillatory Rossby waves [3]. While both types of large-scale motions, controlled by the Coriolis force and thus described by similar dispersion relations, have been observed in numerical simulations and studied theoretically, their properties in the realistic conditions of the solar convection zones are not well-understood. We discuss the physical properties of the gravity-inertial oscillations, particularly their subclass of quasi-toroidal (Rossby) waves in the solar convection zone, taking into the realistic stratification and the differential rotation [6, 4, 5].

The theoretical analysis reveals that the oscillatory Rossby waves may exist in the superadiabatic subsurface layers, the stably-stratified tachocline, and the deeper radiative zone. The near-surface Rossby waves can be excited by supergranular convection [7]. The Rossby waves are strongly affected by the latitudinal differential rotation resulting in a Kelvin-Helmholtz-type instability. The instability of Rossby waves in the tachocline can play a significant role in the solar dynamo. In addition, we discuss the general

properties of the gravity-inertial solar/stellar oscillation modes predicted by the theory, including a curious case of a prograde Poincarè-wave type mode.

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Magnetic activity under tidal influences in the 2+2 hierarchical quadruple system V815 Herculis

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Tidal forces in close binaries and multiple systems that contain magnetically active component are supposed to influence the operation of magnetic dynamo. Through synchronization the tidal effect of a close companion helps maintain fast rotation, thus supporting an efficient dynamo. At the same time, it can also suppress the differential rotation of the convection zone, or even force the formation of active longitudes at certain phases fixed to the orbit. V815 Her is a four-star system consisting of two close binaries orbiting each other, one of which contains an active G-type main-sequence star. Therefore, the system offers an excellent opportunity to investigate the influence of gravitational effects on solar-type magnetic activity using different methods.

Short and long term spot evolution on the subgiant component of EI Eri

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Homogeneous photometric time series spanning decades provide a unique opportunity to study the long-term cyclic behaviour of the rapidly rotationg, subgiant main component of the well-known RS CVn binary EI Eridani.

We use our photometric dataset of more than forty years to analyze the long-term behaviour of EI Eri, while flare activity is investigated using space-borne photometric data obtained with the Transiting Exoplanet Survey Satellite (TESS). We use long-term, seasonal period analysis of our photometric time series to study changes in the rotational period. Short-term Fourier-transform is also applied to look for activity cycle-like changes. We also study the phase and frequency distribution of hand-selected flares.

The rotational period of approximately 2 days for EI Eri makes it impossible to achieve time-resolved surface images from a single ground-based observing site. Thus, for this purpose, spectroscopic data from a multi-site observing campaign are needed. We apply our multi-line Doppler imaging code IMAP[1] to reconstruct four consecutive Doppler images. These images are also used to measure surface differential rotation by our cross-correlation technique.

The seasonal period analysis of the light curve reveals a significant, smooth change in the period, which may indicate the evolution of active latitudes. Temperature curves from B-V and V-I show slight differences, indicating that the activity of EI Eri is spot-dominated. The short-term Fourier transform indicates smoothly changing cycles between 4.5-5.5 and 8.9-11.6 years. Doppler imaging enabled us to track the evolution of different surface features, and cross-correlating the consecutive Doppler maps revealed surface shear of $\alpha = 0.036 \pm 0.007$.

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The rotation rates of solar active regions as a constraint for the global dynamo models

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Sunspots and other surface tracers, presumably generated by the global dynamo, exhibit rotation rates different from that of the surface plasma at the same latitude. This discrepancy is often explained as a result of the magnetic connection between the structure at the surface and its magnetic "roots" at some depth in the convection zone. As derived from numerous analyses, the rotation rate of the plasma in the convection zone changes with latitude and depth. That is why a thorough study of the rotation rate

of different magnetic features at the solar surface may shed light on the mechanisms and depth of their formation.

Due to the existence of solid data sets on white-light observations, the majority of studies of the differential rotation of the Sun were based on measurements of the rotation rate of area-weighted or intensity-weighted centers of sunspot groups. However, K. Petrovay [1] argued that faster decay of the following part of a group results in an artificial proper motion of the area-weighted center. Indeed, we found the rotation rates derived from wight-light images are systematically higher as compared to those derived from magnetograms for the same sample of active regions [2].

In contrast to numerous previous works, in this study we derived the rotation rate by tracking the geometrical center of the entire active region using magnetic field maps (see [3] for details). Our main results are: (i) there exists a clear tendency on larger active regions to rotate slower (this result supports previous findings made by many other authors); (ii) the changes in the rotation rate are observed during the active regions emergence phase. Once the emergence is finished, the rotation rate keeps constant within the expected uncertainties [4]. The latter result is not in agreement with earlier works: sunspots were found to either slow down or speed up during their evolution. This behaviour, often interpreted in the framework of the anchoring hypothesis, was suggested to be due to the changes in the anchoring depth of the magnetic loops forming an active region. We suppose that this point of view should be reconsidered. Besides, an exhaustive global dynamo model should explain the observed dependence of the rotation rate from the active region's size, as well as a discrepancy between the rotation rates of magnetic features and local plasma at the surface.

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Analysis of differential rotation of anti-Hale active regions

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In this work, we analyzed the rotation of anti-Hale active regions across the solar disk. For this analysis, we utilized data on line-of-sight (LOS) magnetic field acquired by SDO/HMI. As a source of bipolar active region (ARs) with reverse polarity (anti-Hale regions) data, we used a catalog of bipolar active regions violating the Hale polarity law for 1989-2018. In total, the rotation rates of 44 ARs observed between 2010 and 2018 were measured. In order to compare the obtained results of the rotation rates of the anti-Hale regions with the rest of the ARs, we performed a χ^2 test for both distributions. The test showed that these distributions are statistically indistinguishable. These results give us a reason to suppose that, if the rooting hypothesis is correct, anti-Hale regions and other ARs are formed at the same depths in the convection zone and belong to the common toroidal flux system.

Lenz's Law at Work in the Solar Interior: Interplay of Magnetic Tension and Differential Rotation

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The dynamic activity of Sun-like stars is governed by strongly magnetized spots which are believed to originate in their convection zones via a dynamo mechanism. However, constraining the exact location of stellar magnetic field generation has not been hitherto possible. Based on analyses of magnetohydrodynamic equations and global helioseismic observations of solar rotation rate variations we demonstrate that dynamic Lorentz forces and an equivalent Lenz's law for magnetic induction conspire together to reveal that sunspots-forming magnetic fields originate in the lower-half of the solar convection zone. We establish novel methodologies to constrain dynamo action and electromagnetic forces at play in the interior of stars that are relevant for angular momentum transport, elemental mixing and the evolution of solar-stellar convection zones.

Removal Of Active Region Inflows Reveals a Weak Solar-cycle-scale Trend In Near-surface Meridional Flow

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Using time-distance local helioseismology flow maps within 1 Mm of the solar photosphere [1], we detect inflows toward activity belts that contribute to solar cycle scale variations in near-surface meridional flow. These inflows stretch out as far as 30 degrees away from active region centroids. If active region neighborhoods are excluded, the solar cycle scale variation in background meridional flow diminishes to below 2 m s^{-1}, but still shows systematic variations in the absence of active regions between Sunspot Cycles 24 and 25. We, therefore, propose that the near-surface meridional flow is a three component flow made up of: a constant baseline flow profile that can be derived from quiet Sun regions, variations due to inflows around active regions, and solar cycle scale variation of the order of 2 m s^{-1} [2]. Torsional oscillation, on the other hand, is found to be a global phenomenon i.e. exclusion of active region neighborhoods does not affect its magnitude or phase significantly. This non-variation of torsional oscillation with distance away from active regions and the three-component breakdown of the near-surface meridional flow serve as vital constraints for solar dynamo models and surface flux transport simulations.

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Observational study of Reynolds stresses associated with solar inertial modes

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The origin of the observed solar differential rotation is still under debate. Conventional theories suggests that the angular momentum is dominantly transported by rotationally-constrained banana-cell convection [1]. However, these giant convection cells have not been observed on the Sun.

Here we study the contribution of the solar inertial modes to the angular momentum balance [2, 3]. We analyze 10 years of SDO/HMI data to characterize the properties of solar inertial modes. We use ring-diagram local helioseismology [4] to obtain the horizontal flows near the surface of the Sun and measure the horizontal eigenfunctions of the equatorial Rossby modes and high-latitude inertial modes at low azimuthal orders m.

We find that the equatorial Rossby modes ($m = 4$) and the high-latitude inertial modes ($m = 1, 2$) show a significant positive (negative) Reynolds stress $\langle v_\theta v_\phi \rangle$ in the northern (southern) hemisphere. This suggests that inertial modes play a role in transporting angular momentum equatorward.

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Differential Rotation of the Solar Chromosphere using multidecadal Ca K spectroheliograms

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Differential rotation is a crucial component of the solar dynamo model [1], and it has been extensively studied in the Sun's interior and photosphere using various techniques. However, the understanding of the chromosphere and upper atmosphere's differential rotation is still limited and has yielded inconsistent outcomes in previous investigations. To address the conflicting results in previous studies, we examined a comprehensive set of Ca II K images from the Kodaikanal Solar Observatory (KoSO) spanning over a century (1907-2007). Through image correlation analysis on consecutive day images, we found that the chromosphere rotates faster than the photosphere by 1.52% with less differential rotation compared to the photospheric values obtained from KoSO white light results [2]. To validate our methodology and results, we applied the same technique to other Ca II K data sources (Meudon and PSPT/Rome), and our findings were consistent across all data sources. In addition, we investigated the solar cycle dependence of differential rotation parameters and examined the north-south asymmetry of the solar rotation profile using the Ca II K images from KoSO. Furthermore, recent investigations are also suggesting that the chromosphere rotates faster than the photosphere [3][4][5] which are further validating our findings.

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The Sun's Large-Scale Flows: differential rotation and meridional circulation
(Invited talk)

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The solar mean-field dynamo operates on several large-scale flows including the differential rotation and the meridional circulation. However, the spatial structure of these flows and their time evolution is not fully understood (see, [3]). The torsional oscillations (TOs, [2]), a chevron-like pattern of the residual velocities, which emerges after subtracting the mean solar rotation profile, herald the magnetic activity of the solar cycle. Sunspot magnetic field begins emerging later in time, around the middle of TO sunspot branch although some observations suggest that small-scale magnetic bipoles may already exhibit their orientation in accordance with the Hale polarity rule of next solar cycle [3] giving a rise so-called extended solar cycle [4]. However, the pattern of TO at the beginning of Cycle 25 is much less regular. The polar branch seems to be suppressed, and the sunspot branch starts quite late. Is this an indication of abnormal behavior in Cycle 25 or our understanding of this phenomenon is incomplete or even erroneous? Also, we do not know yet if the flow pattern plays a direct role in the formation of strong magnetic fields of active regions later in the solar cycle or it is simply a response to magnetic fields, which are developing due to some other mechanism.

The spatial structure of the large-scale flows and their time evolution is not fully understood. Thus, for example, measured meridional flows vary widely from one study to another and different studies provide different estimates for the location of the reverse flow. Moreover, debates continue on whether the circulation exhibits double- or single-cell structure.

This talk will review the current observational knowledge of solar differential rotation, meridional circulation, TO patterns, and other relevant large-scale circulations.

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Meridional Circulation in the Solar Convection Zone: Reconciling Helioseismic Measurements

(Invited talk)

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A key component of solar interior dynamics is the meridional circulation (MC), which has been well observed on the surface and near-surface layers. A modeled deep structure of MC also plays a central role in flux transport dynamo models – the most successful ones to date in explaining the global solar magnetism and the solar cycle. Helioseismic observation of the deep structure of MC, however, has been prone to large uncertainties arising from poorly understood systematics and hence conflicting inferences from different groups/researchers. Here, I present a survey of existing results and the progress being made currently, followed by a discussion of connecting the inferences on MC and the well-determined interior differential rotation and relating them to several new theoretical and numerical models of the dynamics of rotation, convection, magnetic fields and MC. I close with discussing the well-measured temporal variations in rotation and MC in near-surface shear layer and what they imply for the dynamics of deeper layers.

Probing the Sun's Near Surface Shear Layer using HMI Spherical Harmonic Coefficients

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Helioseismic studies have illustrated that the most significant changes with the solar cycle occur in the near-surface shear layer (NSSL, outer 5% below the surface) where the density changes by several orders of magnitude and the rotation rate shows a local maxima. It is believed that a nonlinear alpha-omega dynamo could be operating in this layer where the velocity shear converts a part of the poloidal magnetic field into the toroidal field in addition to the global dynamo operating in the tachocline region. In this context, we measure the large-scale flows in these subsurface layers to provide observational constraints on the temporal as well as latitudinal variations of the flow components.

Here we present measured zonal and meridional components of subsurface flows up to a depth of 30 Mm below the solar surface following a non-traditional approach where we use spherical harmonic (SH) coefficients from Helioseismic and Magnetic Imager (HMI) to reconstruct the Dopplergrams and process them through the technique of ring-diagram analysis. The measurements cover the solar disk at several locations on a uniformly spaced grid with $\pm 75^\circ$ in latitudinal direction and $\pm 37.5^\circ$ from central meridian. Preliminary results computed from few years of HMI observations through this novel techniques indicate that the subsurface flows are consistent with those measured from standard HMI and Global Oscillation Network Group ring-diagram pipelines.

Differential rotation of stars from spot transit mapping: dependence on rotation period and effective temperature

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Stellar rotation is crucial for understanding the evolution of stars, since it provides information about age, angular momentum transfer, and magnetic fields. In the case of the Sun, due to its proximity, sunspots can be observed at various latitudes and longitudes, yielding the solar rotation period and its differential rotation. When a star rotates, starspots on its surface produce brightness modulations in its light curve which enables the measurement of its rotational period. Similar to the solar case, the rotational shear can be inferred from spot transit mapping, that is, when a planet occults a spot on the surface of the star during one of its transits. Here we compare for the first time the differential rotation of seven slowly rotating stars ($P_{\text{star}} \geq 9$ days), with spectral types ranging from M to G derived from previously collected spot transit mapping data from observations of the Kepler space telescope. Moreover, we investigate the relationship between rotational shear, $\Delta\Omega$, with both the star's effective temperature (T_{eff}) and average rotation period (P_{star}). Our findings reveal a significant negative correlation between rotational shear and the mean period of stellar rotation, with a Pearson correlation coefficient of -0.94. However, no correlation was observed between differential rotation and the effective temperature of the stars. These results wre compared with the differential rotation of other stars (fast and slow rotators) obtained by other methods.

3 Global Dynamo and Cycles of Activity

Insight into the global dynamo operation from the two recent solar cycles of space-based observations

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Solar dynamo generates the magnetic flux due to continuous conversion of kinetic energy into magnetic energy. Toroidal field lines (generated due to the differential rotation of the Sun) embrace the Sun symmetrically in the Northern and Southern hemispheres and determine the shape and orientation of emerging flux tubes and, therefore, of active regions on the surface (say, regular active regions). However, the process evolves inside a turbulent medium - the convection zone, which implies an unavoidable intervention of turbulence into the flux generation, and, eventually, into the morphological regularity of emerged active regions. Therefore, classification and analysis of active region's morphological properties on time scales of several cycles should allow us to reveal contribution of turbulence into the magnetic flux generation, at least, on scales of typical active regions. Moreover, this approach can help in solving a long-standing question on presence/absence of a cycle-independent dynamo mechanism responsible for formation of irregular active regions.

