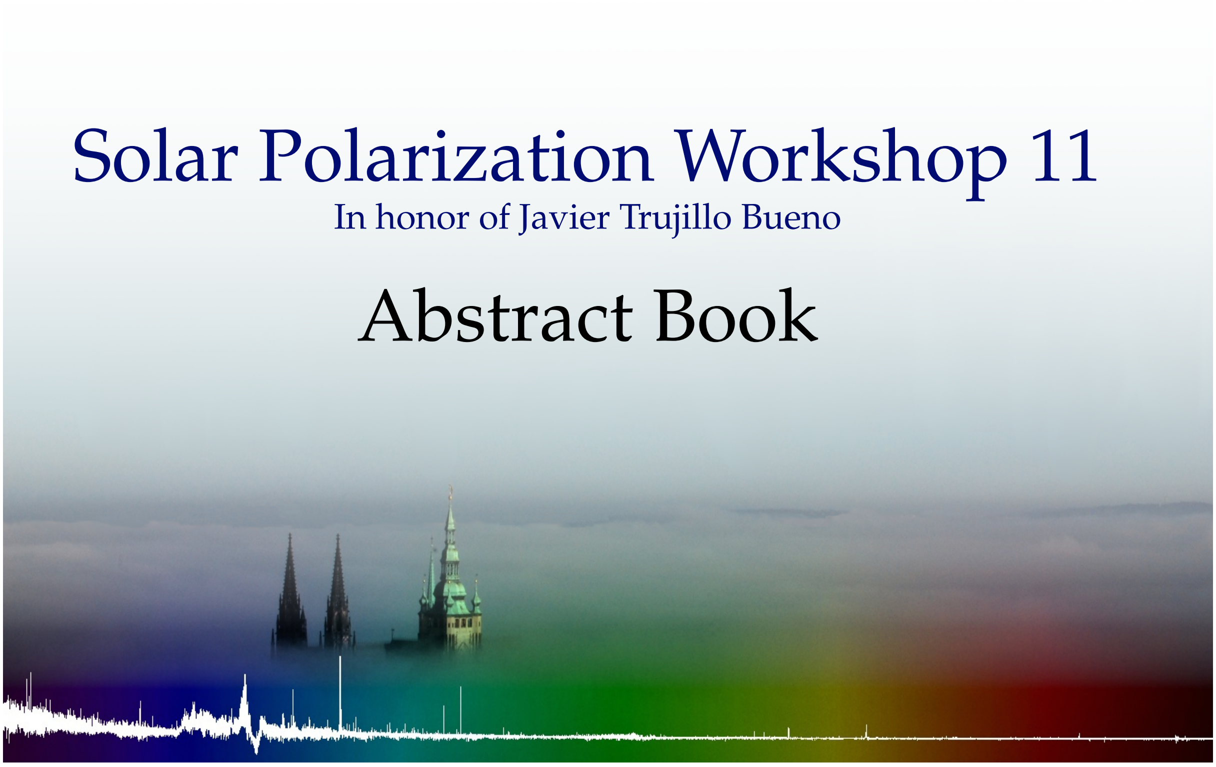
Solar Polarization Workshop 11

In honor of Javier Trujillo Bueno

Abstract Book



Session 1

Instrumentation

Talks

THEMIS: a calibration-free solar telescope

V. Bommier[1] and B. Gelly[2]

[1] LIRA, Observatoire de Paris, 5 place Jules Janssen, 92190 Meudon, France
[2] THEMIS, Tenerife, Canary Islands, Spain

`contact e-mail:` *V.Bommier@obspm.fr*

THEMIS was initially built as a calibration-free telescope, with the polarization analysis performed in F1 focus, before any oblique reflection. Recently, the telescope was improved with installation of an Adaptive Optics apparatus. Owing to an adaptation of all the oblique reflections below the telescope, we would like to show you that it remains a calibration-free telescope, even if the two beams able to provide the light polarization, are now separated before the cameras only. We present you raw images on a sunspot, with two lines: one polarisable line, which displays the sunspot magnetic field polarization, linear and circular, and one unpolarisable line, which does not display any polarization, which shows that the telescope is free of any instrumental polarization, because, if this line had showed any polarization, this polarization would have been of instrumental origin. Those images were recorded on 2024 September 12th.

