Interdisciplinary Physics of the Sun

Spanish-German WE-Heraeus-Seminar

29 June – 04 July 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the Spanish-German WE-Heraeus-Seminar:

The physical understanding of our Sun is in many ways foundation science. Its applications range from the Sun as a calibrated neutrino source, as a laboratory for reactions and decays of light nuclei under plasma conditions and for magnetohydrodynamical processes, to its function as a benchmark for stellar models: Stellar structure, evolution, and seismology can be precisely tested against data from the well-observed Sun. Advanced telescopes and space missions aided by theoretical modelling study the processes that are involved in the continuous reconfiguration of the Sun's magnetic field on the surface and the atmosphere. A continuous solar wind of particles fills interplanetary space, while coronal mass ejections lead to solar storms, posing risks to technology in near-Earth space or on ground. A large number of space missions have advanced our knowledge on the Sun and its influence on the planetary system. Scientists in Germany and Spain have for many years been at the forefronts both of the physics of the solar core (neutrinos and nuclear reactions) and phenomena from the solar interior via the surface to the solar wind. However, these research fields have developed and prospered largely in parallel, with limited interaction. The present workshop aims to bridge this gap and assemble a core group of scientists working on all physical aspects of the Sun. The main concepts of each branch of solar research shall be laid out in dedicated lectures. There shall be ample space for free discussion, with the aim of discovering new interdisciplinary research avenues to address the Interdisciplinary Physics of the Sun.

Scientific Organizers:

Prof. Daniel Bemmerer	Helmholtz-Zentrum Dresden-Rossendorf, Germany E-mail: d.bemmerer@hzdr.de
Prof. Markus Roth	hüringer Landessternwarte Tautenburg, Germany E-mail: mroth@tls-tautenburg.de
Dr. Aldo Serenelli	Institute of Space Sciences (ICE, CSIC), Spain E-mail: aldos@ice.csic.es

Introduction

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Dr. Stefan Jorda
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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 29 June 2025

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 30 June 2025

08:00	*BREAKFAST*	
09:00 – 09:20	Scientific organizers	**Opening**
09:20 – 10:10	Elena Khomenko	**Realistic simulations of the solar magneto-convection including effects of partial ionization**
10:10 – 10:30	**Poster pitches:** - Duresa Temaj - Janna Martens - Ulrich von Kusserow - Richard Jean-Guillaume - Sanghita Chandra - Khalil Daiffallah	
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:50	Bernd Heber	**Solar energetic particles – remote sensing and in situ observations**
11:50 – 12:40	Gaël Buldgen	**Dynamical processes in the Sun and non-standard solar models**
12:40	*LUNCH*	

Program

Monday, 30 June 2025

13:30 – 14:20	Taisuke Nagayama	**Understanding solar opacity: Fundamentals, theoretical foundations, and experimental validation**
14:20 – 15:10	Alba Formicola	**Experimental challenges in Underground Nuclear Astrophysics Laboratory**
15:10 – 15:30	**Poster pitches:** - Gwangson Choe - Aswathi Krishnan Kutty - Max McMurdo - Helena Vila Crespo - Daye Lim - Hanna Strecker	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:50	Daniel Müller	**Solar orbiter: Science highlights and mission status**
16:50 – 17:40	Nazareth Bello Gonzales	**Small-scale structure in the lower solar atmosphere**
17:40 – 18:00	**Poster pitches:** - Hemanth Pruthvi - Peter Hempel - Ajay Kumar Yadav - Andres Vicente Arevalo - Xiang Li	
18:00	*DINNER*	

Program

Tuesday, 01 July 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Fernando Moreno Insertis	**Exploring magnetic flux cancellation from the solar photosphere to the corona.**
09:50 – 10:10	Tanayveer Singh Bhatia	**3D rMHD sunspot models and their implications for other cool stars**
10:10 – 10:30	**Poster pitches:** - Konrad Schmidt - Eva Sola-Viladesau - Robert Kamlah - Vigeesh Gangadharan - Ashish Mishra	
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:50	Frank Stefani	**Solar magnetohydrodynamics: Paradigmatic liquid-metal experiments and some theoretical aspects**
11:50 – 12:40	Francesco Villante	**The response of the sun to modifications of its internal properties**
12:40	*LUNCH*	
13:30 – 15:30	**Poster session**	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:50	Eliana Masha	**Solar pp-chain reactions studied underground**
16:50 – 17:40	Juan Manuel Borrero	**Solar spectropolarimetry**
17:40 – 18:00	Gianluca Imbriani	**Present knowledge of $^{7}Be(p,\gamma)^{8}B$ and $^{3}He(^{4}He,\gamma)^{7}Be$**
18:00	*DINNER*	

Program

Wednesday, 02 July 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Hector Socas-Navarro	**Current status of the European Solar Telescope**
09:50 – 10:40	Alessandra Guglielmetti	**Solar fusion cross sections III: a nuclear physics perspective**
10:40 – 11:00	*COFFEE BREAK*	
11:00 – 11:50	Manuel Collados	**Spectropolarimetry with VTT and GREGOR: 25+ years of successful German-Spanish collaboration**
11:50 – 12:40	Aldo Serenelli	**The standard solar model**
12:40	*LUNCH*	
13:30 – 17:30?	**Excursion**	
18:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 03 July 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Maria Bergemann	**Solar elemental abundances**
09:50 – 10:40	Rachel Howe	**Helioseismology at low-degree: BiSON results through solar cycles**
10:40 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Stefan Krückeberg	**DFG's Priority Programme (Schwerpunktprogramm)**
11:30 – 12:30	**Discussion about a possible DFG priority programme submission in 2026**	
12:30	*LUNCH*	
13:30 – 14:20	Michèle Heurs	**Deutsches Zentrum für Astrophysik and gravitational wave detections**
14:20 – 15:10	Natalie Krivova	**Past solar activity**
15:10 – 15:30	Huidong Hu	**Lateral deformation of two coronal mass ejections in the transition from non-radial to radial propagation**

Program

Thursday, 03 July 2025

15:30 – 16:00	*COFFEE BRREAK*	
16:00 – 16:50	Hardi Peter	**The Corona of the Sun and its connection to the surface**
16:50 – 17:10	Hemanth Pruthvi	**TauSoL imaging spectropolarimeter: Concept and design**
17:10 – 17:30	Álvaro Jesús Quero Ballesteros	**Spectrometry of cosmic-ray neutrons with the high efficiency neutron spectrometry array**
17:30 – 17:50	Matthias Schubert	**First solar line scans with the visible tunable filter VTF at the 4m class Daniel K. Inouye solar telescope**
18:00	DINNER	

Program

Friday, 04 July 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Carsten Denker	**Observations of Solar Magnetic Activity**
09:50 – 10:40	Michael Wurm	**Solar neutrino measurements by Borexino and at future detectors**
10:40 – 11:00	*COFFEE BREAK*	
11:00 – 11:20	Tom Van Doorsselaere	**Global coronal models driven with Alfven and kink waves**
11:20 – 11:40	Yoshiki Hatta	**Solar neutrino flux fluctuations caused by gravity modes**
11:40 – 12:00	Yago Herrera	**Standard solar model and variations with Kernels method**
12:00 – 12:30	Scientific organizers	**Closing**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Sanghita Chandra	**Probing chromospheric fine structures with an Hα proxy in MURaM simulations**
Gwangson Choe	**How much are we missing? Observational Limits on magnetic helicity transport in emerging magnetic structures**
Khalil Daiffallah	**f-mode travel-time signature of sunspot models and plages**
Vigeesh Gangadharan	**The Daniel K. Inouye Solar Telescope observations of shock waves triggered by magnetic vortices**
Peter Hempel	**Gamma-ray angular distribution of the 3He(α,γ)7Be-reaction**
Richard Jean-Guillaume	**Radial and latitudinal structure of the sun: Icosahedral symmetry?**
Robert Kamlah	**Multi-line spectroscopy of a sunspot with a strong light bridge**
Aswathi Krishnan Kutty	**Simulation of sunspots in the chromopshere**
Maria Lukyanova	**New measurement of the 2H(p,gamma)3He reaction at Felsenkeller underground lab**
Xiang Li	**Stereoscopic disambiguation of solar vector magnetic fields using observations from SO/PHI and SDO/HMI**
Daye Lim	**Quasi-periodic pulsations in EUV brightenings**
Janna Martens	**Correlation of microwave signatures in solar flares and near-earth solar energetic particle spectra**
Eliana Masha	**NuFFER - NuPECC Forum for Early Career Researchers**

Posters

Max McMurdo	**Uniturbulence and Alfvén wave solar model in MPI-AMRVAC**
Ashish Mishra	**MRI in rotating flows: Implications for the solar tachocline and dynamo processes**
Hemanth Pruthvi	**PyAstroPol: A python package for polarization ray tracing**
Konrad Schmidt	**Advanced gas target techniques for nuclear astrophysics**
Eva Sola-Viladesau	**Heating, magnetism and geometry of small-scale coronal loops**
Hanna Strecker	**Active region evolution from different viewpoints**
Duresa Temaj	**Towards a reconstruction of the annual solar Irradiance over the past 9 millennia**
Andres Vicente Arevalo	**First 3D inversion of a solar prominence**
Helena Vila Crespo	**Initial steps in the inference of horizontal velocity fields in the solar atmosphere**
Ulrich von Kusserow	**Space weather and earth's climate**
Ajay Kumar Yadav	**Using modern data to understand historical solar observations**

Abstracts of Talks

(in alphabetical order)

Small-Scale Structure in the Lower Solar Atmosphere

N. Bello González

Institut für Sonnenphysik (KIS), Freiburg, Germany

The lower solar atmosphere is a highly structured and dynamic region, shaped by the interplay of plasma motions and magnetic fields. Advances in high-resolution observations and spectro-polarimetric techniques have revealed its fine structure in unprecedented detail. This talk provides a general overview of selected features and processes that reflect the intricacy of the lower layers of the solar atmosphere and its relevance to broader questions in solar physics.