Such an analysis of active regions was performed using the space-based observations of active region's magnetic fields for the 23rd and 24th solar cycles. We found that: i) summed unsigned magnetic fluxes of regular and irregular active regions correlate very well (the Pearson correlation coefficient R¿0.9) with the both, average (per Hathaway, [1]) cycle profile, and with the total flux from all ARs; ii) during an active phase of a cycle, the number of regular ARs exceeds (approximately twice) the number of irregular, however, their fluxes are quite comparable (of about 45-55% each); iii) during the deepest minimum phase, the number and flux of regular ARs considerably dominate, and only a few simplest irregular ARs appear.

We conclude that the solar dynamo operates as a unique process displaying properties of a non-linear dynamical dissipative system with a cyclic behavior. Active regions of all classes evolve synchronously following the cycle. Data show no prerequisites to imply a cycle-independent dynamo mechanism to generate irregular active regions. However, as the solar dynamo modeling (e.g., [2, 3]) demonstrates, turbulent fluctuations is the key ingredient for the dynamo operation, and as such, it deserves further analysis on broader range of scales.

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Solar-cycle observed patterns as revealed from Kodaikanal multi wavelength archive

(Invited talk)

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Kodaikanal Observatory (KSO) has archived more than 100 years of solar images in three different wavelengths namely white light, Ca K and H-alpha. These have been captured through telescopes with unchanged optics, which ensured uniformity in image quality for several cycles. Four sets of data consists of while light photoheliograms since 1904, the Ca-K line spectroheliograms since 1906, H-alpha spectroheliograms since 1912 to 1998 and K-pr prominences spectroheliograms since 1912 to 1998. The butterfly diagrams as produced from these different datasets reveal new trends and features to understand the irregularites of solar cycle behaviors. I will also present the pseudo magnetograms as produced while combining these multi wavelength resources.

The role of nonlinear toroidal flux loss due to flux emergence in the long-term evolution of the solar cycle

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A striking feature of the solar cycle is that at the beginning, sunspots appear around mid-latitudes, and over time the latitudes of emergences migrate towards the equator. The maximum level of activity (e.g., sunspot number) varies from cycle to cycle. For strong cycles, the activity begins early and at higher latitudes with wider sunspot distributions than for weak cycles. The activity and the width of sunspot belts increase rapidly and begin to decline when the belts are still at high latitudes. Surprisingly, it has been reported [1] that in the late stages of the cycles, the level of activity (sunspot number), as well as the widths and centers of the butterfly wings all have the same statistical properties independent of the levels of activity of the cycles during their rise and maximum phases. We have modeled [2] these features using a Babcock–Leighton type dynamo model and shown that the toroidal flux loss from the solar interior due to magnetic buoyancy is an essential nonlinearity in the solar dynamo which leads to all the cycles having similar amount of toroidal flux during their decline phases. Hence all the cycles decline in the same way.

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Exploring the predictability of the solar cycle from the polar field rise rate: Results from observations and simulations

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The prediction of the strength of an upcoming solar cycle has been a long-standing challenge in the field of solar physics. The inherent stochastic and nonlinear nature of the underlying solar dynamo makes the strength of the solar cycles vary in a wide range. Till now, the polar precursor methods and the dynamo simulations, that use the strength of the polar field at the cycle minima to predict the strength of the following cycle, have gained reasonable consensus by providing convergence in the predictions for solar cycles 24 and 25. Recently our work [1] has shown that just by using the observed correlation of the polar field rise rate with the peak of the polar field at the cycle minimum and the amplitude of the following cycle, a prediction can be made much earlier than the cycle minimum. In a follow-up study, we perform SFT simulations [2] to explore the robustness of this correlation against the variation of meridional flow speed, and against the stochastic fluctuations of BMR tilt properties that give rise to anti-Joy and anti-Hale type anomalous BMRs. The results suggest that the observed correlation is a robust feature of the solar cycle and can be utilized for a reliable prediction of the strength of a cycle at least 2 to 3 years earlier than the minimum.

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Advances in global simulations of solar and stellar dynamos
(Invited talk)

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The complexities of the solar and stellar dynamo problem forbid a complete analytic solution making necessary the use of computational models. Global simulations aim to use first principles to unveil all the physics involved, including the development of large scale flows and magnetic field as a consequence of a highly turbulent rotating flow. The current simulations are not yet successful in reproducing the observations because of different reasons. Specially important is the fact that the separation of scales involved in the problem demands a computational power unforeseen in the near future. Nevertheless, recent advances with high resolution simulations are improving our understanding of the dynamics of stellar interiors. Similarly, new techniques of analysis help us to understand better the simulational results. In this work I'll review the recent progress in global modeling of convective dynamos. I'll also present the most relevant issues regarding the the way of reproducing the solar mean-flows and large scale magnetic fields, and will include the stellar perspective as a constrain and challenge for these models.

Two solar minima in the light of reconstructed historical observations

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We present two data sets of sunspot observations reconstructed from historical records made in the early 1800s and 1900s. Both periods can be associated with two minima of the Gleissberg secular cycle, the first one also corresponding to the period of the Dalton minimum.

The first data set is obtained from a series of hand-written notebooks compiled by French astronomer Honoré Flaugergues in 1782–1830. The notebooks were digitized and analyzed for sunspot observations. A number of these observations deliver sunspot positions. All measurements are contact times, but the specific ways of measuring were changing over time. In the first case, the Sun and spots crossed a vertical and horizontal wire, in the second case, a vertical and two mirror-symmetric oblique wires, and in the third case, a rhombus shaped set of cross-hairs. Additionally, timings of two solar eclipses also provided a few sunspot coordinates. For each case we were able to propose reconstruction methods and now present the obtained heliographic coordinates.

The second data set is obtained from catalogs of Zurich Observatory for the period 1887–1920, which contain positional information on sunspots, prominences, and faculae. These catalogs were given in hand-written tabular form and were not systematically analysed earlier. We implemented a neural-network model for handwritten text recognition and boosted the model with self-training approach for automated consistency checks. Now we present the database of reconstructed coordinates that can supplement the sunspot-group catalogs of the Royal Greenwich Observatory.

Both data sets are available in online repositories `https://github.com/observethesun/Flaugergues.git` and `https://github.com/observethesun/zurich_catalogs`.

Nonlinear and stochastic mechanisms of the solar cycle and their implications for the cycle prediction

(Invited talk)

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Solar activity shows an 11-year (quasi)periodicity with a marked, but limited variability of the cycle amplitudes. There is strong evidence that the dynamo, which is responsible for the solar cycle, is of Babcock-Leighton (BL) type. In the framework of the BL-type dynamo, the magnetic flux emergence in the form of active regions (ARs) is the source of a future cycle. Hence properties of ARs' emergence play an important role in modulating solar cycles and are our central concern when we set up a model for predicting future cycle(s).

ARs emergence has the property that strong cycles tend to have higher mean latitudes and lower tilt angle coefficients [1, 2]. The systematic change in latitude has a similar nonlinear feedback on the solar cycle (latitudinal quenching) as tilt does (tilt quenching). Both forms of quenching lead to the expected final total dipolar moment being enhanced for weak cycles and saturated to a nearly constant value for normal and strong cycles [3]. This explains observed long-term solar cycle variability, e.g., the Gnevyshev-Ohl rule.

Meanwhile, the emergence of rogue ARs characterized as big ARs emerging at low latitudes with large tilts significantly affects the solar cycle evolution [4, 5]. The deep cycle 23 minimum and the weak cycle 24 are suggested to be caused by some rogue ARs with a "wrong" orientation of their magnetic polarities in the north–south direction [1]. The widely used bipolar magnetic regions approximation of real ARs can bring significant error when ARs' contribution to the end-of-cycle polar field is evaluated [7, 8]. ARs' real configurations should be adopted. The stochastic properties of ARs' emergence limit the scope of the solar cycle prediction. For physics-based prediction models of the solar cycle, we suggest that uncertainties in both observed magnetograms assimilated as the initial field and properties of ARs emergence should be taken into account [9].

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Recent Developments in the Babcock–Leighton Solar Dynamo Theory

(Invited talk)

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The magnetic field of the Sun increases and decreases in time with a polarity reversal every 11 years. The most interesting aspect here is that the amplitude of the field does not grow all the time, although there is a considerable variation in time. It is believed that a dynamo mechanism, operating in the convection zone of the sun, is responsible for producing these peculiar features in the magnetic field. Based on the limited observations of the solar magnetic field in the 1960s, Babcock and Leighton proposed a mechanism for the maintenance of the solar cycle. However, due to insufficient observational facts, scientists barely recognised this idea, and rather tried to model the magnetic cycle through MHD convection simulation which eventually gave limited success. In recent years, long-term data produced from different observatories enabled us to validate the original idea of Babcock and Leighton. After giving some historical developments of this idea in this presentation, I shall discuss how well the solar cycle can be explained through the dynamo models developed based on the Babcock-Leighton mechanism. I shall also highlight different nonlinear mechanisms responsible for regulating the solar cycle amplitude, causes for making the cycle irregular.

Solar cycle variability induced by stochastic fluctuations of BMR properties and at different amounts of dynamo supercriticality

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Understanding the irregular variation of the solar cycle is a long-standing problem in solar physics. As this irregular variability of the solar cycle strongly affects the global climates and heliosphere in various ways, understanding the variability of the solar cycle is essential. The poloidal magnetic field is known to determine the magnitude of the next solar cycle [1]. As a result, the variation of the poloidal field can cause a variation in the solar cycle. We have explored the variability of the solar cycle at different levels of dynamo supercriticality. We show that for a given fluctuation, the amount of variability in the solar cycle depends on the operation regime of the dynamo. As long as the dynamo does not reach the highly supercritical chaotic regime, for the same amount of variation in the dynamo number (D), we find that the variation in the magnetic field is more in the near-critical regime than in the supercritical regime [2]. Furthermore, we have explored the effects of the irregular BMR properties (emergence rate, latitude, tilt, and flux) on the poloidal field and the solar cycle. We find that they all produce a considerable amount of variation in the solar cycle, however, the variation due to the tilt scatter is the largest [3].

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How supercritical is the solar dynamo

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The growth of a large-scale magnetic field is possible when the dynamo number (D) is above a critical value (D_c). As the star ages, its rotation rate and thus D decreases [1, 2]. Hence, the natural question is how supercritical our solar dynamo is. To answer this question, we have performed three types of experiments in different regimes of the solar dynamo: (i) Computed the amplitudes of the last four solar cycles using the observed polar field, (ii) estimated the recovery rates of the dynamo from the Maunder minimum, and (iii) computed statistics (numbers and durations) of the grand minima. Comparing these results from the different regimes of the solar dynamo with the observations, we show that the D of the solar dynamo is about two times D_c. Hence, our study suggests that the solar dynamo is not highly supercritical or it is not too far from the critical transition.

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Magnetic helicity generation, its flux in the solar convective zone and the solar activity cycle

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Magnetic helicity being a measure of correlation of the magnetic field and electric current plays an important role in astrophysical magnetohydrodynamics as an inviscid invariant. In the context of solar physics, it is extremely important in several aspects. Firstly, its relaxation time is much longer than the turnover time of the solar turbulence, and therefore, observations of magnetic structures such as active regions may bring essential information on its global distribution and intrinsic evolution. Secondly, the local distribution and dynamics of its observational proxies is linked with the potential for solar flaring activity that may abruptly change the helicity balances. Furthermore, the dynamics of helicity balance may be an indicator of the forthcoming flaring processes.

We also review the observations that shed light on the spatial and temporal behavior of magnetic helicity in the Sun. The magnetic helicity being generated by the solar dynamo mechanism and released to the heliosphere (where it is taken out by the solar wind) provides an important constraint to the dynamo models.

The balance of helicity plays a role of a nonlinear feedback which determines complexity of dynamical behaviour of solar activity. The additional equation governing magnetic helicity evolution creates the dynamical chaos added on the cyclic dynamo action. With the advantage of this dynamical chaos we may obtain important observable properties of the solar cycle with a simple self-consistent model of solar dynamo with helicity. That enables us to understand dynamics and make plausible predictions of the solar cycle on relatively short and long ranges. That can also be used to envisage the dynamics of flaring activity.

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Predicting the Solar Cycle: Progress made and Lessons Learnt
(Invited talk)

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The Sun's magnetic field output varies and is most strikingly manifest in the 11 year sunspot cycle. This magnetism, prodouced by a magnetohydrodynamic dynamo mechanism in the Sun's interior, eventually governs the dynamic activity of the Sun ranging from solar radiation, particle flux, solar wind, open flux and solar magnetic storms. This dynamic solar activity modulates planetary space environments, forces atmospheric dynamics and impacts space- and ground-based technologies. Forecasting the solar cycle is therefore of considerable importance. From the fundamental perspective, it is expected that advances in physical understanding of the solar cycle should lead to more accurate forecasts based on solar dynamo models. However, this has been quite challenging with early efforts diverging widely. In this talk, I shall discuss the progress in solar cycle predictions focussing on solar cycles 24-25[1, 2] and demonstrate that physics-based forecasts made before the solar minimum had more or less converged to indicate a weak-moderate sunspot cycle 25 similar or somewhat stronger than the preceding cycle 24. I shall also critically analyse the physics of solar cycle predictability and argue that the Babcock-Leighton mechanism for solar poloidal field generation – relying on the emergence of tilted bipolar sunspot pairs and the subsequent near-surface evolution of their flux – is the dominant driver of solar cycle variability over decadal to centennial time scales.

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Doubling dynamo-wave frequency on fast rotating solar analogs?

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Observations of the magnetic activity on the fast rotating solar analogs show a decrease of dynamo period with an increase of the rotation rate for the moderate stellar rotation periods in the range of 10 ro 25 days.The origin of the dynamo period decrease is currently under debate. We suggest that for this range of the stellar rotation period, the decrease of the dynamo period can be due to doubling frequency of the dynamo waves (see, Pipin, 2021). The frequency doubling or the second harmonic generation is known from nonlinear optics. It is typical for the waves propagation in the nonlinear media. In the dynamo waves, the second harmonics are generated because of the B^2 effects such as the magnetic effects on the large-scale flow, magnetic helicity conservation and magnetic buoyancy effects. Noteworthy, the second harmonics can be found in the solar activity, as well (Sokoloff et al, 2020). For the solar case they are subdominant. However they can become dominant for the fast rotating stars.

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The Sun's slumber is not so deep when it goes to sleep!

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Long-term sunspot observations and solar activity reconstructions reveal that the Sun occasionally slips into quiescent phases known as solar grand minima, the dynamics during which is not well understood. In our recent work [1], we use a flux transport dynamo model with stochastic fluctuations in the mean-field and Babcock–Leighton poloidal field source terms to simulate solar cycle variability including grand minima-like phases.