From TIP@VTT to GRIS@GREGOR: 25+ years of successful near-infrared spectropolarimetry at the Observatorio del Teide

M. Collados

Instituto de Astrofísica de Canarias

`contact e-mail:` *manuel.collados@iac.es*

The Tenerife Infrared Polarimeter (TIP) saw first light at the German VTT of the Observatorio del Teide (Tenerife) in 1998 and was offered as a common-use instrument to the whole community the year after, in 1999. The instrument gave the community access to the near infrared window, from 1 to 2.3 microns, with the range 1 to 1.8 microns offered with spectropolarimetric capabilities and the 2 micron region just in pure spectroscopy. The most popular wavelength intervals were centered at 1.083 and 1.565 microns. Since then, the instrument has gone through a number of improvements that have finally led to its present configuration GRIS (GREGOR Infrared Spectrograph) operating at the German GREGOR telescope, with a three-arm setup for simultaneous observations in several wavelengths. A scanning slit or a slicer-based integral field unit can be selected by the user without a large exchanging effort. In this communication, I will review the main results achieved at both, VTT and GREGOR, since the start of operations.

Polarimeter to UNify the Corona and Heliosphere (PUNCH): Mission Status and First Light

C. E. DeForest, S. E. Gibson, and the Punch Team

Southwest Research Institute National Center for Atmospheric Research

contact e-mail: *craig.deforest@swri.org*

PUNCH comprises a constellation of four spacecraft, launched on 11-Mar-2025, to image the entire inner heliosphere and understand how the solar corona transitions to the solar wind. We will present mission structure and design, early results, status, and information on how to work with PUNCH.

The Sunrise III UV Spectropolarimeter and Imager: New High-Resolution Data of our Sun in the Near-UV

Alex Feller[1], Achim Gandorfer[1], Johannes Hölken[1], Francisco A. Iglesias[1,6], Andreas Lagg[1], Tino L. Riethmüller[1], Sami K. Solanki[1], Thomas Berkefeld[2], Pietro Bernasconi[3], Yukio Katsukawa[4], Jose Carlos del Toro Iniesta[5], and Sunrise III Team

[1] Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany
[2] Institut für Sonnenphysik (KIS), Georges-Köhler-Allee 401a, 79110 Freiburg, Germany
[3] Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland, USA
[4] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[5] Instituto de Astrofísica de Andalucía, Glorieta de la Astronomía s/n, 18008 Granada, Spain
[6] Grupo de Estudios en Heliofísica de Mendoza, CONICET, Universidad de Mendoza, Boulogne sur Mer 683, 5500 Mendoza, Argentina

`contact e-mail:` *feller@mps.mpg.de*

In July 2024 the balloon-borne solar observatory Sunrise successfully completed its third science flight. The stratospheric observatory carried three entirely new post-focus science instruments, all with full spectropolarimetric capabilities, and concurrently covering an extended spectral range from the near ultraviolet (down to 309 nm) to the near infrared (up to 855 nm), largely unaffected by seeing and absorption caused by the Earth's atmosphere. The focus of the significantly upgraded Sunrise III was on sampling a larger height range, from the low photosphere to the chromosphere, providing information on the height-dependent interaction between the magnetic field and hydrodynamic processes. This was achieved close to the diffraction-limited resolution of the Sunrise 1-m telescope, and includes datasets spanning several hours for studies of solar dynamics. The Sunrise UV Spectropolarimeter and Imager (SUSI) is a scanning slit spectrograph covering the range between 309 nm and 417 nm. This extended window includes spectral regions showing a high density of spectral lines, which have so far not been explored at high spatial resolution. A key capability of SUSI is its ability to record up to several hundred spectral lines simultaneously. The rich SUSI spectra can be exploited in terms of many-line inversions and are expected to provide a three-dimensional view of the solar atmosphere with unprecedented height resolution and level of detail. In addition to the spectrograph SUSI also includes a 2D context imager, with two phase-diversity channels for image restoration. In this contribution we describe the main design aspects of SUSI as well as its operation and in-flight performance. We also provide an overview of the extensive dataset as well as briefly highlight a few first results that have already been obtained by the Sunrise team.

Development of SoWiSP, a wide spectral coverage spectropolarimeter

M. Galloway, D. Paillon, and L. Kleint

Astronomical Institute, University of Bern, Sidlerstrasse 5, Bern CH-3012, Switzerland

`contact e-mail:` *michelle.galloway@unibe.ch*

The Solar and stellar Wide Spectral coverage Polarimeter, SoWiSP, is a dedicated instrument for investigating time-dependent energetics of solar flares. With four-state polarisation measurements and a field-of-view the size of an average sunspot, the instrument, currently in the development phase, will allow to probe changes in the solar magnetic structure with a target spatial resolution of 5 arcseconds. The latter is achieved with the use of an integral field unit, which allows for simultaneous spectral acquisition for a spatially multiplexed 60 x 60 arcsecond field-of-view. Unique among spectropolarimeters is its large spectral range in the visible regime, which includes the Balmer continua from 350 nm up to the chromospheric Ca II 854.2 nm line, with a spectral resolving power of 30k at 600 nm. This presentation will describe the science goals, instrument requirements and status of SoWiSP, with emphasis on its unique capabilities for investigating the underlying mechanisms behind solar flares.