3D rMHD models of sunspots and their implications for other cool stars

Tanayveer Singh Bhatia[1], Robert Cameron[1], Sami Solanki[1], Damien Przybylski[1], Mayukh Panja[1]

[1]*Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany*

Abstract: Realistic radiative magnetohydrodynamic (MHD) simulations of sunspots reproduce essential qualitative features of observed sunspots[1][2]. Recently, these models have also been extended to other stellar types[3][4]. A limiting factor for these simulations is the artificial enhancement of horizontal magnetic field B_h at the top boundary to obtain the observed penumbral extent and the Evershed flow. This limits the vertical extent of the simulations to the lower photosphere and the match to observed sunspots is qualitative at best[5]. We report simulations of sunspots in a slab geometry with a self-consistently generated penumbra without any additional enhancement of B_h at the top boundary. We obtain this by prescribing a slight excess entropy in the region surrounding the umbral field trunk. Essential features of observed sunspots are obtained at reasonable resolutions. This marks a first step towards extending sunspot simulations above the photosphere.

References

[1]: Rempel, M. 2012, ApJ, 750, 62
[2]: Rempel, M. 2015, ApJ, 814, 125
[3]: Panja, M., Cameron, R. H., & Solanki, S. K. 2021, ApJ, 907, 102
[4]: Bhatia, T., Panja, M., Cameron, R. H., et. al. 2025, A&A, 693, A264
[5]: Jurčák, J., Schmassmann, M., Rempel, M., et. al. 2020, A&A 638, A28

Solar Spectropolarimetry

Juan Manuel Borrero[1], Ivan Milic[1,] Helena Vila Crespo[1,2], Andreu Vicente Arevalo[1], Markus Schmassmann[1], Manuel Collados[2,3], Matthias Rempel[4], Basilio Ruiz Cobo[2,3]

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[2]Universidad de La Laguna, La Laguna, E-38205 (Spain)
[3I]nstituto de Astrofisica de Canarias, Avd. Via Lactea s/n, La Laguna, E-38205 (Spain)
[4]High Altitude Observatory, NSF National Center for Atmospheric Research, 3080 Center Green Dr., Boulder 80301, USA

Spectropolarimetry refers to analysis of absorption/emission spectral lines and their polarization signals (Stokes vector). Through this method it is possible to infer the thermodynamic, kinematic and magnetic properties of the plasma in the outer solar atmosphere. Of particular interest is the study of magnetic fields as it allows us to investigate electric currents, the solar local dynamo, equilibrium of sunspots, filaments and prominences, and even solar metallic abundances. In this contribution I will provide an overview of the some of the most recent developments in the inference of the physical properties of the solar atmosphere via spectropolarimetry in combination with physical constraints such as mass conservation, magneto-hydrostatic equilibrium, solenoidal magnetic fields, etc. Many of these developments have been possible thanks to a two decade long collaboration between researchers in Spain and Germany.

On the other hand, at its very root, spectropolarimetry is based on the detailed knowledge of the interaction between light and matter and therefore relies heavily in atomic physics. I will offer an overview on how the lack of proper atomic parameters (transition probabilities, hyperfine structure constants, partition functions, collisional rates, ...) directly affect the accuracy to which we can calculate background opacities, measure magnetic fields and infer the solar abundances.

Dynamical processes in the Sun and non-standard solar models

G. Buldgen[1]

STAR Institute, University of Liège, Liège, Belgium

The modelling of the solar interior so far has been limited to so-called Standard Solar Models (see [1] for a detailed review). While these models have enjoyed tremendous successes in the past decades, they neglect a wide variety of dynamical aspects and/or rely on very simplified formulations of complex phenomena. In this review, I will briefly discuss the observational evidence for the presence of dynamical phenomena acting in the solar interior. I will discuss the limitations of current formalisms and their implementation in existing stellar evolution codes as well as current efforts to drive progress in this area. In this respect, helioseismic constraints play a crucial role in helping improving current solar evolution models [2,3] but have also to be put in the global perspective of asteroseismic analyses [4] that may provide complementary yet crucial understanding to improve current solar models beyond the Standard Solar Model framework.

References

[1] J. Christensen-Dalsgaard, Journal **18**, Issue 1 (2021)
[2] A.G. Kosovichev et al., Accepted for publication in Solar Physics (2025)
[3] M.J. Thompson et al. ARA&A, Volume 41, pp.599-643 (2003)
[4] C. Aerts et al. ARA&A, Volume 57, p. 35-78 (2019)

Spectropolarimetry with VTT and GREGOR: 25+ years of successful German-Spanish collaboration

M. Collados[1,2]

[1]Instituto de Astrofísica de Canarias, E-38205, La Laguna, Tenerife
[2] Departamento de Astrofísica, Univ. de La Laguna, E-38201, La Laguna, Tenerife

The Tenerife Infrared Polarimeter (TIP) saw first light at the VTT of the Observatorio del Teide (Tenerife) in 1998 and was offered as a common-use instrument to the whole German and Spanish solar physics community the year after, in 1999. Since then, it has gone through a number of improvements that have finally led to its present configuration GRIS at GREGOR, with a three-arm setup for simultaneous observations in several wavelengths. A scanning slit or a slicer-based integral field unit can also be selected without a large exchanging effort. In this communication, I will review the main results achieved at VTT and GREGOR as a result of the extensive collaboration in the field of spectropolarimetry between German and Spanish institutions.

Observations of Solar Magnetic Activity

Carsten Denker and Meetu Verma

Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

The solar magnetic field drives solar activity on a wide range of spatial and temporal scales and with different morphologies throughout the solar atmosphere, from the photosphere and chromosphere to the transition region and corona. High-resolution observations of the solar magnetic field now provide access to the fundamental scales at which hot plasma and magnetic fields interact. Ground-based solar telescopes with aperture diameters larger than one meter and their advanced instruments have provided many case studies covering all facets of solar activity. This review focuses on high-resolution photospheric and chromospheric observations, linking them to synoptic observations and bridging the gap in spatial and temporal coverage.

Experimental challenges in Underground Nuclear Astrophysics Laboratory

A. Formicola [1]

on behalf of the LUNA collaboration

[1] *Istituto Nazionale di Fisica Nucleare, Piazzale Aldo Moro n.2, Roma, Italy*

Accurate knowledge of thermonuclear reaction rates is important in understanding the generation of energy, the luminosity of neutrinos, and the synthesis of elements in stars. The LUNA Collaboration has shown that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

I will give an overview of the experimental techniques adopted in underground nuclear astrophysics and will present a summary of the main recent results -and achievements.

Decadal review on Solar Fusion Cross Sections III: a nuclear physics perspective

D. Bemmerer 1, A. Guglielmetti 2, W. Haxton 3, Y. Herrera 4, and A. Serenelli 4

1Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
2 Università degli Studi di Milano and Istituto Nazionale di Fisica Nucleare, Milano, Italy
3 Department of Physics, University of California and Lawrence Berkeley National Laboratory, Berkeley CA, USA
4 Institute of Space Sciences, Cerdanyola del Vallès, and Institut d'Estudis Espacials de Catalunya, Barcelona, Spain

The third decadal review of solar fusion cross sections (SF-III) is based on a community consensus formed in a workshop that took place in July 2022 in Berkeley, California, with 50 participants representing many of the groups active in the field.

Such workshop was followed by many subsequent digital meetings and exchanges.

The final outcome is a paper recently accepted for publication on Reviews of Modern Physics (https://arxiv.org/abs/2405.06470).

I will present a nuclear physics based perspective on the SF-III recommended astrophysical S-factors for the main hydrogen burning reactions belonging to the p-p chain, CNO cycle and NeNa cycle. I will also present the main experimental facilities for solar fusion studies. Further, I will discuss the recommendations for future work included in the SF-III paper and conclude with a general outlook.