Our long-term simulations detect a gradual decay of the polar field at the onset of solar grand minima. Although regular active region emergence stops, compromising the Babcock–Leighton mechanism, weak magnetic activity continues during minima phases sustained by a mean-field α-effect; surprisingly, periodic polar field amplitude modulation persists during these phases. Spectral analysis of the simulated polar flux time series shows that the 11-yr cycle becomes less prominent while high-frequency periods and periods around 22 yr manifest during grand minima episodes. Analysis of long-term solar open flux observations appears to be consistent with this finding.

Through numerical experimentation, we demonstrate that the persistence of periodic amplitude modulation in the polar field and the dominant frequencies during grand minima episodes are governed by the speed of the meridional plasma flow – which appears to act as a clock.

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Resonance and stellar dynamos

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Planetary influence on a stellar convective shell can result in a periodic modulation of stellar dynamo drivers. Similar modulation can arise in stellar binary systems. It is why possibility of a parametric resonance in stellar dynamos becomes important.

Using the Parker low-mode dynamo model we investigate the properties of nonlinear parametric resonance. This model is a system of four ordinary differential equations and, in the first approximation, describes the processes of generation and oscillation of large-scale magnetic fields in stellar systems. In the absence of nonlinear suppression effects, the problem, by analogy with a system of harmonic oscillations, allows an asymptotic selection of multiple resonant frequencies. However, despite the fact that at first glance at these frequencies it is reasonable to expect an increase in the amplitude in the nonlinear case, we demonstrate that in the presence of nonlinear terms, the behavior of the system is just the opposite. In particular, resonant suppression of generation can be observed at resonant frequencies, while amplification occurs in the immediate vicinity of these frequencies. The paper discusses the reasons for this behavior, as well as the possibility of the influence of parametric resonance on the establishment of planetary dynamo cycles and on the power of flares in binary star systems.

Correlation of shifted Wolf numbers with their derivatives, dynamo and predictions

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We correlate the mean annual Wolf numbers W and their time derivatives W' for different time shifts of fragments of series W and W' relative to each other. We use the annual mean Wolf numbers W from 1700 to 2022 in version v2. Time derivatives $dW/dt = W'$ were obtained at the same middle of the year as W, by taking the average of the derivative on the left and right. This smoothes some original errors those stem from the observational and contractual definition of W.

The most significant (0.81-0.87) correlation coefficients are obtained with shifts of 2 or 3 years for fragments covering the last 11-44 years. For longer fragments, the coefficients remain significant (at levels of approximately 0.8 or just slightly less, the smallest is 0.76 for the longest fragment) at the same shifts. Therefore, the major phase shift between W and W' is approximately one-quarter of the solar cycle, which physically corresponds to the predominant connection of spots with magnetic energy in accordance with the simplest dynamo model. There is also a significant shift by 8-9 years, which corresponds to anticorrelation coefficients at levels of -0.70 to -0.85 associated as well with the magnetic energy variability. Summing the obtained 2-3 years (one-quarter) and 8-9 years (remaining three-quarter) shifts we are getting the observed variety of dynamo magnetic energy (always positive) periodicities from 10 to 12 years.

Thus, the prognostic period could primarily be for 2-3 years ahead and secondary for 8-9 years. So, we are expecting a relatively long growing phase with sufficiently high maximum and extended duration of the current 25th cycle. More precise predictions need in better than one year time-resolution that we are currently working on.

Manifestations of the turbulent component of the global solar dynamo in the minima of solar activity

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Lines of force of the toroidal magnetic field pass through the turbulent convection zone, and then form active regions (ARs) on the solar surface. In the convection zone, the lines of force can be distorted and deformed and form irregular structures on the surface of the Sun. During minimum of solar activity, the toroidal magnetic field of the old cycle ceases, and the new one is still weak. During this period, it is possible to estimate the influence of turbulence on the formation of ARs.

We analyzed the active regions of two solar minima (between 23rd-24th and 24th-25th solar cycles). All ARs with the total unsigned flux above 10^{21} Mx and located no further than 60° from the disk center were considered. Bipolar and multipolar ARs were divided into regular (consistent with dynamo theory) and irregular, the formation of which was influenced by the turbulence of the convection zone. Unipolar sunspots were considered separately.

It was found that during periods of solar minima, regular ARs significantly prevail in both, the number and the total flux. In terms of flux, irregular ARs make up about a third of the total flux (0.3 and 0.2 in the first and second periods, respectively) and are mainly represented by simplest irregular structures, namely, by bipolar structures of deformed orientation, while very complex multipolar ARs are extremely rare. It is concluded that during solar minima, generation of active regions (with the magnetic flux in the maximum development of above 10^{21} Mx) occurs due to the global dynamo, while turbulence in the convection zone affects only the deformation of magnetic bundles without significant generation of magnetic flux.

Chromosphere activity: relations with Solar cycles (SC)

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The low latitude solar activity modulates geomagnetism, producing coronal mass ejections (CMEs), solar flares, solar energetic particles (SEPs), and associated disturbances. The prediction of the height of the forthcoming SC 25 expressed by the SN has been the subject of many studies [1]. The popular dynamo model is the Babcock-Leighton (B-L) model describing the transformation of a general poloidal field of a rotating Sun into a toroidal field through the differential rotation. It rather well reproduces the behavior of sunspots of different signs for each hemisphere during an SC. The regeneration of the new poloidal field (after 11 years) is another aspect of the model that is left not well understood. The reversal of the dominant polarities in polar regions has been observed to occur during the years of SN maximum since 1970. However, several puzzling features like M-regions, active longitudes, the occurrence of long-living big single sunspots, the cyclonic and widely distorted behavior of extended interacting active regions, the occurrence of coronal holes (CHs) not predictable with the Babcock-Leighton dynamo model, the polar regions cycles and/or field reversals, and finally the large dispersion of heights of SN cycles are the subject of hot debates. More important for practical reasons is the prediction of the solar cycles in advance. Without going too far into the details of the supposed relationships between the polar-region activity cycle and the SN cycle, we point out that a possible relationship concerns the high-latitude polar activity, definitely above the latitude of 70 degrees. At lower latitudes where the polar crown filaments are still observed, it seems well established that the migration of residual sunspot-region magnetic fields are indeed observed. We looked at the activity of polar regions using several proxies: first, the density of polar faculae from visually evaluated HMI of SDO mission WL filtergrams showing a definite recrudescence before SC 25 although the Stanford WSO large-scale magnetograms evaluating polar regions magnetic net fluxes show no definite evidence of SC25 to be significantly different from being of low amplitude as predicted by the NASA Solar Cycle 25 Prediction Panel. second, numbers of cool ejection events from a 15-year survey of the Pic du Midi CLIMSO Halpha observations; third, averaged extensions of the 304 A shell in polar regions related to the polar CH macro-spicule activity. Time variations of these two off-disk parameters qualitatively point to the possibility that SC25 could reach higher levels, of the order of 2 times the height of SC24, in contrast with the moderate height predicted by the SC25 Prediction Panel of NASA and NOAA. The reason for this discrepancy is not clear, although we note that indeed off-disk observations are more convincing instead of the classical on-disk observations. Another interesting parameter seemingly related to this topic is the definite observation of the chromospheric prolateness (ovalisation) in the years of the minimum of 2018–2020 that was discovered in the years 1998–2000 (before SC 23) and that was not well measured in 2010–2011 (before SC24) [2], [3]. In rather cool spectral lines like Halpha or the H and K lines of CaII, the smoothed upper edge of the solar chromosphere is prolated in the North-South direction at the epoch around the minimum solar activity. We again noticed the effect in 2020–2021 full disk images of the Pic du Midi CLIMSO Halpha observations and other images. Accordingly, we plan to come back to the topic of the chromospheric prolateness near the time of SN minima.

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† Deceased.

Modelling the long-term variability of sun-like stars: From subcritical to supercritical dynamos

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The Sun and sun-like stars exhibit irregular cyclic variations in their magnetic activity over long time scales. To understand this irregularity, we employed the flux transport dynamo models to investigate the behavior of one solar mass star at various rotation rates. To achieve this, we have utilized a mean-field hydrodynamic model to specify differential rotation and meridional circulation, and we have incorporated stochastic fluctuations in the Babcock-Leighton source of the poloidal field to capture inherent fluctuations in the stellar convection. Our simulations successfully demonstrated consistency with the observational data, revealing that rapidly rotating stars exhibit highly irregular cycles with strong magnetic fields and no Maunder-like grand minima. On the other hand, slow rotators produce smoother cycles with weaker magnetic fields, long-term amplitude modulation, and occasional extended grand minima. We observed that the frequency and duration of grand minima increase with the decreasing rotation rate. These results can be understood as the tendency of a less supercritical dynamo in slow rotators to be more prone to produce extended grand minima. We further explore the possible existence of the dynamo in the subcritical regime in a Babcock-Leighton-type framework and in the presence of a small-scale dynamo.

A Babcock–Leighton-type Solar Dynamo Operating in the Bulk of the Convection Zone and its Application to Solar-type Stars

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The toroidal magnetic field is assumed to be generated in the tachocline in most Babcock–Leighton (BL)-type solar dynamo models. However, magnetic activity of fully convective stars and MHD simulations of global stellar convection have recently raised serious doubts regarding the importance of the tachocline in the generation of the toroidal field. We developed a BL-type dynamo model [1], in which the dynamo operates mainly within the bulk of the convection zone. The model leads to a simple dipolar configuration of the poloidal field that has the dominant latitudinal component, which is wound up by the latitudinal shear within the bulk of the convection zone to generate the toroidal flux. As a result, the tachocline plays a negligible role in the model, and basic features of the solar cycle are successfully reproduced. The role of meridional flow is weakened compared with flux transport dynamo (FTD) and the cycle period is not sensitive to the speed of meridional flow. Our model opens the possibility for a paradigm shift in understanding the solar cycle to transition from the classical FTD. We further extend this model to solar-type stars and model the effects of starspots on stellar magnetic cycles. By considering the higher latitudes and larger tilt angles of starspots for faster rotators, our simulations reproduce observations that faster-rotating stars have shorter magnetic cycle and stronger activity [2].

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North-South asymmetry of the magnetic fluxes of active regions of different magneto-morphological types in cycles 23 and 24

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Statistical study of 3047 active regions (ARs) from May 1996 to December 2021 was performed using an updated version of the catalog of the magneto-morphological classes (MMC) of ARs CrAO (https://sun.crao.ru/databases/catalog-mmc-ars). According to the magneto-morphological classification of ARs [1, 2], all ARs, except for unipolar spots, were sorted out between two categories: regular (bipolar sunspot groups obeying the Hale's polarity law, the Joy's law and the rule of the leading sunspot dominance) and irregular ARs (all the rest).

Our analysis of the hemispherical asymmenty of cyclic variations of the unsigned magnetic fluxes from regular and irregular ARs showed the following. Both types of ARs demonstrate strong N-S asymmetry and the evidence of a two-humped structure of the cycle known since [3]. Indications of a multi-peak structure can also be noticed.

The regular ARs, in the N-hemisphere, in the solar cycle (SC) 23, form a plateau (without a gap between the two main maxima of the cycle). In the SC 24, a pronounced peak in the first main maximum and several significantly smaller peaks at different phases of the cycle were found for this type of ARs. The regular ARs, in the S-hemisphere, show two well-defined peaks in both main maxima (SC 23). In the SC 24, the pronounced peak is observed only in the second maximum.

Irregular groups time profiles have a different shape. In the N-hemisphere, in the SC 23, the plateau is also observed. However, in the SC 24, we found a classical two-humped structure. In the S-hemisphere, the dominant peaks in the second maximum were found in both cycles.

In general, irregular ARs flux is stronger in the S-hemisphere. Such a dominance might be associated with an influence of the turbulent dynamo in a hemisphere with a weaker toroidal (produced by the global dynamo) field. Weakening of the field in one of the hemispheres might be due to the interaction of the dipole and quadrupole components of the global magnetic field [4].

Author is grateful to V.I.Abramenko for her valuable comments, to R.A.Suleymanova for the data on the SC 23.

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4 Helioseismology and Asteroseismology

The effect of Coulomb interactions on acoustic oscillations in the outer layers of low-mass stars

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All cool stars with outer convective zones have the potential to exhibit stochastically excited stellar oscillations. In our study, we focus on exploring the outer layers of stars less massive than the Sun. We have computed a range of stellar models from 0.4 to 0.9 solar masses to investigate the effects of two physical processes in the envelopes of these stars: partial ionization of chemical elements and electrostatic interactions between particles in the outer layers. In addition to partial ionization, we show that Coulomb effects also affect the acoustic oscillation spectrum. As a star's mass decreases, electrostatic interactions between particles become increasingly important, confirming a well-established result. Our investigation also revealed that their influence on stellar oscillations intensifies with decreasing mass, and for stars with masses below 0.6 solar masses, Coulomb effects prevail over partial ionization processes, leading to significant scattering in the acoustic modes. These electrostatic interactions interactions produce a strong oscillatory behavior in the sound-speed gradient profile, which has diagnostic potential for the future [1].

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Recent Progress in Time-distance Helioseismology: Meridional Circulation, Far-side Imaging, and Sunquakes

(Invited talk)

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Time-distance helioseismology uses solar surface Doppler observations to measure or reconstruct areas that are not directly observable, such as solar interior, far side, or sunquake sources. In this talk, I review our recent results using time-distance helioseismology on meridional circulation measurements, far-side imaging, and sunquakes.

The Sun's meridional circulation is crucial to understanding its dynamo and interior dynamics. However, the determination of meridional circulation is notoriously difficult, and previous studies have provided inconsistent results. I will present our recent results on comparing measurements by different methods using both HMI and GONG data, which also include acoustic-frequency-dependent measurements.

Solar far-side magnetic field is essential for space weather forecasting and solar wind modeling, but its direct observation is not currently available. Helioseismic far-side imaging can map far-side active regions in near-real-time, but it cannot provide magnetic fluxes. I will present a new effort using machine-learning techniques to calibrate far-side helioseismic images into far-side unsigned-magnetic-flux maps.

Sunquakes are helioseismic power enhancements initiated by solar flares. It is curious why some flares cause sunquakes while others do not. Recently, we developed a method to reconstruct the photosphere velocity fields of 60 strong flares in Solar Cycle 24 and found 24 of these flares led to 41 sunquake events. Using these sunquake samples, we examined a hypothesis that relates the occurrence of sunquakes to the photosphere background oscillations.

Inertial modes as probes of solar convection

(Invited talk)

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We discuss observations and models of the Sun's quasi-toroidal modes of oscillation. These modes have periods of order of the solar rotation period and are collectively referred to as 'inertial modes'. They include Rossby modes and shear modes associated with the Sun's latitudinal differential rotation [1, 2, 2]. The observed modes all propagate in the retrograde direction in the Carrington frame and are associated with critical latitudes [3]. They are identified by comparison with the viscous modes of a differentially rotating model of the solar convection zone in two [5] or three [4] dimensions. While the linearly stable modes are likely excited by turbulent convection [5], some high-latitude modes are linearly unstable. In particular, the $m = 1$ velocity pattern observed at high latitudes [8] is not due to giant cell convection but is the manifestation of a baroclinically unstable global mode of oscillation. Very interestingly, the inertial mode eigenfunctions are sensitive to the superadiabatic temperature gradient and turbulent viscosity in the convection zone [9] – quantities that are poorly constrained by p-mode helioseismology.