Proba-3, ASPIICS coronagraph and polarimetry

S. Gunár

Astronomical Institute of the Czech Academy of Sciences

contact e-mail: *gunar@asu.cas.cz*

Proba-3 is the new mission of ESA that will deliver unprecedented observations of the solar corona. That is possible thanks to the unique technology of formation flying, which allows the construction of the giant space coronagraph ASPIICS. Coronagraph ASPIICS, distributed over both satellites of Proba-3, provides high-resolution observations of coronal structures from the low reaches of the solar corona (field of view from 1.1 to 3.0 solar radii). The contribution of Proba-3/ASPIICS to the polarimetric studies of coronal structures has a dual character. In a straightforward way, ASPIICS has the capability to observe corona in the polarized white light (5350-5650) thanks to the set of polarized filters (-60°, 0°, +60°). Moreover, thanks to its low reach, high resolution, and long observing windows (6 hours in a single orbit), ASPIICS will provide detailed information about the orientation, inner structure, and evolution of coronal features from streamers to eruptive prominences and CMEs. This, in collaboration with other instruments (e.g. Solar Orbiter/Metis), will allow more precise investigation of the coronal magnetic field.

Optimizing the signal content of integral field spectropolarimeters

Michiel van Noort

Max-Planck inst. for solar system research

`contact e-mail:` *vannoort@mps.mpg.de*

Over the past decade the development of a number of high resolution spectropolarimetric integral field instruments (IFS) in combination with advances in image restoration techniques have produced high spectral spatial and temporal resolution observations of the solar atmosphere, revealing the solar atmosphere to be a highly structured and dynamic environment. Although the process of image restoration typically preserves the SNR of the raw data and is in addition highly effective in suppressing seeing induced cross-talk, the restored data ruthlessly expose the limited signal produced by even the most magnetically sensitive spectral lines at the highest spatial resolution permitted by the telescope aperture. This problem escalates rapidly with increasing size of the telescope aperture, where a decreased dynamic time scale and an increased resolution requirement render non-IFS instruments (such as slit scanning spectrographs) ineffective. An effective way to circumvent this issue is to increase the number of signal carrying spectral lines by increasing the spectral range, thus boosting the total signal content of the data. A new broadband microlens based IFS (MiHI) is planned that is able to observe a spectral range of up to 30A, allowing for more than 100 spectral lines to be observed simultaneously, without making any compromises regarding the spatial and temporal resolution of the data.

Lithium Niobate Fabry-Pérot Interferometer: Roadmap for Development

H. Pruthvi[1], M. Sigwarth[1], S. Schwinde[2], R. Geiss[2], H.-P. Doerr[1], and M. Roth[1]

[1] Thüringer Landessternwarte (TLS), Sternwarte 5, 07778 Tautenburg, Germany
[2] Fraunhofer-Institut für Angewandte Optik und Feinmechanik (IOF), Albert-Einstein-Straße 7, 07745 Jena, Germany

`contact e-mail:` *pruthvi@tls-tautenburg.de*

Tunable filters are an integral part of the astronomical instrumentation for the so-called imaging spectroscopy, spectral imaging or hyperspectral imaging applications. Fabry-Pérot Interferometers (FPI) have long been used as tunable filters due to their salient advantages such as high transmission, wide wavelength range of operation and high-speed tuning. Solar astronomers are in favour of two flavours of FPIs: piezo-tunable airgap FPIs and electro-optic solid FPIs. The latter were typically constructed with Lithium Niobate, a synthetic electro-optic crystal, and to our knowledge, they are no longer produced for optical interferometric applications. We, at TLS Tautenburg, in cooperation with IOF Jena, aim to revive its development with better specifications, especially larger aperture for large field of view applications like full solar disc observations.