Solar neutrino flux fluctuations caused by gravity modes

Y. Hatta[1,2], M. Kunitomo[3], Y. Nakano[4], S. Sugama[5], H. Ito[6]

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Solar gravity (g) modes have been long sought since the beginning of helioseismology, but there has not been firm detection yet. This is mainly due to the fact that the g-mode amplitudes are too small to detect at the surface (~ a few mm/s in line-of-sight velocity at the photosphere; Belkacem et al. 2022). One promising observable is neutrino that is produced by the nuclear reaction in the core. Lopes & Turck-Chièze (2014) (LT14 hereafter) have made a significant progress by formulating neutrino flux fluctuations caused by g modes. By comparing their formulation with the observed ^{8}B neutrino fluxes, they successfully put constraints on g-mode amplitudes. As we currently have abundant observations of other kinds of neutrinos (such as *pp*, *pep*, ^{7}Be, and *CNO*-cycle), it should be valuable for us to expand upon LT14. With this in mind, we followed LT14 and reevaluated fluctuations in neutrino fluxes caused by g modes based on the assumption of linear adiabatic oscillation. We find that the first-order fluctuation is zero due to geometrical cancellation unless we take into account the "time-delay effect"; that is, neutrinos that are produced in a different part of the Sun will arrive at an observational point on a different time. Such time-delay effects have an angular dependence on the solar inclination angle, resulting in that we may only see dipole g modes with $|m|=1$. Moreover, the fluctuation amplitude is small (~ 10^{-10} in relative difference) when we assume maximum relative temperature perturbation inside the Sun to be 10^{-5}. Therefore, it is at the moment fair to say that we might not be able to detect individual g modes via solar neutrino measurements. On the other hand, we have also found a hint that the second-order effects might cause non-negligible variation in the average neutrino flux. We thus would like to emphasize that it is important for us to keep studying theoretical evaluation of the neutrino flux fluctuations caused by g modes that can eventually enable us to put further constraints on, e.g., the excitation mechanism of g modes.

References

[1] Belkacem, K., Pinçon, C., and Buldgen, G., Solar Physics **297**, 11 (2022)
[2] Lopes, I., & Turck-Chièze, S., ApJL, **792**, 35 (2014)

Solar Energetic Particles – Remote sensing and in situ observations

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Solar Energetic Particles (SEPs) are bursts of high-energy ions and electrons released during solar flares and coronal mass ejections (CMEs). While remote sensing techniques—such as extreme ultraviolet (EUV) and X-ray imaging—allow us to observe the Sun's atmosphere through photons, SEPs provide a complementary "in-situ" perspective on energetic processes occurring in the corona and beyond. By linking SEP measurements to remotely observed flare and CME signatures, students can better understand particle acceleration, magnetic reconnection, and shock wave propagation. Integrating SEP data with photon-based observations deepens our knowledge of solar eruptive events and enhances our ability to predict space weather impacts.

Recommended Reading for Students

- "Introduction to Space Physics" by Kivelson & Russell
- "The Sun as a Guide to Stellar Physics" by O. Engvold et al. (for linking photon and particle observations)

Standard Solar Model and variations with Kernels method.

Y. Herrera[1,2], A. Serenelli[1,2], and F. L. Villante[3,4]

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[4] Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Gran Sasso, 67100 Assergi (AQ), Italy.

Abstract

Our Sun can be used as a laboratory to test aspects of the many areas of physics pertaining its study. It can also provide constrains on new physics theories, such as proposed exotic particles (e.g axions, hidden photons).

A key component in this application is obtaining accurate predictions of the impact on observable quantities introduced in the Standard Solar Model (SSM) by such particles, mainly through the additional energy-loss from their interactions. Theoretical uncertainties from other sources, like variations in composition, opacity or nuclear reaction rates, must also be well constrained. This traditionally requires the calibration of new models, usually done in a per-case basis and involving variations of several parameters, which makes the process cumbersome and computationally expensive.

We present the latest updated version of the SSM (B23/SF-III) and a tool for quickly computing variations due to nuclear rates, composition, and opacity, as well as a second tool for variations due to arbitrary perturbations in energy-loss. The latter, for instance, takes a user-defined energy-loss function and integrates it with a set of precomputed energy-loss kernels (functional derivatives). It outputs first order variations of neutrino outflows, radial profiles for chemical composition, sound speed and several other quantities of interest. We validate the method with actual SSM calibrations that include the aforementioned particles, with good agreement for total energy-losses of up to 0.1 $L_{\odot}$.

Deutsches Zentrum für Astrophysik and Gravitational Wave Detection

M. Heurs[1,2]

[1]Institute for Gravitational Physics, Leibniz University Hannover, Germany
[2]DESY / DZA, Zeuthen / Görlitz, Germany

The German Center for Astrophysics (Deutsches Zentrum für Astrophysik, DZA [1]) is an initiative of the German astrophysics and astroparticle physics communities. It is currently in its build-up phase (which started in April 2023); its research areas are astrophysics, digitisation, and technology development. By 2038, the DZA will employ 1000 people and have a large positive socio-economic effect on the Region of Lusatia.

Gravitational wave astronomy (GWA), along with multi-messenger astronomy, radio astronomy, and optical surveys, is one of the DZA's foci in astrophysics. While the currently operating ground-based gravitational wave detectors (GWDs), e.g. aLIGO and adVirgo, are already generating a wealth of data for GWA, next-generation GWDs – like the Einstein Telescope and Cosmic Explorer – will grant us access to the "dark ages" of the Universe with observations of up to $z = 100$ in gravitational waves, complementing astronomy with electromagnetic radiation, neutrinos, and astroparticles.

This talk will give an overview of the DZA's current status and plans. On the scientific side, it will provide insight into the function principle of interferometric GWDs and some of the advanced technology required for the Einstein Telescope.

References

[1] https://www.deutscheszentrumastrophysik.de/en
[2] ET Steering Committee Editorial Team, "Design Report Update 2020 for the Einstein Telescope" (2020)

Helioseismology at low degree: BiSON results through solar cycles

R. Howe[1]

[1]*University of Birmingham, Birmingham, United Kingdom*

The Birmingham Solar Oscillations Network (BiSON) is a six-site global network of instruments for low-degree helioseismology, sensitive to modes with degree up to 4 [1]. The earliest observations were made in the 1970s and the full network was completed in 1992, so the data cover the whole of Solar Cycles 22, 23, and 24 and parts of Cycles 21 and 25. This enables us to follow the solar-cycle variation of the mode parameters such as frequency, width and amplitude over multiple cycles [2, 3] and see subtle differences between the different cycles, as well as measuring the rotational splitting to high precision by fitting the whole 45-year time series [4]. Recently we have shown that the frequency shifts in spectra from time series shorter than half a solar rotation not only show a clear solar-cycle dependence but are sensitive to activity on the far side of the Sun as well as the visible side [5].

References

[1] S. J. Hale et al., Sol. Phys. **291**, 1 (2016)
[2] R. Howe et al., MNRAS **470**, 1935 (2017)
[3] R. Howe et al., MNRAS **514**, 3821 (2022)
[4] R. Howe et al., MNRAS **526**, 1447 (2023)
[5] R. Howe et al., MNRAS **537**, 909 (2025)

Lateral Deformation of two Coronal Mass Ejections in the Transition from Non-radial to Radial Propagation

Huidong Hu[1], Chong Chen[2], and Rui Wang[1]

[1]National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
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A substantial fraction of coronal mass ejections (CMEs) exhibit a transition from non-radial to radial propagation in the low corona, which determines their propagation direction and affects their space weather impacts. However, the characteristics of CMEs during this directional transition remain poorly understood and insufficiently studied. Using multi-wavelength imaging observations of the solar disk and corona, we investigate the evolution of two CMEs originating from the same active region, both transitioning from non-radial to radial propagation in the low corona. The potential field source surface method is employed to obtain the magnetic field configuration and decay index surrounding the eruption site.

The two CMEs display similar early-stage evolution. After their eruptions, the CMEs initially propagate nearly horizontally. Subsequently, the upper portion of the CME structure bulges and deforms laterally, leading to radial propagation at a latitude offset of more than 20 degrees from the eruption site. The CMEs erupt beneath a system of overlying loops, whose magnetic fields are roughly aligned with the axis of the CME flux rope. Although the decay index above the eruption site reaches the critical value of 1.5 at a low altitude (~20 Mm), the CMEs do not rise radially above the eruption site. This is probably because the overlying loops impose strong magnetic pressure and constrain the radial expansion directly above the eruption site.

During the non-radial propagation phase, the two CMEs move beneath the loops like a bullet in a gun barrel. After they leave the loop system, their upper flanks bulge towards the higher corona, which results in a transition in propagation direction. In the radial propagation stage, the flank of the expanding CME interacts with the loops, resembling the plucking of musical instrument strings. After the directional transition, the previously bulged flank in the non-radial phase becomes the leading edge (nose) of the radially propagating CME. This study presents a detailed picture of how a CME transitions from non-radial to radial propagation through lateral deformation, which fills the gap in the understanding of CME propagation from the corona to interplanetary space.

Present knowledge of $^{7}Be(p,\gamma)^{8}B$ and $^{3}He(^{4}He,\gamma)^{7}Be$.