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Helioseismic Observations of Solar Torsional Oscillations and Evidence for Dynamo Waves

(Invited talk)

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We use Helioseismic data from NASA's missions SOHO and SDO and ground-based network GONG, obtained in 1995-2023 for more than two solar cycles, provide a unique opportunity to investigate variations of the solar interior associated with the solar dynamo and link these variations to the current dynamo models. Critical observational information about the dynamo processes is provided by the cyclic variations of the solar differential rotation, called torsional oscillations. The torsional oscillations closely linked to the evolution of the global magnetic field of the Sun can be measured by helioseismology through the whole convection zone. Our initial analysis of zonal acceleration determined from the SDO JSOC differential rotation data [1] revealed patterns resembling dynamo waves predicted by the dynamo theory [2].

We present a new and comprehensive analysis of the MDI/SOHO, HMI/SDO, and GONG data obtained by an independent measurement of the rotational frequency splitting of solar oscillation modes [3] used to infer the solar differential rotation inside the Sun using the same inversion technique as in [1]. That analysis is performed for observational time series of different durations and intervals, using the same technique for all three data sets, and covering 28 years of nearly uninterrupted helioseismic observations. The results reveal an extended solar-cycle structure of the torsional oscillations and provide strong evidence for hydromagnetic dynamo waves in the solar convection zone. We discuss the relationship of the torsional oscillations to the dynamo processes that govern the solar cycles.

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Temporal variations of solar inertial mode parameters

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The equatorial Rossby modes of the Sun were first observed using helioseismic observations from SDO/HMI [1] and confirmed using GONG data [3]. Additional quasi-toroidal modes, all with periods comparable to the solar rotation period were later reported by Gizon et al. (2021)[2]. Here we use nearly 20 years of helioseismic measurements from GONG and HMI to study the properties of equatorial Rossby modes (m = 3 to 10) and high-latitude modes (m = 1 and 2). The frequencies and amplitudes of some modes are found to vary with time. We study the correlation between mode parameters and the sunspot cycle, and find that some modes are affected by the solar cycle, while others are not. Additionally, we compare the amplitudes of the modes with a model of stochastic excitation by turbulent convection [5] to interpret their dependence with m.

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The influence of small-scale magnetic fields in the photosphere on surface effects for KIC 11295426 and KIC 10963065

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Asteroseismology is a valuable tool for exploring the stellar inner structure and constraining the stellar parameters. For stars with a convection envelope such as solar-like stars, the surface physics is very complex, which leads to the systematic offset between the theoretical frequencies and observed ones.

The small-scale magnetic fields are very important in the stellar atmosphere. They are ubiquitous, and couple with the acoustic waves, affecting the propagation of the acoustic waves.

Considering the effect of the magnetic fields in the stellar photosphere on the oscillation frequencies, we calculate the asteroseismology for solar-like star KIC 11295426 and KIC 10963065. We obtain the stellar fundamental parameters, especially the strength of small-scale magnetic fields in the stellar photosphere. We find that the magnetic fields in the stellar photosphere could not change the stellar inner structure, but they may obviously improve the agreement between the observations and the theoretical models for KIC 11295426 and KIC 10963065. Using asteroseismology, we get the strength of magnetic fields in the photosphere for KIC 11295426 and KIC 10963065 which are consistent with the stellar activity observed by Ca II H&K line and the activity-related frequencies shifts.

Solar/Stellar Rossby Waves and Tidal Waves in Their Surface Layers

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We re-examine physical properties of Rossby waves as well as other tidal waves in contexts of large-scale atmospheric dynamics for solar/stellar oscillations. By the inclusion of magnetic field with various configurations, we further identify basic features of Alfven-Rossby waves and classify magnetized tidal waves in a systematic manner. In particular, we highlight the equatorially trapped magnetohydrodynamic (MHD) tidal waves in the so-called beta-plane approximation with distinct dispersion relations. In reference to solar observations, we offer new perspectives of solar/stellar diagnostics.

Anisotropic seismic ripples from deep locations of seismic sources

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The helioseismic holography technique is used to analyze acoustic waves triggered by flares to probe the "loudness" of their sources. Triggered by the discovery in 2020 of the 10 mHz acoustic energy released from a source located at about 1,150 kilometers beneath the solar surface (flare M9.3, 30/07/2011 [1]) we have expanded the study of the properties of the seismic ripples from this flare and others.

Our analysis focuses on defining the most important physical parameters of the seismic sources (spatial and temporal structure, power, frequency "loudness") necessary to characterize ripples on the solar surface.

Seismic source performances were evaluated based on analyses of signal penetration, ripple frequency, structure. In this work, we focused on both the temporal and spatial complexity of the source. The novelty of the work is related to the simulation of multiple seismic sources triggering acoustic waves simultaneously or with various time-lags, *from a sub-vantage perspective (different depths).* The simulations explain the extended morphology of seismic structures as observed in solar data at different depths [1]. A study case of simulated anisotropic seismic ripples (directionality and polar maps of acoustic power distributions) will be presented and its correspondence to observational data will be analysed.

In conclusion, the physical properties of ripples are strongly correlated with their source location and temporal and spatial structure. This work is relevant for understanding the emergence of acoustic transients from the solar interior and may help in understanding the multitude of seismic solar flare events.

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Convection, rotation, and magnetic activity of solar-like stars from asteroseismology

(Invited talk)

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During the last decade, our understanding of stellar physics and evolution has undergone a tremendous revolution thanks to asteroseismology. Space missions such as CoRoT, Kepler, K2, and TESS have already been observing millions of stars providing high-precision photometric data. With these data, it is possible to study the convection of stars through the convective background in the power spectrum density of the light curves. The properties of the convective background or granulation has been shown to be correlated to the surface gravity of the stars. In addition, when we have enough resolution (so long enough observations) and a high signal-to-noise ratio, the individual modes can be characterized in particular to study the internal rotational splittings and magnetic field of stars. Finally, the surface magnetic activity also impacts the amplitude and hence detection of the acoustic modes. This effect can be seen as a double-edged sword. Indeed, modes can be studied to look for magnetic activity changes. However, this also means that for stars too magnetically active, modes can be suppressed, preventing us from detecting them.

In this talk, I will present some highlights on what asteroseismology has allowed us to better understand the convection, rotation, and magnetism of solar-like stars while opening doors to many more questions. With the coming launch of the ESA PLATO mission in late 2026, even more breakthroughs should be made, helping us in our comprehension of stellar interior dynamics evolution.

Acoustic tomography of the atmosphere of roAp star Alpha Circini

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We present the results of the high-speed high precision HARPS spectroscopy and the multi-frequency acoustic tomography of the atmosphere of the rapidly oscillating chemically peculiar (roAp) star Alpha Circini.

The bisector radial velocity analysis of spectral lines of rare-earth elements which are stratified in the thin, patchy clouds at superficial atmospheric layers was done in order to get the acoustic amplitude and phase cross-sections for a full scale height of the atmosphere. That also helps to take advantage of the atmospheric height effect (the amplification of displacement with the height) and the spatial filter effect (reduction of surface cancellation for non-radial modes in the chemical spots) for detection of multiperiodic pulsation modes. The use of spectral lines of chemical elements overabundant in contrasting chemical spots makes it possible to measure Doppler shifts from local areas on the surface of roAp stars, i.e. apply local asteroseismology [1].

The p-mode spectrum obtained from radial velocities and from TESS photometry both revealed the 60.4 microHz general spacing between the consecutive overtones.

For the high-amplitude modes, we discovered the existence of acoustic nodes at upper levels of the atmosphere, Acoustic cross sections show the zero pulsation amplitudes at the nodes, a 180-degree phase jump, and the gradual increase of amplitude away from the nodes. The bisectors of Na lines that are formed in the atmospheric height well below the clouds of rare-earth elements don't show such nodes. We compared the spectroscopically detected p-mode spectrum with the spectrum obtained from the analysis of TESS photometry and draw conclusions about the advantages of spectroscopic detection of modes in roAp stars compared to space photometry.

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Identifying Submerged Acoustic Sources

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Some solar flares drive tremors, called "sunquakes," in the solar surface, which propagate outward from the flare site over the hour succeeding its impulsive phase. These tremors are a manifestation of acoustic transients that have traveled deep into the solar interior from the location of the flare and have thenceforth been refracted back upward to the Sun's surface tens of thousands of kilometers outside of the flaring region. Here we present a study of two sunquakes; one with evidence of a submerged acoustic source and one with evidence of a superficial source. We apply a novel depth diagnostic dependent on the temporal defocusing of the seismic signature. We then compare this method with the spacial defocusing on which computational helioseismic holography [1] facilitates. Using both new and tried techniques, we verify the existence of a submerged source of 10mHz with the associated flare SOL20140207T10:28 and further apply this technique to other flares with associated doppler signatures.

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A 2D model for the excitation of the linearly stable solar inertial modes by turbulent convection

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Solar inertial modes offer new possibilities to probe the properties of the solar convective zone down to the tachocline, provided we understand the physics of these modes [1, 2]. While linear analysis enables us to compute the complex eigenfrequencies and the eigenfunctions of these modes [3, 4], it provides no information about the mode amplitudes nor about the excitation mechanism. Here we present a 2D model for the stochastic excitation of the linearly stable viscous inertial modes by turbulent vorticity [5]. In this simplified model, differential rotation is modelled by a parabolic shear flow in the equatorial β plane. We find that the mode amplitudes in our model are consistent with the observations ($\sim$ 1 m/s). For large enough azimuthal orders m, the modes may overlap and interfere in frequency space, thus complicating the interpretation of the observed power spectra.

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Solar Rossby waves and their dependence on the solar cycle

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The existence of global-scale vorticity waves in the Sun, known as equatorial Rossby waves, has been established by multiple studies using different helioseismic techniques. In contrast to acoustic waves, Rossby waves lack sensitivity to small-scale and short-time features (such as active regions). They may, however, be affected by properties of the deep convection zone, such as large-scale magnetic fields. In this study, we use 12 years of subsurface velocity fields, obtained from the SDO time-distance pipeline, to add to the repertoire of helioseismic methods enabling detailed observations of solar Rossby waves. The time period covers multiple phases of solar cycle 24, thus allowing an investigation into the cycle dependence of the Rossby waves. Combining the time-distance results with results obtained from the ring-diagram method, we present proof of a time dependence in the average Rossby wave power, which is well correlated with the solar activity. Although the mechanism that amplifies (or dampens) Rossby wave power during the progression of the solar cycle is unclear, this observation may yield new insight into details of the solar cycle and its interaction with large scale flows.

5 Local Processes of Magnetic-Flux Emergence, Sunspot and Starspot Formation

Signature of local (turbulent) dynamo on middle and small scales
(Invited talk)

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The dual nature of the solar dynamo is impressive. On largest scales of the entire star, we observe a regular solar cyclicity and a regular shape of the solar corona during minima. On the smallest observable scales, the magnetic carpet of chaotically distributed opposite polarity elements dominates. On the intermrdiate scales, a phenomenon of sunspot groups – active regions – represent the solar magnetism. Obviously, the global dynamo is uncapable to explain the observed variety of magnetic features. It is thought that, along with the global dynamo, a sort of cycle-independent process of flux generation is at work on the Sun. It is referred to as local, or turbulent, or small-scale dynamo. Unavoidable (in turbulent medium) fluctuations in time and space are the underlying prerequisite for local dynamo.

The role of the local dynamo in the flux production depends on the scale, first of all, on the scale of turbulence. Deeply inside the convection zone, where the typical scale of convection is large (of order of hundred km), turbulence rather distorts the regular toroidal flux bundles when forming active regions, and local dynamo does not generate much flux on scales of typical active regions [1].

As the scale of turbulence decreases when we proceed from the deepest part of the convection zone to the surface, the magnetic Reynolds number increases, and in the near-surface layers plasma becomes highly intermittent, which means that, per Zeldovich [2], the local fast dynamo gets in action. Observations show that in quiet sun areas, more than 35% of the total magnetic energy can be attributed to the local turbulent dynamo action [3], and local dynamo may generate magnetic fields over the entire solar surface [4].

In spite of the rather modest role of the local dynamo in the general flux production, the source of the local dynamo – the velocity and field fluctuations – are the key ingredients of the global solar dynamo per se because the non-zero net product of these entities is the necessary condition for the global dynamo operation.

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Small-scale dynamos in cool stars: magnetic field structure and changes in lower photospheres of F3V to M0V stars

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Some of the quiet solar magnetic flux can be attributed to a small-scale dynamo (SSD) operating in the convection zone. Such a process has been thoroughly studied in solar convection simulations [1, 2]. However, the effect of SSD fields on atmospheres of cool stars and potential observational signatures remains to be investigated.

Here we present 3D rMHD box-in-a-star simulations of the near surface convection and lower photospheres of an F3V, a G2V, a K0V and an M0V star, with and without an SSD mechanism [3]. The PDFs of SSD-associated magnetic fields at the $\tau = 1$ surface are shown to be quite similar for all cases. The M-star shows the absolute strongest fields, but the F-star shows the strongest fields relative to gas pressure. All stars also show a peak in B_h/B_z above the surface, with the magnitude scaling inversely with T_{eff}. The SSD fields also result in reduction of upflow velocities, a slight decrease in granule size as well as formation of bright points in the intergranular lanes. In addition, the spatial distribution of KE and ME is similar for all cases as well, implying a simple pressure scale height proportionality of important scales.

Lastly, we also compute coarse spectra for the F and K-star for a range of viewing angles, highlighting the effect of SSD fields on limb darkening.

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Large-scale electric currents in processes in the solar atmosphere

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In the late 80s of the 20th century, Crimean astronomers, studying the structure of transverse magnetic fields in active regions (ARs), discovered signs of the presence of large-scale vertical electric currents – global electric currents [1]. In 2018–2020, we finalized and adapted the method for detecting large-scale electric currents to the data of modern instruments for studying the Sun, and began studying their dynamics on time scales of 3-5 days [2]. Research carried out during 2020–2023 showed that:

1. Large-scale electric currents with values of the order of 10^{13} A exist in ARs with nonzero flare activity.

2. Large-scale electric currents extend to the upper layers of the solar atmosphere in one part of the AR, and close through the chromosphere and corona in the remaining part of the AR. This assumption for the AR NOAA 12192 is confirmed by the results of numerical simulations performed in 2016 [3].

3. The greater the magnitude of the large-scale electric current, the higher the probability of occurrence of M- and X- roentgen class solar flares in the AR.

4. At the final stages of AR evolution, a nonzero large-scale electric current can have a stabilizing effect on the sunspot, preventing its decay by its own magnetic field.

5. Large-scale electric currents are involved in coronal heating processes. Ohmic dissipation of a large-scale electric current is one of the mechanisms of quasi-stationary heating of coronal matter above the AR.