A stray light correction for SO/PHI-HRT, and an updated cross-calibration with SDO/HMI

J. Sinjan[1], T. L. Riethmüller[1], A. Gandorfer[1], D. Calchetti[1], J. Hirzberger[1], G. Valori[1], and S. K. Solanki[1]
[1] Max Planck Institute for Solar System Research, Göttingen, Germany.

contact e-mail: *sinjan@mps.mpg.de*

The High Resolution Telescope of the Polarimetric and Helioseismic Imager on Solar Orbiter (SO/PHI-HRT) functions in an extreme observational environment. It captures a 0.28 x 0.28 degree field of view, and at perihelion Solar Orbiter is at distance of 0.28 au. The high thermal load and the large illuminating field puts high demands on the instrument in terms of both imaging performance and false light control. Both, in-field and out-of-field straylight within the instrument particularly affect the intensity in any dark regions in the photosphere. From limb observations and a Mercury transit we have quantified the amount of false light within the SO/PHI-HRT instrument and added a correction to the point spread function we nominally use to partially reconstruct the images. We will present the resulting change in the inferred magnetic field vector and continuum intensity, which is particularly stark in the sunspot and plage regions. Finally an updated cross-calibration between SO/PHI-HRT and SDO/HMI will be shown, highlighting a much closer agreement between the two magnetographs in the strong field regions.

The European Solar Telescope: Status Update

H. Socas-Navarro

European Solar Telescope Foundation

`contact e-mail:` *hector.socas@est-project.eu*

The European Solar Telescope (EST) represents a major leap forward in solar physics, aiming to provide unprecedented insights into the Sun's magnetic and dynamic behavior at small spatial and temporal scales. With a 4-meter aperture and cutting-edge instrumentation optimized for high-resolution spectropolarimetry, EST is designed to address key scientific questions concerning the solar atmosphere and its complex magnetic coupling. In this talk, I will present the current status of the EST project, highlighting recent milestones achieved and the ongoing developments in preparation for the construction phase. Special focus will be given to the progress in telescope design and the development of a broad international collaboration within the framework of the EST Foundation.

30 years SPWs — Time for an Assessment

Jan Stenflo

Institute for Particle Physics and Astrophysics, ETH Zurich, CH-8093 Zurich, Switzerland, and
IRSOL Istituto Ricerche Solari "Aldo e Cele Daccò", Università della Svizzera Italiana, via Patocchi 57, CH-6605 Locarno, Switzerland

contact e-mail: *stenflo@astro.phys.ethz.ch*

Modelers and theoreticians continually need magnetic field data while often forgetting that magnetic fields are not observables. What is observed is the polarization of the light from astrophysical objects. The translation from observables to physical parameters depends (1) on the limitations of the instrument used, (2) on the approximations of the theory used to describe the matter-radiation interaction in magnetized media with light scattering, and (3) on the idealizations used to model the structure of the medium. The prime task of the SPW community is to focus on this translation problem. Since our community is relatively small, there have often been well-meaning suggestions to merge our SPW meetings with more mainstream solar physics symposia to integrate us with the dominating fashions. The SPW organizers have however consistently resisted such efforts, because our rationale would then get abandoned: The rationale to explore a vital interface and foundational area of astrophysics that is not addressed by the mainstream. This is the area where we are needed, now and in the future.

DKIST - Capabilities and results achieved with ViSP

Alfred de Wijn

U.S. National Science Foundation National Center for Atmospheric Research, Boulder, Colorado 80305, USA

contact e-mail: *dwijn@ucar.edu*

Since the discovery that sunspots are highly magnetized by Hale in the early 1900s, magnetism has become increasingly important in our understanding of processes on the Sun and in the Heliosphere. Many current and planned instruments are capable of diagnosing magnetic fields in the solar atmosphere through spectro-polarimetry. Four out of five "first-light" instruments of the Daniel K. Inouye Solar Telescope are polarimeters. The Visible SpectroPolarimeter (ViSP) is one of these instruments, designed to operate in the visible and near-infrared spectrum. I will briefly review the history, importance, and challenges of measuring magnetic field in the solar atmosphere, and describe the ViSP, its capabilities, and recent scientific highlights.

Session 1

Instrumentation

Posters

Advancing high-precision spectropolarimetry with the installation of ZIMPOL at GREGOR: current status and future plans

Andrea Francesco Battaglia[1], Renzo Ramelli[1], Francesco Vitali[1], Franziska Zeuner[1], Daniel Gisler[1], Michele Bianda[1], and Svetlana Berdyugina[1]
[1] Istituto Ricerche Solari Aldo e Cele Daccò (IRSOL), Locarno, Switzerland