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New direct experimental methods and techniques, combined with the development of new theoretical tools have opened new avenues to explore nuclear reactions of signi cance for nucleosynthesis at or near the actual temperatures of stellar burning. The main difficulty of direct measurements is determined by the background, which, together with the low cross sections, set a limit on the energy range that can be investigated with a simple setup on the earth's surface. Essentially there are three sources of background, cosmic rays, environmental radioactivity and beam-target induced nuclear reactions. Each of these sources produces background of a different nature and energy, so that each reaction studied needs special care to suppress the relevant background component. We will show two different experimental approaches that have been used to study processes of astrophysical interest. In particular, we will focus our attention on underground experiments and the recoil mass separator approach used to measure 7Be(p,g)8B and 3He(4He,g)7Be.

Realistic simulations of the solar magneto-convection including effects of partial ionization

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Realistic simulations of the solar upper convection zone and its atmospheric layers have become essential tools for unraveling complex magnetohydrodynamic processes in the Sun and complementing observational studies. These simulations also serve as laboratories for testing new ideas. One such idea involves incorporating partial ionization and other non-ideal effects—such as ambipolar diffusion, the Hall effect, and the Biermann battery effect—as potential mechanisms for explaining non-radiative heating in the solar chromosphere and transition region. In this talk, I will critically review realistic simulations that account for these physical processes and discuss potential future directions for this line of research.

Past solar activity

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A wealth of exciting high-cadence, high-spatial and high-spectral resolution data have been collected, revealing the dynamic nature of our star. Yet the Sun also varies on much longer timescales than those covered by modern observations. Photographs of the Sun have been taken since the 19th century, and systematic sunspot counts have been made since the early 17th century. Using these data, we can trace the Sun's history over the past few centuries, albeit with increasing gaps and decreasing accuracy as we go further back in time. To study the Sun's more distant past, we have to rely on indirect proxies of solar magnetic activity, such as cosmogenic isotope concentrations in terrestrial archives. Taken together, these records carry information about solar behaviour over millennia, but this information must be carefully extracted using physical models. Developing such models requires an understanding of physical processes on the Sun, which is, in turn, informed by modern observations. This talk will review how we connect these diverse data sources – from satellite imagery to ancient trees and ice cores – to understand the mechanisms behind, and reconstruct the long-term variability of the Sun.

DFG's Priority Programme (Schwerpunktprogramm)

Stefan Krückeberg1

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This talk presents DFG's funding scheme "Priority Programme / Schwerpunktprogramm".

Solar pp-chain reactions studied underground

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The proton–proton (pp) chain is responsible for about 99% of the energy produced in our Sun and is the dominant energy generation mechanism in low-mass stars. Despite the huge scientific effort in the last decades, the nuclear physics input of the pp chain remains a significant source of uncertainty in the standard solar model, affecting predictions of stellar evolution and solar neutrino fluxes. Matching the high-precision solar neutrino data requires equally precise nuclear cross-section measurements. However, the extremely low cross sections at solar energies make experimental studies highly challenging, highlighting the crucial role of low-background underground laboratories such as LUNA, Felsenkeller, and other facilities. A general overview of the pp chain and the role of the underground laboratories to constrain the pp-chain reactions, as well as some preliminary results from the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction which controls the flux of the $^{7}\mathrm{Be}$ and $^{8}\mathrm{Be}$ neutrinos, will be presented.

Exploring magnetic flux cancellation from the solar photosphere to the corona.

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May 7, 2025

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Magnetic flux cancellation is often understood as the direct meeting at low atmospheric levels of magnetic patches with opposite polarity, accompanied by a simultaneous reduction in their magnetic flux — and, in some cases, the complete disappearance of one or both of them from magnetograms. Observational studies of this process over the past decades have primarily relied on magnetograms and Doppler maps derived from photospheric or chromospheric spectral lines. A smaller number of studies have employed spectropolarimetric data inversions.

In parallel, theoretical investigations have been conducted using either analytical approaches or idealized, purely coronal MHD numerical models. Radiation-MHD models that incorporate self-consistent subphotospheric convection have also been explored; however, these typically extend only up to the low chromosphere and assume geometrically simple initial magnetic field configurations.

In this lecture, I will present recent results from a radiation-MHD simulation performed with the Bifrost code. This model spans from the uppermost layers of the solar interior to the corona; in it multiple episodes of magnetic flux emergence and cancellation take place. We analyze the temporal evolution of a few cancellation events, compute observational proxies, and investigate the fascinating magnetic topology at and around the cancellation site. Our study provides a three-dimensional picture of the events taking place above a cancellation site, and offer a perspective beyond the traditional dichotomy of Ω-loop retraction versus U-loop rise often used to interpret observations.

Solar Orbiter: Science Highlights and Mission Status

D. Müller[1]

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This talk will present science highlights and a status report of the ESA/NASA Solar Orbiter mission. Solar Orbiter aims to address key questions of solar and heliospheric physics pertaining to how the Sun creates and controls the Heliosphere, and why solar activity changes with time. To answer these, the mission carries six remote-sensing instruments that observe the Sun across a wide range of wavelengths and spatial scales, and four in-situ instruments that measure the state of the solar wind as it flows past the spacecraft. Solar Orbiter was launched in February 2020 and started its nominal mission phase in December 2022. In February 2025, a Venus gravity assist manoeuvre initiated the mission's out-of-ecliptic phase: Solar Orbiter's highly elliptical orbit will get progressively more inclined to the ecliptic plane, which enabled the first detailed observations of the Sun's unexplored polar regions. Solar Orbiter's science return is significantly enhanced by coordinated observations with other space missions, including Parker Solar Probe, SDO, SOHO, STEREO, Hinode and IRIS, as well as ground-based telescopes like DKIST and SST. This talk will present examples of such collaborative efforts and outline future opportunities for participation of the entire science community.

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Understanding Solar Opacity: Fundamentals, Theoretical Foundations, and Experimental Validation

T. Nagayama

Opacity is essential for understanding the Sun's structure and evolution, influencing energy transport and stellar dynamics. This talk provides an overview of opacity, covering its opacity basics, theoretical calculation methods, and ongoing experimental validations. I will first explain what opacity is and derive the Rosseland mean opacity to clarify its assumptions and the complexities of solar opacity. Next, I will discuss how opacity is computed from first principles without free parameters, highlighting the physics involved in opacity calculations and the approximations that require experimental validation. Finally, I will outline ongoing opacity experiments aimed at testing the validity of approximations used in opacity models. This can be done by measuring frequency-resolved iron (or oxygen) opacities at solar interior conditions and comparing them with calculated opacity spectra. The credibility and challenges associated with benchmark opacity experiments will be explained. High-energy-density opacity theorists and experimentalists are working together to test and ensure the accuracy of this important physics input for understanding the Sun.

The Corona of the Sun and its connection to the surface

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The corona of the Sun is the magnetically structured outer atmosphere of our home star. It is composed of plasma heated to a million Kelvin or more, almost two orders of magnitude hotter than the surface. The (comparably slow) evolution of the magnetic field at the surface is injecting the energy to heat the plasma and is driving the dynamics in the corona. The spatial and temporal scales cover a wide range, from the smallest resolvable jet features to large-scale flares. The larger of these events can lead to disruptions of the heliosphere and govern space weather.

In the classical scenarios, promoted for several decades, the energy is injected into the corona by either waves or fieldline braiding. However, observations indicate that the energy flux through waves might not be sufficient to heat active region coronal loops and direct observational evidence for fieldline braiding is sparse. At the same time, observations hint at a prominent role of small reconnection events for the energization of coronal loops, small coronal brightenings or little jets feeding the solar wind. 3D model play a key role for the interpretation of the data because they can provide synthetic observables that can be directly compared to actual observations. This is then a rigorous test to the processes included in the models.

The direct link from the corona back to the surface (or vice versa) is more complex that it might seem at first. The rapid expansion of the magnetic field from the photosphere into the chromosphere and the variability and complex structure of the chromosphere makes it difficult to unambiguously link the surface to the corona, even in a 3D model, where all information is available.

Recent progress in instrumentation now provides us with sub-arcsec spatial resolution for observations of the upper atmosphere (IRIS, EUI/Solar Orbiter) in the extreme UV (EUV). The near future will bring coronal EUV spectroscopy, better than 0.5 arcsec, through Solar-C and MUSE. Considering the rapid magnetic expansion, these coronal observations will match observations at very high spatial resolution with the new DKIST solar facility on Hawaii and hopefully with the 4m European Solar Telescope. The combination of these space-and ground-based observations will open a new era for an understanding how the magnetic field on small scales in the photosphere sustains a hot corona and can drive small- and large-scale coronal structures unstable.

TauSoL Imaging Spectropolarimeter: Concept and Design

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Tautenburg Solar Laboratory (TauSoL) is a pathfinder for Solar Physics Research Integrated Network Group (SPRING). SPRING is a ground-basednetwork of synoptic solar telescopes that is proposed to continuously monitor the Sun. TauSoL is a container-based full-disc solar telescope installed at the site of the Thüringer Landessternwarte Tautenburg (TLS), Germany. The principal instrument is a multi-line spectropolarimeter using Fabry-Pérot interferometer, a tunable filter that is chosen due to its wide wavelength range of operation and high speed of operation. The instrument is currently under development and is expected to see the first light in the Summer of 2025. This first prototype of the instrument aims to solve the calibration problems associated with full-disc spectropolarimetric data recorded with such tunable filter.