Our research on large-scale electric currents and the processes in which they take part continues.

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Subsurface Flows in Active Regions with Peculiar Magnetic Configurations

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The emergence of active regions in each solar cycle is primarily governed by three laws. While Spörer's law defines the latitude of emerging sunspots that decreases with time from mid-latitudes toward the equator as the solar cycle progresses, Hale's law dictates the leading and trailing polarities of active regions in each hemisphere. The tilt of active regions described by Joy's law is crucial for converting a toroidal field to a poloidal field in dynamo models. According to Joy's law, the leading sunspots are closer to the equator than the trailing spots, However, some active regions emerge in each cycle that do not follow these laws and the decay of such regions is believed to have adverse effect on the magnetic flux transportation to the poles and ultimately on the strength of the polar fields. We present a detailed analysis of the evolution of subsurface flows beneath these peculiar active regions in the upper 5% layer below the surface and compare their characteristics with the active regions having typical configurations. We also study the zonal and meridional components of subsurface flows in both polarity regions separately to better understand their role in flux migration. The analysis is performed using the local helioseismology techniques of ring diagram and the result is compared with those from time distance.

Exploring Sun's Bipolar Magnetic Region Tilts and the Phenomenon of Tilt Quenching through Magnetic Field Dependenc

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The tilt of the bipolar magnetic region (BMR) is crucial in the Babcock–Leighton process for the generation of the poloidal magnetic field in the Sun. Based on the thin flux-tube model of the BMR formation, the tilt is believed to be caused by the Coriolis force acting on the rising flux tube of the strong toroidal magnetic field from the base of the convection zone[1]. We extend the work of [2] and analyze the tracked information of the BMR from Michelson Doppler Imager (1996–2011) and Helioseismic and Magnetic Imager (2010–2018), to understand the magnetic field dependence of BMR tilts. In most of the cases we note that the tilt of BMRs increases initially and then get settled during their evolution. Moreover, we also find that the slope of Joy's law (γ_0) initially increases slowly with the increase of $B_{\max}$. However, when $B_{\max}$>2 kG, γ_0 decreases. The decrease of observed γ_0 with $B_{\max}$ provides a hint to a nonlinear tilt quenching in the Babcock–Leighton process[3]. Furthermore, we also note that the scatter of the BMR tilt around Joy's law systematically decreases with the increase of Bmax as the bigger BMRs are expected to less buffeted by convection. We finally discuss how our results may be used to make a connection with the thin flux-tube model.

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Early Detection of Active Region Emergence in the Solar Interior Using Acoustic Power Maps and Machine Learning Data Analysis

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Building a reliable forecast for the onset of solar eruptive activity has become increasingly important to mitigate a potential impact on various activities in space and the Earth's environment. Therefore, detecting active regions before their appearance on the solar surface is crucial to enable the development of early warning capabilities for upcoming Space Weather disturbances. We prepared a catalog of emerging active and quiet-Sun regions to identify characteristic features in the evolution of acoustic power density to predict magnetic flux emergence using the advantage of whole solar disk observations and develop a machine learning model to capture variations of the acoustic power flux density associated with upcoming magnetic flux emergence. In this study, we utilize the Doppler shift and the continuum intensity full-disk

images obtained with a 45-sec cadence from the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) to perform local tracking of 30x30-degree patches in the vicinity of active regions before their emergence on the solar surface. This approach allows us to follow the response of the acoustic power density in various oscillation frequency bands to the upcoming emergence of magnetic flux and investigate the potential of the machine learning approach to predict the emergence of active regions using the acoustic power maps as input.

Interaction of different dynamo instabilities in the convection zones of solar-like cool stars: role for magnetism and dynamics

(Invited talk)

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Numerical simulations of the solar convection zone constitute one of the most important tools to study solar and stellar dynamics and dynamos. Despite of many decades of attempts, it still remains difficult to reproduce both the correct differential rotation profile and solar-like magnetic cycle in one and the same model. Arguably, these simulations are currently far removed from the realistic parameter regime of the Sun and stars. Furthermore, when the numerical resolution has improved, and consequtively the Reynolds numbers have been increased, no asymptotic behavior has not yet been found.

Recently idealized numerical simulations of low magnetic Prandtl number plasmas, approaching the conditions in the deep solar convection zone, have shown that vigorous small-scale dynamo generating magnetic fluctuations can be excited [1]. This calls for studying the effect of this instability to convection zone dynamics and also its interactions with the large-scale dynamo instability. Until recently, it has been very challenging to run setups capable to excite these both types of dynamo instabilities, and integrate them over long enough time scales. Currently, such modelling efforts are starting to become possible, albeit at the moment working at magnetic Prandtl numbers of unity. In this contribution, we will review the results from the state-of-the-art numerical models, capable of simultaneously capturing these two dynamo instabilities under solar-like conditions, and present one possible interpretation of the results so far obtained.

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Large-scale Subsurface Flows Associated with Solar Emerging Active Regions

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We investigate the evolution of subsurface flows during the emergence and growth of active regions using the time-distance helioseismology analysis of the full-disk Dopplergrams from the Helioseismic and Magnetic Imager onboard the Solar Dynamics Observatory. The analysis is performed by tracking 30x30-degree patches of the active region areas during their passage on the solar disk, including the periods before and after the emergence. The flow maps, covering the range of depths from 0 to about 20 Mm, are obtained using 8-hour data series with one-hour shifts. The time-distance analysis is based on two travel-time measurement procedures and two types of sensitivity kernels developed for the SDO/HMI time-distance helioseismology pipeline [1]. The inversions are performed using the multi-channel deconvolution technique [2].

We present an analysis of a large set of emerging active regions, which reveals strong vortical and shearing flows before and during the emergence of magnetic flux, as well as the process of formation of large-scale converging flow patterns. The results show that the subsurface flow dynamics play a significant role in the formation and evolution of active regions and provide important constraints on the emerging-flux theoretical models.

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Decay of unipolar active regions

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We calculated decay rate of total unsigned magnetic flux for 910 ephemeral and sunspot-containing active regions using data from Solar Dynamics Observatory. Most of the active regions follow the power law dependency between the peak magnetic flux and the magnetic flux decay rate:

$$DR \sim \Phi_{max}^{0.70},$$

where DR means the magnetic flux decay rate, and Φ_{max} stands for the peak magnetic flux.

At the same time, a cluster of unipolar active regions show decay rates, significantly lower than expected from the power law dependence. The peak magnetic fluxes of ARs in the cluster vary in a narrow range of $(2-8) \times 10^{21}$ Mx. This behavior could be a manifestation for special mechanisms, interfering the decay of this type of active regions.

Modeling LOS magnetograms of emerging active regions

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Active regions (ARs) appear in the solar atmosphere as a consequence of the emergence of magnetic flux tubes [1]. The magnetic field of these flux-tubes acquire twist during their formation and rise through the convection zone, producing so called magnetic flux-ropes (FRs). Due to the presence of twist, during the emergence of these FRs the photospheric line-of-sight (LOS) magnetograms show an elongation of the AR polarities known as magnetic tongues. Since the magnetic tongues can affect the measurement of AR characteristics obtained during their emergence phase (e.g. their tilt angle, magnetic flux and size, among others), direct estimations of the FR global quantities which do not consider this effect have to be revised [2]. Obtaining a good estimation of tilt angle evolutions and spatial variations plays a key role in constraining flux-transport dynamo models, as Joy's law is fundamental for the formation and evolution of the polar field [3].

In this work we use an analytical 3D model of a toroidal FR from which synthetic LOS magnetograms can be constructed by projecting the vertical component of the field over successive planes at different heights. We have seen in previous works that this simple model with 8-free parameters can reproduce most of the global features observed during the emergence of bipolar ARs (e.g. tilt angle and magnetic tongues extension) [4]. We study the emergence of 8 bipolar ARs using magnetograms from the Michelson Doppler Imager (MDI) on board SOHO. Our method uses a probabilistic scheme based on the Bayes theorem to infer the most probable intrinsic parameters of the emerging FR, assuming a normal distribution for the differences between the model and the observations. We propose upgraded versions of the simple model by introducing different improvements (temporal correlations of the parameters, radial twist profile of the FR, and variable cross-section); this allows us to estimate expectation values for the tilt angle, magnetic helicity and magnetic flux, which are consistent with the observed ARs.

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Evolution of a nanoflare-scale magnetic reconnection event in the quiet Sun

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Low-lying loops in the quiet Sun are a reliable source of energy for atmospheric heating, but the mechanisms by which they realistically evolve are somewhat enigmatic. To address the origins of atmospheric heating events in the quiet Sun, we utilize our fully stratified, convection-driven, 3D MHD simulation *Bifrost* (see [1]) to specifically explore the evolution and eventual major reconnection between several magnetic loops. In [2], we use a set of Lagrangian markers to reliably isolate relevant reconnecting magnetic features based on their proximity to quasi-separatrix layers (see [3], [4]). We determine that the most relevant features are a magnetic flux rope and a magnetic arcade, which reconnect with a nearly antiparallel horizontal field in the corona.

In [5], we zoom in on the buildup of the magnetic flux rope in the corona. This flux rope is *not* associated with flux emergence or major flux cancellation, but rather self-orders in the corona via the inverse cascade of helicity (see [6]). We demonstrate the inverse cascade of helicity by isolating pairs of field lines that undergo component reconnection, which then contribute to the development of individual flux bundles which contribute to the overall helicity of the flux rope itself. We also discover that the flux rope attempts to relax to a linear force-free field according to Taylor's theory (see [7]) but cannot do so completely. This is primarily because the system is continuously driven, and also because the flux rope eventually reconnects with the overlying field anyway. However, the tendency of a flux rope to attempt to relax toward a linear force-free field had not been shown before this study.

Finally, we demonstrate that the eventual nanoflare-scale reconnection event could potentially be seen in various instruments including SDO/AIA and the future MUSE mission [8]. We calculate synthetic EUV intensities for FeIX at 171 Å and FeXII at 195 Å for comparison with the AIA 171 and 193 channels, as well as the 171 channel of MUSE. We determine that such a nanoflare-scale event would be visible in these channels, and that two systems of bi-directional jets can be seen as evidence of two different magnetic features undergoing reconnection at the same time. In this presentation, I will discuss the origin, evolution, and buildup of what eventually becomes a nanoflare-scale reconnection event, and explain how certain observational signatures can serve as clues toward explaining the mechanisms by which the quiet Sun's atmosphere can be heated.

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Flux Emergence Evolution as a Topological Entity

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Emergence of parcels of magnetized plasma into the solar atmosphere forms one of the main building blocks of active regions as well as small scale magnetic bipoles on the solar surface, whose evolution can be observed remotely at various levels of resolution. The common depiction of magnetic field consists of bipolar, distorted, twisted field line loops, however a variety of observed plasma phenomena in the laboratory, solar, heliospheric and astrophysical environment indicate intermittent formation of highly structured, spatially localized complex structures, facilitating adaptation of topological methods, extending the research of emerging macroscopic MHD fluxes into knots, links and braids. Combining mathematical considerations, remote images and in situ satellite observations at solar vicinity, one may construct new characteristics of those braided/knotted magnetic structures, applying Braid and Knot Theory to physical configurations, deducing their topological invariants, constraining the evolution and stability while delineating the relaxation path to magnetized equilibria.

The evolution of the observed topological magnetic field structures may be followed from their photospheric emergence with their unique geometry, through their 3d braid configuration in the overlying solar corona, to their impulsive release in violent solar activity or ejection as knotted structures into the solar wind. The braided coronal magnetic structures (e.g. [1]) offer the following evolutionary scenario: (a) braided coronal fields fluctuations based on Artin braid Group theory [2], (b) interaction with new active fields leading to stable Markov moves [3] due to preservation of the equivalent knot invariant, (c) braids' reconfiguration path with pre-existing magnetic fields, morphing them into magnetic knots [4] whose stability is boosted by their topological invariants, (d) major reconfiguration violating the equivalent knot invariant leading to eruption or (e) incorporation of the knots into the expanding solar wind and (f) intermittent recombination of knots through Knot Sum into elongated chain of field inversions, resulting in magnetic switchbacks. Similar structures are proposed for the description of Herbig-Haro [5] outflows as observed during planet formation and to laboratory experiments of high-energy density jets driven by toroidal magnetic field [6]. We conjecture that a large number of astrophysical bodies exhibit similar observable localized quasi-stable helical magnetic structures.

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Magnetic field and radial velocity fluxes at the initial stages of the evolution of solar active regions based on measurements at the photospheric level

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As of today, there is no established consensus about the connection between the physical processes occurring in the convection zone and photosphere of the Sun and the associated solar activity. One of the common ideas about the origin and evolution of active regions (AR) is the hypothesis about the emerging magnetic flux tubes [1]. To test this hypothesis, it is necessary to study the dynamics of changes in the magnetic fields and radial velocities in the AR at its initial stages of evolution. If the hypothesis of the emerging magnetic flux tubes is correct, both phenomena should be interrelated: with an increase in the magnetic flux, the upflows detected in the radial velocities should increase.

In this work, we perform a systematic study of the behavior of the magnetic fields and the radial velocities at the initial stages of evolution of ARs. We utilize the observations of the line-of-sight magnetic field made by the GONG (Global Oscillation Network Group) network of ground-based telescopes and select 30 emerging ARs suitable for our analysis. We filter the magnetogram region corresponding to the significantly large magnetic fluxes. Contrary to the expected increase of the upflow signal by the emerging flux hypothesis, we observe the decrease of the upflows and the intensification of the downflows at the emerging stages of ARs. Therefore, our analysis indicate potential inconsistencies between the hypothesis of the emerging magnetic flux tubes and the observed behavior of the ARs at their initial stages of evolution.

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Some recent results on sunspots and starspots
(Invited talk)

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Sunspots are the most visible magnetic structures on the solar surface, representing the largest magnetic flux tubes to cross the solar surface. Although they have been observed using telescopes for over 400 years, many of their properties and much of the physics underlying them have long been unknown or not well understood. The last decade has seen considerable advances in our knowledge of these fascinating structures, both from high spatial resolution observations and from radiation MHD simulations. Together, these techniques have uncovered or provided explanations for many of the properties of and features in sunspots. These include the fine-structure of the penumbra and the driver of the Evershed flow, as well as the regular presence of magnetic fields well in excess of 5 kG.

Far less is known about spots on other stars. On rapidly rotating, i.e. active stars, spots have mostly been imaged via Doppler imaging. Molecular lines have also played an important role for such stars. For more slowly rotating stars (similar to the Sun in that respect), the presence of starspots is mainly deduced from the variability of the stellar radiation. Just like sunspots, starspots influence their host star's variability partly by their limited lifetime and evolution and partly by their passage across the stellar disk carried by stellar rotation. Finally, the occultation of starspots by transiting exoplanets has become a new tool for determining coverage and properties of starspots. Spacecraft such as Kepler and TESS have played a decisive role in providing information on the spot coverage of other stars, producing many surprises on the way. For example, many stars that are otherwise similar to the Sun in age, temperature, metallicity and rotation, turn out to show much larger and more regular variability, suggesting a larger or at least different spot coverage. Whereas properties, such as surface distribution and partly the size or lifetime of starspots can be deduced from observations, to uncover the physical properties of starspots, such observations have considerable limitations. Instead, three-dimensional radiation-MHD simulations have turned out to play a very significant role.