`contact e-mail:` *andrea.francesco.battaglia@irsol.usi.ch*

Solar spectropolarimetric observations play a crucial role in diagnosing magnetic fields throughout the solar atmosphere as well as detecting anisotropies in radiation fields and collisional processes. High sensitivity polarimetric observations enable the study of faint polarization signals, particularly those arising from scattering processes in both the quiet Sun and active regions, including flares. The Zurich Imaging Polarimeter (ZIMPOL) represents a state-of-the-art instrument that minimizes seeing-induced spurious effects, which usually limit polarimetric precision, through its fast modulation capabilities (up to 42 kHz). This design allows to achieve a precision of 10^{-5} in fractional polarization units.
Following the optical optimization of the GREGOR telescope in Tenerife, the aim is to investigate small-scale structures by studying solar magnetism through high-precision polarimetric observations using ZIMPOL at the largest European solar telescope. In addition, we aim to continue offering the ZIMPOL system to a broader community and implement a remote observing mode with ZIMPOL. Several observing campaigns have been carried out successfully, and more are planned, particularly in preparation for the installation of the ZIMPOL system at GREGOR, complementing existing instruments to explore the visible part of the solar spectrum. This poster presents the current status and future plans of the ZIMPOL at GREGOR project.

The Wide-band High-resolution Imaging Spectro-Polarimetric Explorer (WHISPER) for the 1.6-meter Goode Solar Telescope

W. Cao[1], V. Yurchyshyn[1], H.-P. Doerr[2], J. Chae[3], and M. van Noort[4]

[1] Big Bear Solar Observatory/New Jersey Institute of Technology, USA
[2] Thüringer Landessternwarte Tautenburg, Germany
[3] Seoul National University, South Korea
[4] Max Planck Institute for Solar System Research, Germany

`contact e-mail:` *doerr@tls-tautenburg.de*

Adaptive optics and image restoration have enabled solar spectropolarimetry at an angular resolution on a par with imaging, but photon noise limits the diagnostic power of such high-resolution data. This is a problem of increasing severity for larger telescopes because the solar evolution time scale decreases as aperture increases, further limiting the photon collection time. WHISPER, a next-generation facility instrument under development for the GST at the Big Bear Solar Observatory, addresses this by instead expanding in the wavelength dimension to collect more photons. The instrument is specifically designed for many-line inversion schemes, which simultaneously invert dozens or even hundreds of spectral lines, leading to more precise and accurate inference of atmospheric parameters. WHISPER's primary wavelength passband spans 10 nm, from 516 to 526 nm, which includes the chromospheric Mg I triplet at 517 nm, the well known Fe I line pairs near 525nm, as well as a plethora of additional spectral lines, many of which with a significant magnetic sensitivity. While the fundamental noise problem and the benefits of many-line inversion are covered elsewhere in this workshop, this contribution focuses on the specifics of the instrument which is expected to see first light in 2027.

SoWiSP: An Echelle spectropolarimeter for flare observations

D. Paillon, M. Galloway, and L. Kleint

Astronomical Institute, University of Bern, Sidlerstrasse 5, CH-3012, Bern, Switzerland

`contact e-mail:` *dorian.paillon@unibe.ch*

The Solar and stellar Wide Spectral coverage Polarimeter (SoWiSP) is a ground-based spectropolarimeter, tailored for observing solar and stellar flares. It is currently under development by the Space Weather group at the University of Bern.
SoWiSP is being developed in two versions: a solar and a stellar instrument, the former additionally including an integral-field unit. Its design features an Echelle spectrograph with a double-beam setup, targeting a polarization sensitivity of 10^{-3}. I have conducted spectroscopy simulations for Echelle instruments with Python while the global optical design has been performed with Code V.
The nighttime instrument will be installed and commissioned at the Swiss Optical Ground Station (OGS) in Zimmerwald, with privileged access to a 80 cm Ritchey-Chrétien telescope, for long-term monitoring of flaring M-dwarfs. We aim to obtain first light in 2025.

I will present the current status and future developments of the stellar version of SoWiSP, with a focus on its optical capabilities as well as the planned observation strategy at the Swiss OGS.

The Multi-slit Spectro-Polarimeter for the 2.5-meter Wide-field and High-resolution Solar Telescope

Z. Xu[1], Y. Zhong[1], Z. Li[2], M. D. Ding[2], C. Fang[2], Q. Hao[2], Q. Liu[3], S. Liu[3], and X. T. Mi[3]

[1] Yunnan Observatories, Chinese Academy of Sciences, Kunming, 650011, China
[2] Nanjing University, School of Astronomy and Space Science, Nanjing, China
[3] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun, China