Pruthvi, H., et al, 2024, Proc. of SPIE Vol. 13096 130968B-1

Roth, M. et al, 2024, SolPhys, 299:44

Spectrometry of cosmic-ray neutrons with the High Efficiency Neutron Spectrometry Array

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The High Efficiency Neutron Spectrometry Array (HENSA) project focuses on the development and application of high-efficiency neutron spectrometers [1], with uses in cosmic-ray neutron studies and space weather research. HENSA is based on the Bonner Sphere System (BSS) [2, 3], but incorporates a modified geometry that achieves an increase up to ten times the detection efficiency of conventional BSS. Its extended-energy-range version covers thermal energies up to 10 GeV, allowing full-spectrum neutron measurements on 30–60-minute timescales. These data complement the Neutron Monitor Network [4], enabling near real-time monitoring of spectral variations during the solar cycle and solar events such as Ground Level Enhancements (GLEs) and Forbush Decreases (FDs).

In 2020, a HENSA detector was deployed in a campaign to study the cosmic-ray neutron spectrum under quiet solar conditions at the beginning of Solar Cycle 25. This enabled mapping across magnetic rigidities from 5.5 to 8.5 GV and altitudes from sea level to 3000 m, extending previous studies [5]. Based on these results, a new spectrometer, HENSA++, has been developed with improved energy resolution. Since 2024, it has been under commissioning, first in Valencia (sea level, Rc = 7.5 GV) and later at the Observatorio Astrofísico de Javalambre (1957 m, Rc = 7.07 GV) [6].

This talk presents an overview of HENSA for cosmic-ray neutron studies, results from the 2020 campaign, and early findings from HENSA++. We include a temporal analysis of the neutron spectrum and preliminary studies of recent GLEs. We conclude with prospects for continuous monitoring during the second half of Solar Cycle 25.

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First solar line scans with the Visible Tunable Filter VTF at the 4m class Daniel K. Inouye Solar Telescope

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The Visible Tunable Filter (VTF) is a narrowband tunable filter instrument for imaging spectro-polarimetry. After more than a decade of development at the Institute for Solar Physics (KIS) located in Freiburg Germany, the highly sophisticated instrument is installed at the U.S. National Science Foundation (NSF) Daniel K. Inouye Solar Telescope (DKIST) on Maui/Hawaii. The VTF is a Fabry-Pérot based filter system designed to perform at the diffraction limit of a 4m class telescope in a wavelength range between 520 and 860 nm. The field of view is 60 arcsec with a spatial resolution of 20 km @520 nm and a spectral resolution of SR=100,000. In a technical campaign at the end of 2024, the instrument was optically fine-aligned and pointed on the Sun for the first time. Thus, line scans in FeI 630.25 nm and NaD 588.9 nm could be recorded to verify the optical alignment to the boresight of the telescope, as well as the spectral and spatial performance.
The diameter of the etalon glass plates scales with the size of the telescope aperture. For a 4 m class telescope like DKIST the clear aperture of the etalons have to be approximately 220 mm. To meet the demanded scientific goals, the requirements on accuracy and stability in controlling the air gap and its uniformity, are in the order of a few atoms. Up to now, such large etalons were never built before. Furthermore, the instrument is equipped with a filtergram channel where the light is additionally analyzed by a ferro-electric liquid crystal based polarimetric modulator to derive the Stokes vector. Also, a broadband channel is available which takes 10% of the incoming light to acquire context images for later image reconstruction techniques. The VTF is designed to perform in high cadence to be able to study the highly dynamic sun with given spatial resolution of a 4 m class telescope. Therefore, the etalon tuning time is below 40 ms and the polarimetric modulator switch time below 10 ms. Thus, the instrument is able to acquire a line scan for the full field of view for e.g., the iron line FeI 630.25nm within 15 s with an accumulated signal to noise ratio SNR of approximately 700 which corresponds to a magnetic sensitivity better than 20G in Stokes V. For a single line scan, around 12 million spectra will be recorded within a second. In the recent work, the VTF team was able to take around 2 TB of first light data and gather extremely useful first-hand knowledge in running such an instrument at a 4m class telescope which is unique on our planet. The presented work will give insides in the challenges which had to be solved and show first measurements and analyzes to demonstrate the instrument functionality.

Current status of the European Solar Telescope

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The European Solar Telescope (EST) is advancing towards its construction phase as the most powerful solar telescope in Europe, designed to observe the Sun at unprecedented spatial and temporal resolution. Featuring a 4.2-meter aperture and an innovative polarization-free optical train, EST integrates a suite of advanced subsystems including an adaptive secondary mirror (ASM), a multi-stage Pier Optical Path (POP), and a Coudé distribution system optimized for high-precision polarimetry and diffraction-limited imaging across a 380–2300 nm spectral range. The project's baseline includes a design for integrated Multi-Conjugate AO (MCAO), ensuring stable, high-quality correction over a wide field of view. Significant progress has been made in the design but also on the administrative and political fronts to prepare for construction. This presentation will update the German and Spanish solar physics communities on the current status of the project and its next steps .

Solar magnetohydrodynamics: Paradigmatic liquid-metal experiments and some theoretical aspects

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Recent decades have seen great progress in the experimental investigation of fundamental hydrodynamic effects that are relevant to solar physics [1]. For such studies, liquid metals are particularly suited, partly owing to their low Prandtl numbers that are comparable to those in the solar convection zone, partly due to their high electrical conductivity, which allows to study a wide variety of magnetohydrodynamic phenomena. In the first part of the talk, we present some of the key liquid-metal experiments on Rayleigh-Bénard-convection, Alfvén waves, the magnetorotational and Tayler instability, and the dynamo effect. We discuss what has been learned so far from those experiments and what can be expected from future ones, including the precession-driven DRESDYN dynamo experiment at Helmholtz-Zentrum Dresden-Rossendorf.

In the second part, we elaborate on a model of the solar dynamo that aims at explaining its various periodicities on widely different time scales in a self-consistent manner [2]. Starting with Rieger-type periodicities, we show that the two-planet spring tides of Venus, Earth and Jupiter are able to excite magneto-Rossby waves in the solar tachocline with typical periods between 100 and 300 days and amplitudes of m/s or even more. We show that the quadratic action of these waves contains a beat period of 11.07 years, and argue that the axisymmetric part of the resulting α-effect may indeed be strong enough to synchronize the entire solar dynamo via parametric resonance. A secondary beat between the arising 22.14-year Hale cycle and the 19.86-year periodic motion of the Sun around the barycenter of the solar system may explain the Suess-de Vries cycle. The spectrum resulting from this double-synchronized dynamo model turns out to be in remarkable agreement with climate-related data. We also discuss the emergence of another beat period of 1.723 years as a candidate for the quasi-biennial oscillation (QBO), which could also explain the astonishing regularity and "quietness" of the solar dynamo.

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Global coronal models driven with Alfven and kink waves

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In recent years, the so-called AWSOM models are a new generation of solar atmospheric models, which incorporate the heating and forces of Alfven waves on top of more classical effects. They are outperforming older models capturing most aspects of the solar corona, but are still lacking in open field regions because of the lack of reflections and turbulence development. In this contribution, I will highlight our development of a new formalism that allows to describe the kink wave on coronal plumes and loops in a similar way as the Alfven waves in the AWSOM models. In this new development, we generalise the Elsasser variables to Q-variables in order to follow waves that are not Alfven waves. I will explain the governing equations, and highlight early outcomes of the proof-of-concept in 1D configurations, where I show that kink wave driving leads to additional coronal heating.

The response of the Sun to Modifications of its Internal Properties

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The Standard Solar Model (SSM) is a fully predictive framework that does not contain free parameters, enabling us to treat the Sun as a laboratory for fundamental Physics. This makes it possible to use observations of solar neutrinos and helioseismic data to place constraints on both standard and non-standard alterations to the solar internal structure. In this talk, we first review the Linear Solar Model (LSM) approach—a method that is both straightforward and accurate—for calculating the effects of generic (small) modifications of the physical inputs adopted in SSM construction. We then apply this framework to explore how general modifications in energy production and/or energy transport affect the observable properties of the Sun. We finally discuss the implications of recent solar neutrino measurements for solar physics.

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Solar neutrino measurements by Borexino and at future detectors

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The thermonuclear fusion processes powering our Sun are an abundant source of low-energy neutrinos at MeV energies. Easily penetrating the outer layers of the Sun, these neutrinos provide a unique way to study the solar interior. Since the 1960ies, their signals have been studied by a suite of underground detectors and played an important role in the discovery of neutrino oscillations. The state-of-the-art of solar neutrino detection is set by the Borexino experiment that operated from 2007 to 2021 at the Gran Sasso Lab and performed a high-precision energy-resolved measurement of the neutrino spectrum.

The talk reviews the generation of the solar neutrino spectrum in hydrogen burning, Borexino’s experimental program that measured the rates of several fusion reactions in the proton-proton chain and its first-ever measurement of the faint neutrino signal from the solar CNO cycle. The results have been used to study the energy dependence of solar neutrino oscillations and to derive independent constraints on solar metallicity. Finally, it discusses the prospects of future neutrino (and dark matter!) experiments for solar neutrino measurements and the impact their results may have on our understanding of the Sun as a neutrino source.