The talk will provide an overview of selected results from recent years on sunspots and starspots.

Observational study of bipolar magnetic regions: Support of thin-flux tube rise model?

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The Bipolar Magnetic Regions (BMRs) are the strong magnetic feature, consisting of two magnetic polarities separated by a neutral line, observed on the surface of the Sun. They are found to be tilted with the equatorial line, which statistically increases with their latitudes, this is popularly known as Joy's law [1]. The thin flux tube model suggests that the magnetic field concentrated in flux tubes rises from the base of the convection zone to emerge as BMRs on the surface [2]. As flux tubes rise, torque induced by the Coriolis force acting on diverging flows developed at the apex of tubes produces the tilt in the BMRs. Despite the popularity of the rising flux tube model as an explanation for the formation of BMRs, observational support is limited [3]. In this work [4, 1], we study the evolving properties of BMR throughout their lifetimes by analyzing line-of-sight magnetograms from Michelson Doppler Imager (MDI) and Helioseismic and Magnetic Imager (HMI) for the past two solar cycles. Our analysis employs an automatic detection algorithm and an in-house developed automatic algorithm for tracking the BMRs to study their evolution. The evolutions of BMR tilt, foot separation, and magnetic properties hint at the theory of rising thin flux tubes behind the formation of BMRs and tilt quenching as a possible mechanism for quenching in the Babcock-Leighton dynamo model.

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An automatic algorithm to track bipolar magnetic regions in magnetograms to study the evolution of their properties

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Bipolar magnetic regions (BMRs) indicate strong, concentrated magnetic fields on the solar photosphere. They consist of opposite polarities, separated by a neutral line, and are observed to be tilted with respect to the equator. Understanding BMR properties is crucial to gaining insight into solar dynamo and magnetism. But the majority of studies consider each detection of the BMR as a new one. However, this will contribute different weightage to different BMRs as bigger BMRs live for a longer time. Furthermore, BMR properties evolve significantly over their lifetime. Hence, tracking is essential to overcome these limitations. In our study [1], we have developed an automated algorithm that can detect and track BMRs from the line-of-sight magnetograms of MDI (1996-2012) and HMI (2012-2021) throughout their lifespan/disk passage. The algorithm provides comprehensive data on various BMR properties, including tilt, lifetime, area, position, and magnetic properties. Unlike the already existing data products of tracked active region information, our algorithm is fully automatic and efficient and provides a homogeneous dataset with all the information of tracked BMRs from 1996. Furthermore, it can be easily adapted to any available magnetogram data. Here, we present the details of the algorithm and how various properties of BMR evolve over its lifetime.

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The simplest magnetohydrodynamic sunspot model

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Let us integrate the scalar product of the magnetic field vector with the induction equation over the entire volume of the sunspot, including its deep parts. We obtain the time derivative of $B^2/2$ (B is the rms magnetic field) equal to the difference between the specific powers of the Lorentz force L and magnetic diffusion. The diffusion term is proportional to B^2, which gives the simplest equation for a sunspot: $BdB/dt = L - B^2/\tau$. Here τ is the diffusion time, and L/μ_0 (in SI) is estimated by the ratio of the fraction d of solar luminosity to the volume of the convective zone. With approximate equality of kinetic and magnetic energy d =0.5. The steady-state magnetic field $(L\tau)^{1/2}$ corresponds to a typical and generally accepted observed value of 0.3T (3 kG) with again a well-known typical sunspot lifetime, which can be correlated with a τ duration of 3 days.

The solution of the aforementioned simplest equation gives at the initial moment the greater the derivative of the magnetic field, the smaller the value of the initial field. It is possible that such large and even potentially huge derivatives are associated with solar flares. This relationship can be identified based on observations. With a zero initial field, an infinite derivative is obtained. This is physically impossible and corresponds to the well-known fact that some seed field is needed to generate a magnetic field.

Helioseismic Measurement of Subsurface Magnetic Field Characteristics in Developed Sunspots

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There exist several techniques to isolate the contribution of various properties to the travel time of acoustic waves, such as from flows and sound speed perturbations [1]. These isolated contributions are then inverted to determine the underlying perturbations; for example, differences in the incoming and outgoing travel times can be inverted to determine the subsurface flow [2]. However, isolating the travel time contribution from the magnetic field has proven difficult; a standardized method for measuring properties of the subsurface magnetic field, such as now exists for flows and sound speed perturbations [3], has yet to be developed. Here, we derive a technique to isolate the horizontal magnetic field's contribution to acoustic travel times under the assumption of locally uniform magnetic field which slightly perturbs the acoustic wavevector. This technique directly measures the direction of the horizontal magnetic field (i.e. the field azimuth) without the need for inversion, and provides a direct proxy of the horizontal field's magnitude.

This technique is validated against two independent magnetohydrodynamic (MHD) simulations. The first MHD simulation contains a uniform, inclined magnetic field and is used to show that the measured properties are independent of the measurement scheme's orientation. The second MHD simulation includes a realistic sunspot which serves as a test of the assumptions used in the technique's derivation, as well as a reference for observational analysis since the subsurface structure here is known. While the inner few Mm's of the sunspot are not well resolved—the horizontal magnetic field sharply changes direction here—the measured azimuth strongly agrees with the *in-situ* values and the measured travel time anisotropy is consistent with with predictions from ray theory. We then examine several sunspots observed by the Helioseismic and Magnetic Imager (HMI) whose size and shape remain relatively stable over a 24 hour period. Dopplergram series of these active regions are used to compute maps of the subsurface magnetic field azimuth and a proxy for the horizontal component, and we examine the depth-dependent structure of these properties. The results of this investigation are presented fully in [4].

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Properties of Mean Phase Travel Time Deviations Preceding the Emergence of Large Active Regions during Solar Cycle 24

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There has been a significant effort over the past decade to develop and improve space weather forecasting systems using a variety of space- and ground-based observations. Such systems, however, rely almost entirely on characteristics of existing active regions, and the forecasting of emerging magnetic flux remains an open problem. In this work, we investigate properties of helioseismic travel times at relatively large depths ($z = -40$ to -70 Mm) preceding the emergence of 46 large active regions during Solar Cycle 24. The active regions selected for study are observed by the Heliosemsic and Magnetic Imager (HMI), and chosen such that they satisfy the following criteria: that their maximum area is greater than or equal to 150 millionths of solar hemisphere (MSH); that the active region emerges within 45 heliographic degrees of disk center; and that Dopplergram observations are uninterrupted spanning the period 72 hours prior to and 24 hours after flux emergence.

The mean phase travel time of acoustic waves in the previously mentioned depth range are measured using both a traditional cross-correlation analysis and using the difference-minimization method described by Gizon & Birch [1]. These travel times, in combination with quiet Sun mean travel times measured in the same solar cycle, are used to compute maps of the mean phase travel time deviations. We then compute the peak time of the perturbation index—defined to be the area-integrated mean phase travel time deviation beyond a certain threshold for each time moment—and time lag of maximum correlation between the mean phase travel time deviations and the surface magnetic flux. Of the 46 studied active regions, 36 of these have correlation lag times which precede the flux emergence. We additionally find a weak correlation between the maximum flux rate and the correlation lag times, where the correlation lag time increases (becomes more negative) for quicker flux emergence. The results of this investigation are presented fully in [2].

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Convective flows and the lifetime of sunspots

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The lifetime of individual sunspots and pores is analyzed according to the data of the processing of observations of the HMI/SDO space Observatory in the period 2010-2022. It is found that the lifetime of individual sunspots and pores differs from the Gnevyshev–Waldmeier rule formulated for groups of sunspots. The dependence of the lifetime has a different pattern for different types of spots. For pores, the lifetime does not depend on the polarity of the magnetic field and has a logarithmic form from the area: $T_{pr} = 0.24(\pm0.01) + 0.55(\pm0.14) \cdot lg(S_{mx})$. For regular sunspots with a developed penumbra, the dependence on the area has a linear form, but depends on the polarity of the magnetic field. For sunspots with a magnetic field of the leading polarity: $T_{sp}^{ld} = -0.62(\pm 0,2) + 0.036(\pm 0.002) \cdot S_{mx}$. For sunspots of trailing polarity: $T_{sp}^{tr} = 0.95(\pm 0,1) + 0.01(\pm 0.001) \cdot S_{mx}$.

The decay time and the total lifetime of sunspots is related to the rate of matter flow in sunspots. The average vertical speed of matter in sunspots decreases with their increasing area. Moreover, the flow rate of matter in the sunspots of the trailing polarity is higher than in the sunspots of the leading polarity. This difference in the velocity of matter explains the difference in the lifetime of the sunspots of the leading and trailing magnetic polarity.

The Wilson effect according to the analysis of averaged shapes of sunspots in 1919-2022

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A new method for estimating the Wilson effect based on the analysis of averaged shapes of sunspots has been developed. For the analysis, we used HMI/SDO data in 2010-2022 and processing data of RGO 1919-1972 and Kislovodsk 1954-2022 photographic plates. To do this, we have constructed averaged photosphere-penumbra and core-penumbra boundaries in various ranges of sunspot areas. Then we tracked the shape of sunspots at various distances from the center of the disk in the eastern and western hemispheres

It was found that the sunspots are not symmetrical and there is a shift of the boundary of the umbra of the sunspots to the western edge of the sunspot. This shift has a significant impact on estimates of the Wilson effect. We estimated the value of the Wilson depression for sunspots of different areas. The magnitude of the depression varies from 100 km for small sunspots to 1000 km for large sunspots. There is some imbalance of the Wilson depression at the eastern and western boundaries of the umbra-penumbra, depending on the area of sunspots and their latitude. The effects of the influence of matter flows on the formation of the Wilson effect are discussed.

The Dynamics of Magnetic-Flux Emergence: Sunspot Formation and Evolution
(Invited talk)

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The emergence of magnetic flux in sunspots on the Sun (or starspots on other stars) is the photospheric signature of the dynamo. Sunspots have been observed for hundreds of years [1, 2]. The eleven year periodicity in their appearance is the measure of the solar activity cycle [3]. In the last decade, there has been a considerable effort to digitize historical observations. These observations have provided statistics on active region (AR) parameters such as: areas, latitudes, tilt angles, and bipole separation. This has revealed the cycle dependence of these AR parameters, as well as features such as active region nests.

Modern observations now include magnetic imaging of the Sun, unveiling the fundamental magnetic nature of sunspots. Magnetic observations produce measurements of the flux distribution, magnetic helicity, polarity separation, and asymmetry of active regions. These measurements have shed light on the role of ARs in creating the Sun's polar magnetic field, thus seeding the next cycle. In particular, they have highlighted the significance of "rogue" ARs, whose extreme properties can change the course of the next cycle.

Unfortunately, the majority of observations have been limited to the near-side of the Sun. Magnetic measurements are only reliable for a window of ~ 7 days, when the ARs are within 60° of the disk center. While the smallest ARs only live for a few days, the largest can live for a few Carrington Rotations. The Solar Terrestrial Relations Observatory (STEREO) observed the far-side of the Sun for several years and for the first time (when combined with near-side observations) captured full 360° views of the active latitudes. This has enabled long-term evolution studies of individual ARs over their entire lifetimes, which show a standard pattern of AR growth and decay [4].

This talk will review the current observational knowledge of the local processes of magnetic-flux emergence (i.e., sunspot formation) and evolution, including observed patterns of sunspot emergence and evolution, small-scale motions, and the local dynamo.

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Super flares in M stars and associated characteristics of active regions and magnetic fields

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There is a renewed interest in the scientific studies of M stars in the recent times. This is because these low mass stars hosts many potentially habitable extra solar planets. In this paper we will study the characteristics of active regions which produces super flares in M dwarfs making use of relevant astronomical data. Energy of solar/stellar flares is understood to be related to the size and magnetic flux content of the active regions which produces the same. There is a theoretical upper limit to the magnetic flux content in solar active regions in which for a limiting flux of 7.23×10^{23} Mx the size of the active regions will be comparable to that of the solar radius. We cannot apply this scaling law to infer the size of the active regions in M stars which produces super flares of energy 10^{34}–10^{36} ergs because the radii of these stars are relatively small (0.3 to 0.7 solar radii). The magnetic flux associated with M star super flares is inferred to be between 10^{24}–10^{25} Mx. Further in contrast with kilo gauss fields found for sunspots we estimate magnetic fields of the order of 100–1000 kG for active regions in M stars. The emergence of exceptionally large magnetic flux in M stars is possibly related to higher poloidal to toroidal magnetic flux amplification factors in these stars compared to our Sun.

Hysteresis near the transition of the large-scale dynamo in presence of the small-scale dynamo

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In Sun and sun-like stars, there is a critical dynamo number for the operation of a large-scale dynamo, below which the dynamo ceases to operate. This region is known as the subcritical region. Our study explores the possibility of operating the dynamo in the subcritical region using a Babcock–Leighton-type kinematic dynamo model. We find hysteresis behavior near the transition of the large-scale dynamo. As in the Sun, both large-scale (global) and small-scale (local) dynamos are expected to operate at the same time and location; we check the hysteresis behavior in a numerical model in which both large- and small-scale dynamos are excited. For this, we use the Pencil Code and set up an $\alpha\Omega$ dynamo model with uniform shear and helically forced turbulence. We have performed a few sets of simulations at different relative helicity to explore the generation of large-scale oscillatory fields in the presence of small-scale dynamo. We find that in some parameter regimes, the dynamo shows hysteresis behavior, i.e., two dynamo solutions are possible depending on the initial parameters used. A decaying solution was observed when the dynamo was started with a weak field, and a strong oscillatory solution was seen if the dynamo was initialized with a strong field. Thus, the hysteresis of the large-scale dynamo is also observed in the presence of the small-scale dynamo. However, the regime of hysteresis is quite narrow for the case without the small-scale

dynamo. Overall, our work highlights the complex interplay between small-scale and large-scale magnetic fields in driving the long-term variability of solar and stellar dynamos.

A live homogeneous database of solar active regions based on SOHO/MDI and SDO/HMI synoptic magnetograms

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Recent studies indicate that a small number of rogue solar active regions (ARs) may have a significant impact on the end-of-cycle polar field and the long-term behavior of solar activity [1]. The impact of individual ARs can be qualified based on their magnetic field distribution [2]. This motivates us to build a live homogeneous AR database. First, we develop a method to automatically detect ARs from 1996 onwards based on SOHO/MDI and SDO/HMI synoptic magnetograms [3]. The method shows its advantages in excluding decayed ARs and unipolar regions and being compatible with any available synoptic magnetograms. Then we calibrate the identified AR flux based on the co-temporal SDO/HMI and SOHO/MDI data. Finally, we present the database of ARs, which provides basic parameters such as location, area, flux, and key parameters including the initial and final dipole fields of each AR. The homogeneity and reliability of the database are verified by comparing it with other relevant databases. Based on the database, we find that ARs with weaker flux show weaker cycle dependence. ARs with strong flux contribute most to the difference between cycles 23 and 24. The final dipole fields of several rogue ARs significantly reduce the end-of-cycle dipole field of cycle 23, which supports the previous study [1]. This constantly updated database covering more than two complete solar cycles is expected to be a valuable resource for understanding and predicting the solar cycle. The database and detection codes are publicly accessible online.