`contact e-mail:` *xuzhi@ynao.ac.cn*

We developed a multi-slit spectropolarimeter for the 2.5-meter wide-field and high-resolution solar telescope of China (WeHoST) with the ability to simultaneously observe the full Stokes profiles of the Fe I 617.3 nm and Mg I b 517.3 nm lines within a solar region up to 300 arcsec $\times$ 300 arcsec. Being a spectrograph, four slits are employed, achieving a spectral resolution of approximately 0.001 to 0.0014 nm and a spectral band of about 0.7 nm for each slit. A polarimeter, which is based on a dual-beam setup, has been equipped with this spectrograph and adopts a spatial-temporal modulation scheme. It includes an achromatic waveplate as a modulator and a polarizing beamsplitter as an analyzer. In addition, an assembly is designed to calibrate the instrument polarization of the telescope. Here we present the main characteristic of the design, layout, and the current state of this spectrograph

Session 2

Observations and Data Analysis

Talks

Investigating the evolution of the magnetic field during a X-class flare using the spatially-coupled STiC

D. Arramy and J. de la Cruz Rodriguez . A. Pastor Yabar

Institute for Solar Physics, Dept. of Astronomy, Stockholm University, AlbaNova University Centre, 106 91 Stockholm, Sweden

`contact e-mail:` *dimitri.arramy@astro.su.se*

Active regions can store magnetic energy over large structures in form of magnetic twist. Eventually, the magnetic configuration becomes unstable a the field reconnects to a lower energy configuration, closer to a potential field, releasing the energy excess in the form of heat, radiation and kinetic energy. In this study, we perform inversions of a time series of an X-class flare observed in the Fe I 6173 and Ca II 8542 A lines. We study the spatial distribution and time evolution of magnetic fields in the photosphere and chromosphere during the reconnection process and their relation with other physical parameters from the model. This study is also new in that it employs a spatially-coupled NLTE inversion method (spatially-coupled STiC) to derive the model atmosphere.

Superstrong magnetic fields are common in bipolar light bridges

S. Castellanos Durán[1], A. Korpi-Lagg[1], and S. Solanki[1] M. van Noort[1]

Max Planck Institute for Solar System Research, Germany

`contact e-mail:` *castellanos@mps.mpg.de*

Bipolar light bridges (BLBs) are bright features in sunspots located between two umbrae with opposite magnetic polarity. Recent observations revealed intriguing cases of BLBs with very strong magnetic fields of the order of 8.2 kG. Since these observations were only a handful, it is a question of whether BLBs with extraordinarily strong fields are very rare. We used the most extensive set of spectropolarimetric observations of sunspots with BLBs compiled so far, consisting of data acquired with Hinode/SOT-SP. We analyzed these data using a state-of-the-art inversion technique, which accounts for the data degradation caused by the intrinsic PSF of the telescope. We identified 98 individual BLBs within 51 distinct sunspot groups. Since 66% of the identified BLBs were observed multiple times, our sample contained a total of 630 spectropolarimetric scans. Our analysis showed that 89% of the (individual) BLBs contain magnetic fields stronger than 4.0 kG, at the height of maximum magnetic sensitivity, with even higher field strengths in deeper layers. We also found that BLBs display a unique continuum intensity and field strength combination, forming a population well-separated from the umbrae and the penumbrae.

Spectropolarimetry: deciphering the magnetism of the Sun and stars

M. J. Martínez González

Instituto de Astrofísica de Canarias, Tenerife, Spain

`contact e-mail:` *m.j.martinez@iac.es*

It is well known to this audience that spectropolarimetry remains the only method capable of providing quantitative and reliable information about magnetic fields. For over a century, the analysis of the Sun's polarised spectrum has unveiled a wealth of physical mechanisms governing the interaction between solar plasma and magnetic fields. This includes the discovery of the magnetic nature of sunspots, the solar magnetic cycle and its polarity reversals, and the presence of small-scale, chaotic magnetic fields even in the quietest regions of the solar atmosphere. In this talk, I will present how spectropolarimetric observations have advanced our understanding of the Sun's magnetic field, with a particular focus on my research field. I will also highlight how this work helps bridge our solar knowledge to the study of magnetic fields in other stars.

Progress towards routine full-disk NLTE inversions of the SOLIS/VSM Ca II 854 nm observations

Sanjay Gosain

National Solar Observatory

`contact e-mail:` *sgosain@nso.edu*

Routine NLTE inversions of the full-disk spectropolarimetric observations in the Ca II 854 nm spectral line, by the SOLIS/VSM instrument, presents us with a rather challenging task. This is due to the vast amount of spectral profiles (3 million) and the time-consuming iterative complex NLTE radiative transfer computations needed to find the best-fit model atmosphere. We present some strategies that we have experimented with in dealing with this problem. Apart from using parallel computation, we study the neural-network approach, K-means clustering approach, and searching a library of pre-calculated spectra from a grid of model atmospheres. We present our results and discuss the pros and cons of each approach.