Abstracts of Posters

(in alphabetical order)

Probing chromospheric fine structures with an Hα proxy in MURaM Simulations

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The 3D structure of spicules is difficult to study using observations. We use MURaM simulations, which includes a non-equilibrium (NE) treatment of hydrogen, where their full structure can be investigated. By applying a novel Hα proxy, we identify numerous off-limb spicules and on-disk rapid blue- and redshifted excursions (RBEs and RREs) in an enhanced network simulation.

An analysis of an RBE in the simulations, observed at a Doppler shift of 37 km/s, revealed that it is driven by flux emergence and magnetic reconnection. Lorentz forces compress the plasma, generating pressure gradients that propel a jet along the field line containing the RBE. We further find a heating front associated with it, driven by viscous and resistive heating, propagating at Alfv´enic speeds.

We also investigated multiple off-limb spicules in the simulations with the Hα proxy and found both type I and type II spicules. Their apparent speeds range from 20 km/s to 190 km/s. Two spicule-like features with distinct morphologies — one with a sheet-like structure and the other tube-like were studied. The sheet-like feature exhibits an apparent speed of 190 km/s, attributed to the rippling effect of a plasma sheet along the line-of-sight. The tube-like feature has a lower apparent speed of 60 km/s. Both spicules have RBE counterparts.

The morphological properties and lifetimes of both spicule-like features and RBEs/RREs are comparable to observations. We find a common driving mechanism for the studied features where the work is done by Lorentz force, driving flows by the build-up of gas pressure gradients.

How Much Are We Missing? Observational Limits on Magnetic Helicity Transport in Emerging Magnetic Structures

Gwangson Choe, Sunjung Kim and Sibaek Yi

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Magnetic helicity transport through the solar surface is a key quantity in understanding solar activity and coronal dynamics. In principle, this transport can be determined with high precision by tracking the motion of magnetic field footpoints — assuming infinite spatial resolution. However, at the polarity inversion line (PIL), footpoint velocities formally diverge during flux emergence or submergence, creating a "blackout region" where helicity flux estimates become unreliable. This raises an important question: how much helicity flux is systematically underestimated due to this observational limitation?

To quantify this effect, we model the emergence of Gold-Hoyle and Lundquist force-free flux ropes through the photosphere and compute the associated helicity injection, explicitly excluding contributions from the blackout region near the PIL. Our results show that when the blackout region spans just one-tenth of the flux rope's diameter, nearly 50% of the helicity flux remains unaccounted for. Since we assume perfect resolution outside this region, real-world estimates are likely subject to even larger underestimates — particularly for small-scale emerging structures.

These findings highlight a fundamental observational limit in measuring magnetic helicity transport and underscore the need for careful interpretation of helicity flux in solar active regions.

f-mode travel-time signature of sunspot models and plages

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Two main models have been proposed to describe the magnetic subsurface structure of sunspots: the monolithic model and the cluster model. However, despite its relevance, this problem remains an important open question and challenge in current solar physics. In this work, we investigate the travel-time signature of two sunspot models such as the above, using numerical simulations of surface gravity (*f*-mode) wave propagation. We have shown that the travel-time shift and caustics patterns can be used to distinguish between a monolithic and a clustered model, as well as to differentiate between a compact and a loose cluster configuration [1].

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The Daniel K. Inouye Solar Telescope observations of shock waves triggered by magnetic vortices

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Chromospheric image sequences recorded with the Daniel K. Inouye Solar Telescope (DKIST) have revealed propagating arc-shaped bright fronts that originate from chromospheric bright grains seen at the center of the arc. Photospheric G-band bright points located underneath the chromospheric bright grains are found to interact with co-located vortices prior to the appearance of the chromospheric bright fronts. Using realistic three-dimensional magnetohydrodynamic simulations, we have been able to identify events that show a striking similarity with the observed phenomenon. These simulations reveal that the arc-shape structures are weak shock fronts triggered by the vortex dynamics of the underlying magnetic flux concentration. We provide the first evidence of vortex-driven magnetoacoustic waves emanating from small-scale magnetic flux concentrations leading to an observable shock front in the ambient medium.

Gamma-ray angular distribution of the ^{3}He(α,γ)^{7}Be-reaction

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The ^{3}He(α,γ)^{7}Be reaction is the major production channel for primordial ^{7}Li (decay product of ^{7}Be). In addition, it plays an important role for hydrogen burning in the Sun, where it controls the intersection between the pp-I and pp-II chains. Its cross section has been studied previously, by ^{7}Be activation, by recoil detection, and by in-beam γ detection. However, the γ-ray studies typically used just one detector in close geometry, leading to some dependence on the theoretically predicted γ-ray angular distribution.

We have measured the γ-ray angular distribution at energies E = 450-1220 keV at the Felsenkeller 5MV underground accelerator, using an α-beam on ^{3}He-implanted solid targets and 20 germanium detectors. In addition, we have measured the absolute astrophysical S-factor at one energy, 1213 keV, by activation with underground low-level counting.

We will compare the data with new predicted angular distributions from a hybrid theory that blends clusterbased effective field theory and phenomenological approach.

Radial and Latitudinal Structure of the Sun: Icosahedral Symmetry?

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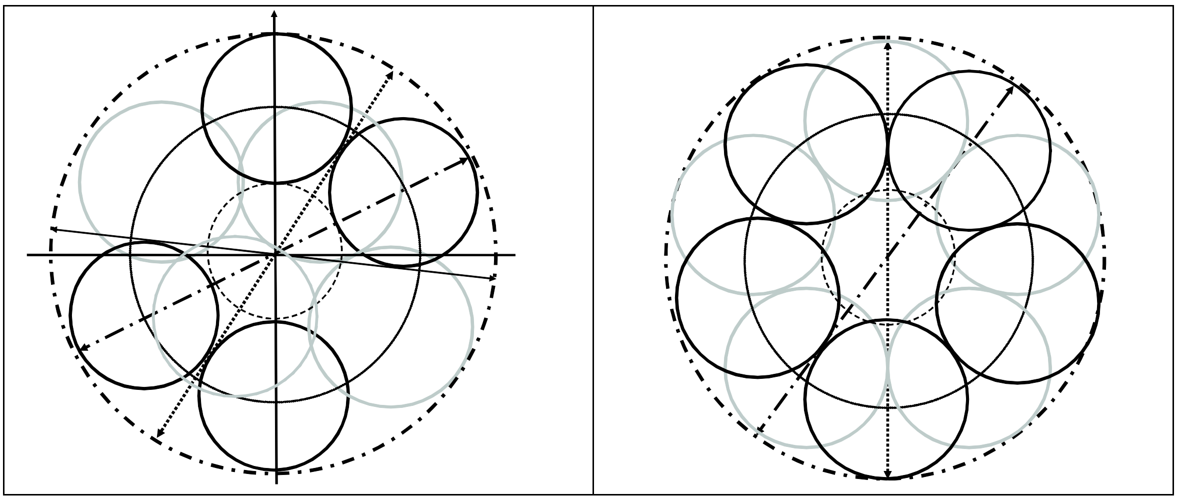
The radius r_1 of the energy-generating solar core is constrained to be ≈ 0.30 R_{SUN} based on neutrino detections [1], or up to ≈ 0.315 R_{SUN} in some standard solar models. The radius r_2 of the fully radiative zone with *fully* rigid rotation, based on helioseismological measurements by MDI and HMI, is 0.65 ± 0.01 R_{SUN} [2]. These two radii are consistent with a three-layer radial structure with icosahedral symmetry within the circumscribing sphere with radius R, verified for exactly r_1 = 0.3108… R and r_2 = 0.6554… R [3]. A central sphere with radius r_1 is tangential to twelve spheres with radius r ' = 0.3445…. R : two hemispheric sets consisting of a polar sphere and five "toroidal" spheres in a plane perpendicular to the polar axis. The centers of the "toroidal" spheres lie at latitude ± $\tan^{-1}(1 / 2)$ = ± 26.56...° vs. the equator. In the Sun, ≈ 26.6° is the typical latitude of the first sunspots at sunspot minimum [4]. In the icosahedral geometry, in each hemisphere an axial cone is defined at latitude 58.28…° by the circle threading the tangential points between the five "toroidal" spheres. In the conical isorotation surfaces inferred from measurements by MDI and HMI in the bulk of the convective zone, the only radial meridional isotach i_{rad} is at 58° ± 2° latitude [5]. This demarcation line between two differential-rotation regimes with opposite gradients is approximately superposed with the variable boundary of unipolar caps at 55°-60°.Yet, in GONG inversions, i_{rad} > 61° latitude and r_2 < 0.63 R_{SUN}.