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Flux emergence simulation and atmosphere response at ephemeral region scale

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Flux emergence at different spatial scales and with different amounts of flux occur across the solar surface. The larger of these emergence events form active regions, and the emergence process has been studied using radiative magnetohydrodynamics (rMHD) simulations. Studies of the emergence at the smallest scales due to the Sun's small-scale dynamo have also been studied. We here complement these previous studies by simulating intermediate-scale ephemeral regions. We use the radiative MHD code MURaM to simulate the emergence of an untwisted magnetic flux tube of ephemeral region scale with a density nonuniformity into a background atmosphere with a small unipolar open field. We find half of the tube's magnetic flux emerges. The emergence involves many small bipole which emerge, forming complex loop structures seen in synthetic Atmospheric Imaging Assembly(AIA) 171 Å images. The atmosphere reaches $10^5 K$ at $3Mm$ above the surface. The heating produces hot (around $1 \times 10^6 K$ to $3 \times 10^6 K$) regions with only a small part of the volume having higher temperature. The evolution of the emergence seen different AIA filters show an a pattern of a major brightening accompanied by smaller brightenings, indicating the emergence procsee is complex and involves emergence of smaller features. Our simulation provides a reference example of a less twisted ephemeral region emergence and the atmospheric response.

Chromospheric activities of pre-main-sequence stars

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Observational studies of chromospheric activity have been extensively carried out for main-sequence stars. It is revealed that young solar-type stars have strong surface magnetic field, enormous starspots, and strong chromospheric emission lines.

We investigated chromospheric activities of pre-main-sequence (PMS) stars by spectroscopic and photometric observations. First, we studied the Ca II infrared triplet ($\lambda 8498, 8542, 8662$ Å) emission lines [1]. We conducted high-resolution spectroscopy with Subaru/HDS in addition to use of archival spectra obtained by Keck/HIRES, VLT/UVES, and VLT/X-Shooter. Most PMS stars have narrow Ca II IRT emission lines whose intensities are as large as the maximum of the zero-age main-sequence (ZAMS) stars. The chromosphere of most of PMSs is suggested to be completely filled by the Ca II emitting region. Second, we forcused on faint chromospheric emission lines. After estimating the effective temperature from the spectroscopic data and subtracting the photospheric absorption component, many faint chromospheric emission lines such as Mg I and Fe I are detected as an emission line for more than half of the PMS stars.

We also searched the periodic light variation caused by a starspot. The light curves of 26 PMS stars were obtained from TESS photometric data [2]. The amplitudes of the light curves are $0.001 - 0.552$ mag. We found that the light variations and Ca II emission line strengths of PMS stars are as large as those of the most active superflare stars and two orders of magnitudes larger than those of the Sun, and are located on the extensions of the superflare stars. In summary, PMS stars have very active chromosphere driven by strong dynamo process due to the fast rotation and the long convection timescale.

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Secondary flux emergence in ephemeral regions

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As a relatively active region on the quiet Sun, the ephemeral region (ER) exhibits highly complex emergence processes. We have studied the detailed sub-emergence processes of five ERs observed by Helioseismic and Magnetic Imager (HMI) aboard Solar Dynamics Observatory (SDO). The maximum unsigned magnetic flux for each of the five ERs is around 10^{20} Mx. We find that each of them has dozens of secondary flux emergences (SFEs) which we define as a bipole that arises close to the main polarities and coalesces with them after a period of evolution. The average emergent magnetic flux for each SFE in each ER is approximately 5×10^{18} Mx. Benefiting from observing the whole process of emergence and decay, we can study the connection between small magnetic features and the evolution of the dominant polarities from a holistic perspective (articles pertaining to the characterization of the moving magnetic features in the activity region can be found in [1] and [2]). Using a layer-by-layer analysis approach, we propose a subsurface field configuration of Ω-shaped loop and speculate that the relation between SFE and ER may be the independent emergence of magnetic flux tube from the same magnetic rope as that of the dominant polarities.

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Solar activity reconstruction from the Georg Eimmart's archive of 1616 – 1720

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Historical sunspot records provide piece by piece more information on the solar variability on a centennial scale. In this work, we analyze sunspot observations from archives of Georg Christoph Eimmart, which is the second-richest data set of the Maunder minimum after archives of the Paris observatory. Cumulatively, we process 109 drawings of the solar disk reported by seven observers. Sunspots were assigned into groups; areas and sunspot positions were evaluated. Reconstructed parameters are compared to those by [1, 2, 3], the group numbers version 1.21 by [4], and contemporary astronomers of the Maunder minimum. Particular attention is paid to the estimation of uncertainties in historical reports. The hypothesis of long-lived (up to four solar rotations) sunspot groups during the Maunder Minimum is considered. Comparison of the observations by La Hire and Muller of 1719 – 1720 suggests that the observations by La Hire were for astrometric purposes rather than aimed to sunspot counting.

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6 Miscellaneous

PoET: Mapping the Sun in space and time

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High resolution spectroscopy plays a key role in the effort to detect and characterise other Earths. This objective remains, however, challenged by astrophysical noise from the host stars, whose oscillations, granulation, and magnetic activity distort the observed spectra. Existing methods usually tackle the problem without a detailed understanding of the individual sources of variability and are insufficient to reach the required precision levels. A new approach is needed. In this talk I will present the main scientific motivation and the concept of PoET, the Paranal Solar Espresso Telescope.

PoET will connect to the "planet hunter" ESPRESSO spectrograph (ESO-VLT) and provide the unique capability to point to any region of the solar disk and obtain ultra-high resolution (>200 000), precisely wavelength calibrated spectra of the resolved solar disk and covering the full optical domain (380-780 nm) in one single shot.

PoET data will provide the detailed behaviour of thousands of spectral lines, formed in different depths of the solar photosphere, and sensitive to different physical conditions. This will probe in unique detail solar convection processes and 3-D atmosphere modeling. Finally, the PoET data will allow to map our star and understand in unprecedented detail the contribution of each solar feature to spectral variability. This will be vital in distinguishing the minute 'signals' of Earth-like planets from the overwhelming 'noise' created by their host stars.

Features of the solar minimum 24/25 in the evolution of polar and non-polar coronal holes

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Coronal holes are an integral part of the solar activity cycle because they represent the Sun's open magnetic field. The evolution of coronal holes is closely related to the evolution of the large-scale solar magnetic fields. Coronal holes are a reflection of global internal processes in the Sun. By analyzing the dynamics of coronal holes, in particular, their areas, we can judge the dynamics of the Sun and the progress of the cycle. The solar activity cycle 24 that recently ended was one of the weakest cycles for the last 100 years of observations. It differed from the previous cycles in a number of parameters. Cycle 24 is known to have a lower maximum and lower flare activity than the previous cycles. This cycle exhibited a relatively large north–south asymmetry of the polar field inversion: the sign of the field at the north pole changed more than a year earlier than at the south pole. The cycle also had a strong asymmetry of the hemispheres in many parameters. It must be said, solar minimum 23/24 exhibits features that differ notably from features commonly seen in minimum 22/23 and earlier minima. The polar coronal holes were less dominant than those in previous solar minima, but the low-latitude coronal holes, which are not commonly seen during previous solar minima, were relatively large and persist many rotations. Since the 24th solar cycle and the minimum preceding it were of a special nature, we wanted to at least partially answer the question whether solar minimum 24/25 is another unusual period?

The goal of this study is to reveal the features of the evolution of polar and non-polar coronal holes in the period from December 2018 to December 2020. The study is based on the material of observations obtained by the Atmospheric Imaging Assembly instrument in the Fe XII 19.3 nm line on board the Solar Dynamics Observatory spacecraft.To localize coronal holes and calculate their areas, we used the Heliophysics Event Knowledgebase.

Analysis of the evolution of the areas of polar and nonpolar coronal holes in the solar minimum 24/25 revealed a number of features. Hemispheric asymmetry is manifested both in the indices of solar activity and in the localization of the maximum regions of polar and nonpolar coronal holes. The area imbalance of the hemispheres is minimal for polar coronal holes and is pronounced in the areas of non-polar coronal holes and spots. The areas of polar coronal holes are significantly larger than the areas of non-polar ones and make a significant contribution to the total area of all coronal holes on the Sun's disk. The total area of the polar coronal holes approached the average level of values – about $(12.5 \pm 0.8) \times 10^4\ Mm^2$. While the area of all non-polar coronal holes is only about $0.5\times 10^4\ Mm^2$. Of course, the concept of "unusual solar minimum" is multifaceted, but as far as the evolution of two types of coronal holes is concerned, it was similar to earlier minima, in contrast to the 23/24 minimum.

The dynamo magnetic fields in ultra-massive white dwarfs

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Ultra-massive white dwarfs ($1.05\mathrm{M}_{\odot} < \mathrm{M}_{\mathrm{WD}}$) are particularly interesting objects that allow us to study extreme astrophysical phenomena. As the white dwarfs cool down, a crystallization process occurs in their core, releasing latent heat and redistributing their chemical components. This chemical redistribution is thought to induce a convective mixing in a significant portion of the star and some authors suggest that this should drive a dynamo magnetic field.

We present a new method for revealing the core-chemical composition in ultra-massive white dwarfs that is based on the study of magnetic fields generated during the crystallization process. Oxygen-Neon (ONe) white dwarfs crystallize at higher luminosities than their Carbon-Oxygen (CO) counterparts. Therefore, the study of magnetic ultra-massive white dwarfs in the particular domain where ONe cores have reached the crystallization conditions but CO cores have not, may provide valuable support to their ONe core-chemical composition, since ONe white dwarfs would display signs of magnetic fields and CO would not. We apply our method to eight white dwarfs with magnetic field measurements and we conclude that these stars likely harbour ONe cores.

We suggest that efforts should be placed in measuring magnetic fields and rotation periods in crystallizing white dwarfs.

Stellar activity in open clusters

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Stellar magnetic activity depends on multiple parameters one of which is stellar age. The members of open clusters are good targets to observe magnetic activity at a given age of the stars since their ages are generally more precisely determined than that of field stars. Choosing multiple clusters, each with different age, gives us insight to the change in magnetic activity at different stages of stellar evolution. With the analysis of these stars we can also refine the parameters of gyrochronology, which is a method for estimating the age of low-mass, main sequence stars from their rotation periods.

Within one cluster stellar activity can manifest in different ways at different locations of the color-magnitude diagram. This activity and its level could also be characterized with rate and energy of the occurring flares. The flare frequency distribution of different types of stars can also be discerned.

Photometric analysis of ground-based observations can provide multi-color light curves, color-magnitude diagrams and information on longer term periodicity while space-borne observations are more precise and more suitable for finding short term periodicity and flares. X-ray data can indicate the level of activity of a given star. For our work we choose targets that have been observed with a ground based telescope and in one of the TESS sectors and also have archival X-ray data. Here we present the first results of this on-going multi-wavelength investigation of ultimately 10 open clusters.

Influence of Solar Activity on LEO Satellites

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This work is devoted to exploring the impact of Coronal Mass Ejections on thermospheric density and plasma drag and relationships between them using various analytical and statistical techniques. It aims to explore the impact of solar radiation and solar wind forcing on thermospheric density. We are interested in analysing the seasonal distributions of Kp index and F10.7 during Solar Cycle 24 as well as the variations of Kp index caused by changes in solar activity features. Using the atmospheric model NRLMSISE00, we also addressed the perturbation forces on three LEO satellites with various eccentricities and altitudes. In this regard, we conclude that solar activity affects the upper atmosphere by rapidly altering the geomagnetic field.

The HRS high-resolution extraterrestrial solar reference spectra for disk-integrated, disk-center, or intermediate cases
(Invited talk)

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Accurate knowledge of the solar spectrum and its chemical composition represent essential data for solar physics, astronomy, cosmology, and geophysics. The determination of high-resolution solar reference spectra (disk-integrated, disk-center, or intermediate cases) is fundamental and represents key inputs for interpreting remote sensing measurements that uses sunlight. In this work, we present several new solar irradiance reference spectra at high resolution representative of solar minimum conditions. The High-resolution extraterrestrial solar Reference Spectra (HRS disk-integrated) is developed by normalizing high spectral resolution solar line data to the absolute irradiance scale of the SOLAR-ISS reference spectrum [1]. The resulting HRS disk-integrated solar spectrum has a spectral resolution varying between 1.0 and 0.001 nm in the 0.5 – 4400 nm wavelength range. We have also developed a solar HRS disk-center solar spectrum, which spans 650 – 4400 nm at 0.02 to 0.001 nm spectral resolution. We implemented several solar spectra (HRS intermediate cases) for ten different solar view-angles from $\mu = 0.9$ to $\mu = 0.05$ [2]. Finally, we developed several spectra (Disk center and Disk-Integrated Spectrum) based on solar modeling (MPS-ATLAS based on Kurucz solar linelists and Vald3 solar linelists).

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Trajectories of Coronal Mass Ejection from Solar-type Stars

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The Sun and other solar-type stars have magnetic fields that permeate their interior and surface, extends through the interplanetary medium, and is the main driver of stellar activity. Stellar magnetic activity affects physical processes and conditions of the interplanetary medium and orbiting planets. Coronal mass ejections (CMEs) are the most impacting of these phenomena in near-Earth space weather, and consist of plasma clouds, with magnetic field, ejected from the solar corona. Precisely predicting the trajectory of CMEs is crucial in determining whether a CME will hit a planet and impact its magnetosphere and atmosphere. Despite the rapid developments in the search for stellar CMEs, their detection is still very incipient. In this work we aim to better understand the propagation of CMEs by analysing the influence of initial parameters on CME trajectories, such as position, velocities, and stellar magnetic field's configuration. We reconstruct magnetograms for Kepler-63 (KIC 11554435) and Kepler-411 (KIC 11551692) from spot transit mapping, and use a CME deflection model, ForeCAT, to simulate trajectories of hypothetical CMEs launched into the interplanetary medium from Kepler-63 and Kepler-411. We apply the same methodology to the Sun, for comparison. Our results show that in general, deflections and rotations of CMEs decrease with their radial velocity, and increase with ejection latitude. Moreover, magnetic fields stronger than the Sun's, such as Kepler-63's, tend to cause greater CME deflections.