Magnetic field and waves in solar prominences

K. Ichimoto[1,2], Y. Hashimoto[2], D. Yamasaki[3], Y. Huang[2], S. Ueno[2], A. Asai[2], and T. T. Ishii[2]

[1] Ritsumeikan Univ., Shiga, Japan
[2] Faculty of Science, Kyoto Univ., Kyoto, Japan
[3] JAXA, Kanagawa, Japan

`contact e-mail:` *ichimoto@kwasan.kyoto-u.ac.jp*

The magnetic field of solar prominences is an important ingredient that governs their presence, structure and destabilization process. A number of studies on the magnetic field have been conducted by spectro-polarimetric observations, but the field direction and strength of prominences are still discrepant among the studies partly due to the ambiguity inherent in the Stokes inversion. In this study, we performed spectro-polarimetric observations of about ten prominences on the solar limb including both quiescent and active region prominences in He I 10830 A using the Domeless Solar Telescope at Hida Observatory. Using the HAZEL code, magnetic fields of each prominence were derived, and it is found that the field strengths of quiescent prominences are less than 40 G, which is consistent with previous studies, while the field strengths of active region prominences are less than 120 G, which is inconsistent with some of the previous studies which estimated field strengths of on-disk active region filaments as 400 - 800 G. To determine the field direction which suffers from the 90 deg. ambiguity in the Hanle diagnosis, we focus on the Alfvenic wave propagating across the prominences, i.e., if it is detected, the direction of the propagation will directly infer the direction of the magnetic field. Motivated by this idea we investigated more than 100 prominences on the solar limb using fulldisk H-alpha images taken by Solar Dynamics Doppler Imager at Hida Observatory. It is found that the waves with a period of about 4min propagating with a coronal Alfven speed across the prominences are quite common for side-view prominences, and their propagation direction is mostly horizontal with respect to the solar limb rather than vertical. The fact that the waves are observed only in Doppler signal but not in intensity suggests the incompressive, or Alfvenic, nature of the waves. This finding supports the horizontal field configuration for majority of the prominences.

Overview of the scientific discoveries of the CLASP missions

R. Ishikawa[1], R. Kano[1], A. Winebarger[2], D. McKenzie[2], J. Trujillo Bueno[3], Frédéric Auchère[4], N. Narukage[1], D. Song[5,1], T. J. Okamoto[1], L. Rachmeler[6], and Clasp team

[1] National Astronomical Observatory of Japan, Tokyo 181-8588, Japan
[2] NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
[3] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[4] Institut d'Astrophysique Spatiale, F-91405 Orsay Cedex, France
[5] Korea Astronomy and Space Science Institute, Daejeon 305-348, Republic of Korea
[6] National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Boulder, CO 80305, USA

`contact e-mail:` *ryoko.ishikawa@nao.ac.jp*

The magnetic field in the solar atmosphere plays a crucial role in the transfer of energy from the photosphere to the corona. The layer, where the ratio of gas pressure to magnetic pressure equals unity, is located in the chromosphere, and in the upper chromosphere, the magnetic field dominates the structuring and dynamics of the plasma. Therefore, measuring the magnetic field in this region is critical for understanding solar activity in both the chromosphere and the corona. To achieve this, we must measure and model the polarization of ultraviolet (UV) spectral lines that originate in the upper chromosphere, as they encode valuable information about the magnetic fields. To this end, a series of sounding rocket experiments CLASP were conducted in 2015 (CLASP), 2019 (CLASP2), and 2021 (CLASP2.1). The first flight succeeded in the spectropolarimetric observations of the hydrogen Lyman-a line (121.57 nm), achieving high polarization sensitivity and accuracy of 0.1%. For the first time, CLASP detected linear polarization produced by the scattering of anisotropic radiation in VUV lines and observed polarization signals indicative of the Hanle effect in the upper solar chromosphere. In the second and third flights, by refitting the CLASP instrument, we carried out spectropolarimetric observations across the Mg II h k lines, which are also strong UV spectral lines of great interest for probing the magnetic fields in the upper chromosphere. These missions yielded unprecedented measurements of polarization signals caused by the joint action of scattering processes and the Hanle, Zeeman and Magneto-Optical effects. Furthermore, through coordinated observations with the Solar Optical Telescope (SOT) aboard the Hinode satellite, we produced magnetic field maps extending from the photosphere to the upper chromosphere in an active region. In this talk, we summarize the scientific findings from the series of CLASP experiments.