Meridional View | Polar View



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Multi-line spectroscopy of a sunspot with a strong light bridge

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A detailed spectroscopic study was conducted on a mature, unipolar, round sunspot with a fully developed penumbra. The sunspot was observed on 2019 May 15, using the echelle spectrograph at the Vacuum Tower Telescope (VTT) at the Observatorio del Teide in Tenerife, Spain. During its evolution, the sunspot developed light bridges that divided the umbra into three distinct cores of negative polarity. The spectroscopic dataset comprises spatially resolved scans of the Cr I, Hα, and Hβ lines and covers a field of view of 104" × 194". These high-resolution, ground-based observations are complemented by full-disk synoptic data from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO). Spectroscopic diagnostics provide insights into line-of-sight (LOS) velocities and other spectral line properties from the photosphere to the chromosphere. Applying Background-subtracted Solar Activity Maps (BaSAMs) to the Cr I data reveals a ring of enhanced photospheric activity surrounding the sunspot, which is consistent with SDO observations. In the chromosphere, an extensive and stable Hα filament, as confirmed by Hα BaSAMs, is present throughout the VTT observations. The spectroscopic analysis indicates height-dependent velocity gradients, with increasing Doppler velocities from the photosphere to higher layers. The light bridge exhibits persistent, near-zero redshifts at photospheric heights, while a related, jet-like feature is blueshifted. The opposite sides of the penumbra exhibit red- and blue-shifted flows that reverse in the chromosphere, particularly in Hβ. Blueshifts dominate both the umbra and the light bridge in both Hα and Hβ, with the strongest values in the moss region and the associated jet. These results underscore the effectiveness of multi-line spectroscopy in probing the interaction between magnetic and flow structures in sunspots across atmospheric layers.

Simulation of sunspots in the chromosphere

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Sunspots are one of the most prominent features of the solar surface and are characterized by a dark central core called the umbra, which is surrounded by a collection of filamentary structures called the penumbra. The penumbra is on average considerably brighter than the umbra but darker than the surrounding quiet Sun. At the photospheric level, the nearly horizontal Evershed flow is directed outward from the outer edge of the umbra along penumbral filaments. On the other hand, in the chromosphere, the flow is reversed and the plasma flows inwards towards the umbra. Radiative magneto-hydrodynamic (rMHD) codes have simulated sunspots in the upper convection zone and photosphere (Heinemann et al., 2007; Rempel, 2009). Models of sunspots that include a realistic treatment of the chromosphere and corona have not yet been performed. However, strong magnetic field regions such as sunspots and active regions are the location at which the initiation of solar flares and other eruptive phenomena that drive space weather occurs. The structure and evolution of the chromospheric field will be important in understanding magnetic reconnection and processes that are important for flare initiation. In this poster, we will present preliminary simulations that extend the previous simulations higher into the solar atmosphere.

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Stereoscopic disambiguation of solar vector magnetic fields using observations from SO/PHI and SDO/HMI

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The solar vector magnetic field is inferred from spectropolarimetric observations of the polarization in magnetically sensitive spectral lines. However, the transverse component of the magnetic field has a 180° ambiguity in its orientation. Traditional single-view methods for resolving the ambiguity require assumptions on the properties of the photospheric magnetic field[1]. Solar Orbiter (SO), and its onboard magnetograph (the Polarimetric and Helioseismic Imager, PHI), make it possible for the first time to avoid such an assumption, and to remove the 180° ambiguity purely using observations from two different vantage points. The Stereoscopic Disambiguation Method (SDM), which was developed based on this idea, has been successfully tested on simulated data and first science data from the High Resolution Telescope (SO/PHI-HRT) acquired in spring 2022[2,3]. In this work, we applied the SDM to a number of SO/PHI-HRT datasets and corresponding datasets from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO). The SDM successfully disambiguates the vector magnetograms in strong field areas, and for a large range of separation angles between the viewpoints. Quantitative diagnostic metrics on different observational configurations were studied to evaluate the reliability of the SDM in localized areas. Furthermore, we compared the disambiguation results obtained by the SDM and the most widely used, single view-point disambiguation method.

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Quasi-Periodic Pulsations in EUV Brightenings

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Extreme-ultraviolet (EUV) observations have revealed small-scale transient brightenings that may be caused by the same physical mechanisms as larger-scale solar flares[1,2,3]. A notable feature of solar and stellar flares is the presence of quasi-periodic pulsations (QPPs), which are a potentially intrinsic characteristic[4]. We investigated the properties of QPPs detected in EUV brightenings, which are considered to be small-scale flares, and compared their statistical properties with those observed in solar and stellar flares[5,6]. We extracted integrated light curves of 22,623 EUV brightenings in two quiet Sun regions observed by the Solar Orbiter/Extreme Ultraviolet Imager and identified QPPs in their light curves using Fourier analysis. Approximately 2.7% of the EUV brightenings exhibited stationary QPPs. The QPP occurrence rate increased with the surface area, lifetime, and peak brightness of the EUV brightenings. The detected QPP periods ranged from approximately 15 to 260 seconds, which is comparable to the periods observed in solar and stellar flares. Consistent with observations of QPPs in solar and stellar flares, no correlation was found between the QPP period and peak brightness. However, unlike the trend observed in solar flares, no correlation was found between the QPP period and the lifetime or length scale. The presence of QPPs in EUV brightenings supports the interpretation that these events may be small-scale manifestations of flares.

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Correlation of Microwave Signatures in Solar Flares and Near-Earth Solar Energetic Particle Spectra

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Within previous studies, the relationship of microwave signatures in solar flares and in-situ Solar Energetic Particle (SEP) fluxes and spectra has been investigated. This study continues and expands earlier efforts, considering both electron and proton signatures in relation to solar microwave emission in the 8-17 GHz range.

The primary aim of the study was to confirm previous results, using new and corrected data products, and to find new empirical relationships between microwave radiation in solar flares and SEP events, for potential operational use in forecasting.

We found 38 events between the years 2000 and 2024 that were suitable for analysis. The data quality for all events was critically assessed and corrected when necessary. Fluences of the microwave bursts and peak fluxes of the particle events were calculated, considering both electrons and protons across a wide energy range. The resulting data set was then subjected to statistical analysis. We also introduced renewed restraints on confinement in the corona and the magnetic connection of the spacecraft to the flare site, using WIND/WAVES measurements of type III bursts as evidence of escaping electrons.

We confirmed positive correlations between microwave fluences and proton peak fluxes in the tens of MeV range, as well as electron peak fluxes from a few keV up to approximately 1.1 MeV. In contrast, protons in the 250–800 MeV range show no clear association with microwave emission, with several events exhibiting strong microwave bursts but lacking high-energy proton enhancements. No significant correlations were found of the spectral hardness of the SEPs and flare characteristics in the 8-17 GHz range, for either protons or electrons within the studied energy ranges. However, the electron-to-proton peak flux ratio appears to be related to the ratio of microwave fluences at 8–9 GHz to those at 15–17 GHz. In most cases, the limitations regarding magnetic connection and confinement resulted in an increase in correlation quality.

While some findings from previous studies were confirmed, others — despite apparent visual correlations — lack statistical significance. Larger, comparative studies, which extend both to further wavelengths in the GHz/MHz range and to other particle energies, are necessary in order to make statements about the underlying acceleration and transport processes.

MRI in Rotating Flows: Implications for the Solar Tachocline and Dynamo Processes

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Angular momentum transport via the magnetorotational instability (MRI) is central to astrophysical disk dynamics. Alongside its helical (HMRI) and azimuthal (AMRI) counterparts, the MRI's relevance to dynamo processes is well-established. Here, we discuss a novel axisymmetric MRI that emerges in viscous and resistive rotating flows with positive shear – a configuration directly applicable to the solar equatorial tachocline – under the influence of a helical magnetic field and the condition of a non-unity magnetic Prandtl number. This instability offers a potential avenue for understanding magnetic activity in this crucial solar region. Furthermore, we address the experimentally under-explored interaction between thermal convection-driven turbulence and the AMRI, a phenomenon of broad astrophysical significance. Our linear analysis demonstrates that convection lowers the critical Hartmann number for AMRI onset. It’s implication on the dynamo process at magnetic Prandtl number =<1 will also be discussed. These findings collectively advance our understanding of magnetized rotating flows in both astrophysical and solar contexts, opening new avenues for future research.

PyAstroPol: A Python Package for Polarization Ray Tracing

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Astronomical telescopes and instruments alter the radiation which they collect in a multitude of ways. One of the key aspects, instrumental polarization (IP), describes how the state of polarization of an incident beam is altered by the optics. This would lead to inaccurate measurements of the state of polarization i.e., polarimetry. In order to rectify these effects, polarizing properties of the optical system are to be determined thoroughly through experiments, analysis or a combination of both. *PyAstroPol* aims to produce the IP models for the astronomical optics by means of polarized ray tracing as well as considering the interference effects to some degree. It is an attempt to eliminate the reliance on expensive optical modelling software that are hard to incorporate into instrument data pipelines.

Advanced Gas Target Techniques for Nuclear Astrophysics

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At the underground Dresden Felsenkeller laboratory, an innovative gas target system has recently been installed and commissioned. Designed for operation in both jet and static modes, this state-of-the-art apparatus enables comprehensive studies of nuclear astrophysics reactions that underpin our understanding of nucleosynthesis processes following the Big Bang, within solar and stellar burning, and during explosive astrophysical events. In this contribution, the unique features and capabilities of the combined gas target system will be discussed and preliminary results from our recent investigation of the $^{14}N(\alpha,\gamma)^{18}F$ reaction will be presented.