Preliminary results on the flux rope existence of 15 Feb 2011 magnetic cloud event using nonlinear force free-field (NLFFF) model and the observational evidence of its CME deflection by a coronal hole

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The interactions between the two large-scale phenomena, coronal holes (CHs) and coronal mass ejections (CMEs) has a direct impact not only on space weather but also on the relevant plasma physics. Upon their relative location, the CH may deflect a CME away or toward the Sun-Earth line [1]. A coronal-hole influence parameter (CHIP) is used to describe that effect, depending on the CH area, the distance between the CH and the eruption region, and the magnetic field strength within the CH at the photospheric level. Here we report on the first direct observation of CME deflection during the 2011 February 15 CME, which was associated with an X2.2 flare (S21W21) on 01:44 UT from STEREO/COR1 and COR2 observations. The CHIP is computed for the 2011 February 15 CME to be 0.73 G with a deflection angle of 62?. We use the AIA 193 A image from the Solar Dynamics Observatory (SDO) for CH identification and SDO/HMI for determining the magnetic field strength inside the CH. The largest CH (centroid at S59W15)) was close to the CME eruption region (S21W21). We measured the deflection angle as 38?, using STEREO/COR2 images. This deflection angle is not too different from that obtained from the coronal hole observations. We also investigate the Flux Rope (FR) existence by examining its topology in the corona using the Nonlinear Force Free Field (NLFFF) extrapolation [2]. The NLFFF extrapolation model is applied to the 15 Feb. 2011 active region 11158. The results confirmed the flux rope existence.

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Modeling of the solar flare chromosphere and thermal sub-THz radiation

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The origin of the sub-terahertz (sub-THz) component of radio emission from M- and X-class solar flares, which is characterized by the increase flux with frequency in the 100-400 GHz range, is considered. On the basis of equations of 1D non-LTE radiation hydrodynamics we simulated the distribution of the plasma density and temperature inside the flare loop caused by the interaction of non-stationary beam of accelerated electrons with the chromospheric plasma. The FLARIX numerical code was used to calculate the dynamics of the flare plasma parameters at different heights which are compared with F-CHROMA solar flare model database obtained with the RADYN numerical code. The calculated time profiles of spectral fluxes of the thermal sub-THz emission are in a good agreement with the observational data. The role of the chromospheric condensations in generation of sub-THz radiation is discussed.

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Center-to-limb variation of spectral lines and continua observed with SST/CRISP and SST/CHROMIS

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Observations of center-to-limb variations (CLVs) of spectral lines and continua provide a good test for the accuracy of models with a solar and stellar atmospheric structure and spectral line formation. They are also widely used to constrain elemental abundances, and are becoming increasingly more important in atmospheric studies of exoplanets. However, only a few such data sets exist for chromospheric lines. We have created a set of standard profiles from mosaics made with the CRISP and CHROMIS instruments of the Swedish 1-m Solar Telescope (SST). For each spectral line, we used a mosaic that ranges from the center to the limb. Each of these mosaics were averaged down to 50 individual spectral profiles and spaced by 0.02 in the μ scale. These profiles were corrected for p-mode oscillations, and their line parameters (equivalent width, line shift, full-width at half-maximum, and line depth) were then compared against literature values whenever possible. We present a set of 50 average profiles that are spaced equidistantly along the cosine of the heliocentric angle (μ) by steps of 0.02 for five continuum points between 4001 and 7772 Å, as well as ten of the most commonly observed spectral lines at the SST (Ca II H and K, Hβ, Mg I 5173 Å, C I 5380 Å, Fe I 6173 Å, Fe I 6301 Å, Hα, O I 7772 Å, and Ca II 8541 Å). We compare our profiles to existing literature, as well as Sun-as-a-star models to find deficiencies in them.

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Characterizing Solar Spicules and their Role in Solar Wind Production using Machine Learning and the Hough Transform

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The solar winds originate from the Sun and are classified into fast and slow solar winds. The fast solar winds are proposed to originate from the coronal holes at the solar poles, while the slow solar winds may originate from the streamers or the equatorial region of the Sun. Spicules are jet-like structures observed in the chromosphere and transition region of the Sun. Recently, rotating spicules exhibiting spiral motion have been observed, possibly indicating the presence of vorticity and Alfvén waves in the spicules. These rotating spicules may play a role in energy transfer to the upper solar atmosphere. However, their small sizes require high resolution observations to detect the rotation, and they may appear as macrospicules without clear rotation signatures in lower resolution data [2],[5].

In this study, machine learning and the Hough algorithm were used to investigate spicules in more than 3000 raster frames of the Sun. The study aimed to determine factors affecting the production and feeding of solar winds. The Hough transform was used to identify spicules and determine their characteristics, such as rotational velocity, position, and angle. Doppler maps were created from the Mg II k spectrum to identify twisted spicules, and their spatial, temporal, and spectral characteristics were compared to the Hough transform properties and provided as training data for the machine learning model. The model was trained and tested using data from the Hough transform and Doppler maps, and spicules with a high probability of rotation were identified. The accuracy of the models was around 80% for the polar region and approximately 95% for the equator region. The study's findings provide insights into the characteristics of spicules and their impact on solar winds. The study's procedures and results are presented in detail in the article [3]. The study analyzed around 11500 spectral images and identified more than 12000 spicules, of which 2077 were classified as rotating spicules exhibiting spiral motion. The percentage of rotating spicules was found to be higher at the solar poles (21%) compared to the equatorial region (4%). In general, more rotating spicules were observed on the western side compared to the eastern side of the Sun, while the numbers were comparable between the northern and southern hemispheres.

The rotational velocities and angular deviations of the detected spicules were measured, as were their Doppler velocities [1]. The number of rotations in the spicules depended on their diameters, with the broader spicules exhibiting multiple complete rotations. The rotating spicules may expand into mini-eruptions similar to spine-type spicule eruptions, based on the conservation of rotation and magnetic helicity. Both chromospheric and transition region observations indicate the presence of ephemeral magnetic flux tubes and plasma confined within coronal holes. These structures may be connected to the open magnetic field lines that accelerate the fast solar wind. Statistical analyses and machine learning techniques reveal differences in Alfvénic wave propagation in spicules and macrospicules between polar coronal holes and equatorial quiet/active regions. These differences may arise from magnetic reconnection at X-points between mini-loops. However, the origins of spicules remain elusive. Interchange reconnection between mini-loops may play a role in spicule formation and ejection. Higher resolution and longer timescale observations are required to fully resolve the sources of the fast solar wind and the roles of mini-loops. Coronal holes exhibit many helical plasma jets that could reflect primary fast solar wind acceleration sites. Mini-loops at the feet of jets may indicate magnetic reconnection and ejection. The observations support Alfvénic fast solar wind acceleration in coronal holes. Two critical components are helical motions of spicules and mini-loops that eject plasma. Magnetic reconnection in mini-loops may accelerate plasma into helical jets and feed the fast solar wind. The fine structures observed, such as helical chromospheric jets, suggest a complex Alfvén critical surface for the transition to fast solar wind. The helical motions can be interpreted as Alfvén waves that accelerate plasma to high latitudes. Twisting spicules are thus linked to high-speed polar winds and likely drive particle acceleration and mass loading in the fast solar wind. In summary, the high-resolution observations and analyses provide new insights into the potential roles of torsional motions, Alfvénic waves, spicules, mini-loops, and magnetic reconnection in the acceleration of the fast solar wind from coronal holes. The results support the view that these dynamically coupled small-scale structures and processes contribute significantly to the origin and heating of the fast solar wind.

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Physical Properties of the Solar Atmosphere Derived from Comparison of Spectro-Polarimetric SDO/HMI Observables with 3D Radiative MHD Simulations

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In this study, we compare the SDO/HMI line-of-sight observables (magnetic field, velocity, continuum intensity, and line depth) with the related physical properties for dynamo simulations performed using the "StellarBox" 3D Radiative MHD code. The modeling of the Fe I 6173 Å Stokes profiles is performed using the SPINOR radiative transfer code in the LTE approximation. The reproduced SDO/HMI line-of-sight pipeline is applied to the modeled spectra, and the observables are synthesized with high (numerical) and SDO/HMI (instrumental) resolutions. Correlations between the observables and the physical properties at various heights in the atmosphere are studied for a set of view angles (0, 30, 45, 60, and 75 degrees away from the solar disk center). It is found that SDO/HMI velocity and magnetic field (less prominently) observables are correlated with physical parameters at certain heights of the solar atmosphere. These heights increase

from about 100-150 km above the photosphere for the disk center case to 300-600 km above the photosphere for the 80-degree case, however, are almost the same for the 0-60 degree projection angles. The integrated unsigned magnetic flux calculated from the observables underestimates the actual magnetic flux at the strongest correlation heights for about 40% on average. The integrated continuum intensity as calculated from the observables is about 4-8% larger with respect to its actual values. In addition, we discuss the problem of the contribution of unresolved magnetic elements to solar brightness based on the modeling data. The results improve physics-based interpretations of the SDO/HMI observables and provide a better understanding of the physical properties of the solar atmosphere.

Thermal instability in the impulsive phase of solar flares with sub-THz component

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The analysis of several flare events showed that the subterahertz (sub-THz) radiation for which the flux increases with frequency is hardly associated with hot ($5 \times 10^5 - -10^7$ K) coronal plasma. The sub-THz flux of radiating hot plasma according to the DEM calculations based on AIA/SDO data turned out to be much less than the observed values. This suggests that the contribution of hot plasma during the impulsive phase of solar flares to the sub-THz optically thick radiation is quite small. We suggest that this can be caused by the development of thermal instability in hot EUV coronal loops. As a result, the plasma temperature of these loops decreases and the contribution of hot plasma to the sub-THz radiation is diminished.

Using the detailed analysis of several solar flares with sub-THz emission component in different wave ranges, we obtained indications in that favour of the existence of thermal instability in flare EUV loops. In particular, based on the two-dimensional distributions of temperature and emission measure obtained from the AIA/SDO EUV intensity data, it was found that significant temperature changes occur near the flare maximum. The temperature drops near the impulsive phase of the flare, while the emission measure noticeably increases.

The relationship between the sub-THz emission of flares and the thermal source in the solar chromosphere is substantiated.

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Levels of stabilization of velocity and magnetic induction in the convective zone of the Sun

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To obtain the equation for the evolution of the rms and mass-average velocity $u(t)$, we integrate the scalar product of the velocity vector by the momentum equation over the entire volume of the convective zone and divide the result by the mass of the zone. We obtain that udu/dt is equal to the specific integral power of the Archimedes buoyancy force A minus the specific power of the diffusion force u^2/T_u and Lorentz force $ub^2/(L\rho\mu_0)$. Here, the original integrals are presented in terms of their components, to which they are directly proportional. T_u is the diffusion time, b is volume mean and mean square magnetic field, L is the characteristic outer scale of about 100 Mm, and ρ is the mean density. In a similar way, we integrate over the volume the scalar product of the magnetic field vector and the induction equation. Finally we get the system

$db/dt = ub/L - b/T_b$, $udu/dt = A - ub^2/(L\rho\mu_0) - u^2/T_u$.

The stable stationary points of this system are:

$u_S = L/T_b$, $b_S = \pm\sqrt{\rho\mu_0[T_bA - L^2/(T_uT_b)]}$.

For the self-evident $u_S = 100$ m/sec, we get $T_b = 10^6$ sec, which is close in order of magnitude to the average lifetime of sunspots. Dividing the known solar luminosity by the mass of the convective zone, we roughly estimate $A \approx 10^{-2}$ W/kg, which gives $T_bA = 10^4$ J/kg. The same value is obtained by assuming $L^2/(T_uT_b)$ for turbulent quantities $T_u = T_b$. Therefore, for successful generation of a magnetic field, it is necessary to satisfy the threshold condition

$T_u > T_b$.

If this condition is met with a good margin, then the field b_S is slightly less than 1 T (10^4 G). On the contrary, if the excess of T_u over T_b is not too large, then a significant decrease in the magnitude of the magnetic field is possible and even the arrival of the stationary points of the above system in the vicinity of trivial (in the magnetic field)

$b_S = 0$, $u_S = \pm\sqrt{AT_u}$.

These stationary points are unstable and therefore they are likely to be rarely reached (for example, with a huge random fluctuation), which is apparently similar to the Maunder minimum. Interestingly, in this case, the value of the root-mean-square velocity is very significant (more than 100 m/s with the parameters adopted above) with a catastrophic decrease in the magnetic field.

Exploring Damping Properties of *IRIS* Bright Points using Deep Learning Techniques

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In a recent study [1], Doppler shift in the *IRIS* solar spectrum was explored to analyze the evolution of longitudinal oscillations with damping. The researchers utilized deep learning techniques to examine the statistical properties of damping in different regions. They found that damping rates between network and inter-network bright points in active regions and the quiet Sun exhibited clear differences - about 80% of the network's bright points damped in quiet areas, while 72% did in coronal hole areas. In contrast, this figure approached 33% in active areas. For inter-network bright points, these values are 65%, 54%, and 63%, respectively [3]. Most of the energy of the network's bright points was transmitted to higher levels, while internetwork bright points' energy mostly returned to lower layers [2]. This issue may be directly related to the effects of damping at network and inter-network bright points. The damping rates of magneto-acoustic waves in the TR and corona appear to increase with plasma density. Furthermore, the investigators found that the damping rates of waves with higher frequency increase more sharply than those with lower frequency. Such findings could provide useful insights into the heating processes in the solar atmosphere. Another research looked at the percentage of oscillating waves in bright points, which revealed that only a small percentage of IRIS bright points are oscillating and that their dampening can be investigated [4]. Another essential factor to consider when studying bright points is the link of bright points in various levels of the solar atmosphere. These bright areas, according to study, can be seen from the photosphere to the corona and have relations to one another [5].

In summary, recent studies have revealed clear differences in damping rates of magneto-acoustic waves in *IRIS* bright points depending on the region of the solar atmosphere. These differences could contribute to the heating mechanism in different regions. Additionally, small-scale magnetic structures, such as *IRIS* bright points, are a critical driver of plasma motion and heating in the solar atmosphere. Moreover, most of the energy of network's bright points was transmitted to higher levels, while internetwork bright points' energy mostly returned to lower layers. The heating rate was found to be more efficient in areas with weaker magnetic fields, such as internetwork bright points, than in areas with stronger magnetic fields, such as network bright points. Finally, studying bright points could provide vital insights into the heating processes in different regions of the solar atmosphere.

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Sub-THz emission from stellar flares and energy release diagnostics

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A comparative analysis of sub-THz emission of stellar flares at red dwarfs and Sun-like stars has been carried out. ALMA observations indicate that the sub-THz emission flux from stellar flares with a characteristic duration of 10 s is an order of magnitude greater than for solar flares. Its spectrum decreases with frequency for red dwarfs and can increase for Sun-like stars. The sub-THz emission from stellar flares can be linearly polarized, and the degree of linear polarization can reach tens of percent. We show that these types of spectrum slopes and linear polarization can be caused by the synchrotron emission of ultrarelativistic electrons. Some of the observed relationships between sub-THz, low frequency radio, and X-ray emissions of stellar flares are discussed.

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Detecting coronal mass ejections with machine learning methods

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Flares on the Sun are often associated with ejected plasma: these events are known as coronal mass ejections (CMEs). These events, although are studied in detail on the Sun, have only a few dozen known example on other stars, mainly detected using the Doppler-shifted absorption/emission features in Balmer lines and tedious manual analysis. We present a possibility to find stellar CMEs with the help of high-resolution solar spectra.

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