Heating, magnetism and geometry of small-scale coronal loops

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Abstract

Coronal bright points (CBPs) are ubiquitous, highly energetic events that are often seen accompanying other dynamic and eruptive phenomena in the solar atmosphere. Their large energy output, their similarity to active regions and their connections to other events make them especially interesting to understand the solar corona [2].

The main constituents of CBPs are small-scale coronal loops. We aim to understand these structures in terms of how they are being heated and sustained for the typical lifetime of a CBP (hours to days) [2], and compare the characteristics of simulated loops to recently-published observational data [3].

We extract and analyse the hottest loops of three different state-of-the-art r-MHD Bifrost [1] simulations of CBPs. We explore their magnetic and geometrical properties to obtain statistical insights about the average hot loop. Additionally, we study the heating and cooling mechanisms acting on the loops, a fundamental aspect to accurately model the energy balance of these structures and their contribution to the coronal heating.

The simulated loop properties are found to be well in agreement with the results by [3], the first detailed study of this kind found in the literature. For the heating/cooling, we find enhanced conductive heating focused on the footpoints in all cases and, only for 3D simulations, very strong Joule heating in the footpoints, in accordance with the results by [4]. This suggests the presence of a strong source of entropy stemming from magnetic reconnection at the footpoints, which is consistent with other findings in this work and is only revealed when performing 3D simulations.

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Active region evolution from different viewpoints

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The evolution of active regions has long been studied from Earth's vantage point with data from instruments such as the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO). It has allowed uninterrupted monitoring of the photospheric magnetic field of active regions, but only while they transit the Earth facing solar hemisphere. Complementary methods, like helioseismic far-side imaging indicate whether an active region is present on the Sun's far side but remain limited by the lack of magnetic field information. Thus, the complete evolution of the magnetic flux of an active region - from its emergence through its eventual decay - has so far not been quantitatively studied.
The ESA/NASA Solar Orbiter mission allows observing the Sun from different vantage points. Among its suite of instruments, the Polarimetric and Helioseismic Imager (SO/PHI) is the first to acquire polarimetric data of the solar photosphere from outside the Sun-Earth line. The spacecraft moves on a unique heliocentric orbit, allowing it to observe the Sun for extended periods each year at a longitudinal separation greater than 130º from the Sun-Earth line. Then, it has a good view of the solar far side, giving access to direct observations. During these periods, SO/PHI performs regular synoptic observations.
The combination of SO/PHI's direct observations of the magnetic field on the solar far side with data from HMI allows following and probing active regions well beyond the very limited window available from a single viewpoint. The almost uninterrupted tracking enables studying the evolution of active regions over multiple solar rotations.
In this contribution, we present results of active regions tracked over several solar rotations, which in some cases means over their full lifetime. Thus, the connection of the magnetic field of these active regions with the structure and dynamics of the overlying corona can be determined with almost no interruption over their full lifetimes by combining SO/PHI and HMI data with those from extreme ultraviolet instruments on Solar Orbiter and SDO.

Towards a reconstruction of the annual solar Irradiance over the past 9 millennia

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The Sun, being the nearest star to Earth, sets the conditions for life on Earth and is one of Earth's climate change drivers. Space-based observations since the late 1970s have detected variations in solar irradiance. However, the length of this record is insufficient for a reliable assessment of the role of the Sun in climate variability. Consequently, reconstructions of past solar irradiance variations are needed. Irradiance variability on climate-relevant time scales is primarily driven by the solar surface magnetism in the form of dark sunspots, bright facular, and the network. Thus, reconstructing past solar irradiance requires information about the historical solar magnetic activity. The longest direct proxy of solar activity is the sunspot number, which has been recorded over the past 400 years and which can be used to account for the sunspot darkening. However, direct proxies of the facular brightening cover a significantly shorter period of time. This is unfortunate, as it is the component that is most important for understanding the long-term irradiance changes. We use the Spectral And Total Irradiance REconstructions (SATIRE) model, recently revised to account for the emergence of small-scale magnetic features when only sunspot observations are available, to reconstruct solar irradiance from the directly observed sunspot number. Our reconstruction shows a good agreement with the directly measured irradiance changes, with a correlation coefficient of over 0.9.

Indirect proxies of solar activity, such as concentrations of cosmogenic isotopes, e.g., 14C and 10Be, in terrestrial archives allow reconstructions of sunspot numbers over yet longer periods of time. In particular, sunspot numbers derived from cosmogenic isotope data extend back nine millennia but are only available with decadal resolution. Thus, information about individual solar cycles is lost, except for the last millennium, where unique, very accurate 14C measurements recently allowed a reconstruction of annual sunspot numbers. Based on earlier findings that the solar cycle strength and length are generally correlated with the mean overall solar activity level, we first study the relationships between the decadally averaged sunspot numbers and various solar cycle parameters and validate this approach using a synthetic record of decadally averaged sunspot numbers for the telescopic era. We find a fair agreement with the observed

record and apply the derived relationships to reconstruct the annual sunspot number and then irradiance over the nine Millennia.

First 3D inversion of a solar prominence

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Solar prominences, dense plasma structures suspended in the million-degree corona, are critical to understanding solar magnetic fields and their dynamics. Traditional spectropolarimetric inversions, relying on one-dimensional or slab geometries, have been limited by their inability to capture multidimensional radiative transfer effects and resolve the 180° ambiguity in magnetic field orientation, leading to conflicting reports. This talk presents the first application of POLARIS, a consistent 3D inversion code, in real prominence observations. This novel approach overcomes the limitations of prior methods by simultaneously solving the three-dimensional radiative transfer equations and inferring the full magnetic vector. Using spectropolarimetric data of a prominence, we reconstructed the magnetic field, temperature, density, and velocity fields within a prominence, providing insight into its three-dimensional structure and dynamics. In addition, uncertainty estimation was performed, highlighting the importance of high-quality data with high S/N and resolution. This method accounts for complex physical processes, including the Hanle and Zeeman effects, and ensures physical consistency across the model. Our results reveal the intricate interplay of magnetic and plasma properties, offering new perspectives on prominence stability and topology. This pioneering work paves the way for future studies to resolve long-standing debates about prominence magnetic configurations and their role in solar activity, enhancing our understanding of the Sun's dynamic atmosphere.

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Initial steps in the inference of horizontal velocity fields in the solar atmosphere

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The inference of horizontal velocity fields in the solar atmosphere is of fundamental importance, as it facilitates the study of electric currents, Poynting flux, and gas pressure. The present work addresses the inverse problem of the induction equation in ideal magnetohydrodynamics, aiming at deriving the horizontal velocity components in the solar atmosphere. Our approach assumes that spectropolarimetric inversions provide direct access to $\mathbf{B}(x, y, z)$, $v_z(x, y, z)$ and $\frac{\partial \mathbf{B}}{\partial t}$.
Our methodology consists in discretizing the system of partial differential equations into a linear system via 5-point centered finite differences. Next, this is validated through synthetic analytical test cases, which are used to demonstrate the effectiveness of the approach under different boundary conditions and constraints. These test cases are set up on a case-by-case basis. At present we are able to determine $v_y(y, z)$, as well as $v_x(x, y)$ and $v_y(x, y)$.
The ultimate objective of this method is to achieve the reconstruction of the complete horizontal velocity field in the three-dimensional domain $v_x(x, y, z)$ and $v_y(x, y, z)$ from inversion-derived data, thereby providing a more physically consistent perspective on plasma flows in the solar atmosphere.

Space Weather and Earth´s Climate

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Space Weather in the Earth system is significantly influenced by the magnetic Sun and Cosmic Radiation from the distant Universe. It exerts a highly complex influence on the climate in the various atmospheric layers of the Earth and in the oceans.

Fascinating illustrations and videos will provide a clear overview of the diverse influences.

Using modern data to understand historical solar observations

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Solar irradiance is one of the key external forcing agents of Earth's climate. To quantify the effect of its variability on climate, knowledge of past irradiance changes over as long periods of time as possible is required. As direct measurements are only available for less than a half-a-century, this necessitates reconstructions of irradiance with the help of models. The main driver of irradiance changes on climate-relevant timescales is the solar surface magnetism, and thus proxies of past solar magnetic activity are crucial for such reconstructions. One such proxy is the brightness of the Sun in the Ca II K spectral line.

Images of the Sun in Ca II K have been taken since 1892 at different sites around the globe, with data from individual observatories covering different time intervals. Combining these data has the potential to give insight into changes in solar surface magnetism and thus irradiance over more than a century. However, such a combination requires accounting for differences in instruments and observational settings. One crucial issue is varying passbands among and across the various observational archives.

To study the effect of different passbands on the Ca II K observations, we make use of the recent state-of-the-art data provided by the balloon-borne observatory Sunrise 3. Using high spectral-resolution Sunrise 3 data, we simulate different passbands used in historical archives and study the relationships between Ca II K intensity as would be observed with such filters. These results will allow a cross-calibration of various historical observations.