First near-continuous monitoring of NOAA 13664 from emergence to decay: magnetic field evolution, complexity parameterization and flaring output

I. Kontogiannis[1,2], Y. Zhu[1], K. Barczynski[3], S. Berdyugina[2], and L. K. Harra[1,3]

[1] ETH-Zurich, Hönggerberg campus, HIT building, Zürich, Switzerland
[2] Istituto Ricerche Solari Aldo e Cele Daccò (IRSOL), Locarno, Switzerland
[3] PMOD/WRC, Dorfstrasse 33, 7260, Davos Dorf, Switzerland

`contact e-mail:` *ikontogianni@phys.ethz.ch*

Between April and August 2024, the Solar Orbiter mission monitored a significant portion of the Sun's far side, enabling near-continuous tracking of one of the most complex active regions ever recorded—from emergence to decay. We combined full-disk line-of-sight magnetograms from SO/PHI and SDO/HMI to construct a 94-day time series of deprojected maps of the line-of-sight magnetic field of NOAA AR 13664 and its follow-ups, NOAA 13697 and 13723. This dataset was complemented by EUV coronal imaging from EUI/FSI and AIA (171/174 Å), along with flare detections from STIX and GOES. The region evolved into an extremely complex configuration due to repeated flux emergence events, reaching peak complexity roughly one month after its initial appearance. This was followed by a prolonged, gradual decay phase lasting about six weeks, during which sporadic flux emergence continued, and subsequently by a more rapid decay that led to the region's disappearance. Flaring activity was exceptionally intense near the peak phase, with multiple X-class flares culminating in an X16 event. Although flare output decreased significantly afterward, it remained elevated for over one month before dropping sharply during the final two weeks. Using the combined magnetogram data, we derived time series of four non-potentiality parameters—the longest such dataset to date for a single active region. Despite originating from two different instruments, the parameter values are consistent, capturing the region's full evolution and showing strong correlation with the flare index. These results highlight the critical role of multi-vantage-point observations in understanding the evolution of the magnetic field during flux emergence and the causes of active region eruptivity.

SUNRISE III/SCIP observations of three-dimensional magnetic fields in the solar atmosphere

M. Kubo[1], Y. Katsukawa[1], Y. Kawabata[1], T. Oba[2], T. Matsumoto[3], R. T. Ishikawa[4], Y. Naito[5], T. Shimizu[6], H. Hara[1], F. Uraguchi[1], T. Tsuzuki[1], K. Shinoda[1], T. Tamura[1], Y. Suematsu[1], J. C. del Toro Iniesta[7,8], D. Orozco Suarez[7,8], M. Balaguer Jimenez[7,8], C. Quintero Noda[9], S. K. Solanki[2], A. Korpi-Lagg[2], and SUNRISE-3 team

[1] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[2] Max-Planck-Institut fur Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 G ottingen, Germany
[3] Institute for Space-Earth Environmental Research, Nagoya University, Furocho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
[4] National Institute of Fusion Science, 322-6 Oroshi-cho, Toki, Gihu 509-5292, Japan
[5] The Graduate University for Advanced Studies, SOKENDAI, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[6] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
[7] Instituto de Astrofiısica de Andaluciıa (IAA-CSIC), Glorieta de la Astronomia s/n, 18008 Granada, Spain
[8] Spanish Space Solar Physics Consortium, S3PC
[9] Instituto de Astrofiısica de Canarias, 38205 La Laguna, Tenerife, Spain

`contact e-mail:` *masahito.kubo@nao.ac.jp*

Precise polarization measurements of numerous spectral lines across a broad wavelength range are essential for exploring the three-dimensional structures of the magnetic field in the solar atmosphere. They provide fundamental insights into the heating mechanisms and dynamic phenomena in the solar atmosphere. The third flight of the SUNRISE balloon-borne stratospheric solar observatory successfully completed 6.5 days of observations in July 2024. One of the focal-plane instruments onboard SUNRISE is the Sunrise Chromospheric Infrared Spectro-Polarimeter (SCIP) that is a slit-scanning spectropolarimeter to measure the polarization state of multiple spectral lines in the 850 nm and 770 nm wavelength bands, including chromospheric and photospheric lines, with the spatial resolution of 0.2". SCIP has obtained unprecedented spectropolarimetric data for various solar targets, including the quiet Sun regions, emerging flux regions, dark filaments, flares, and off-limb regions. In these targets, we find the interesting Stokes profiles associated with fine-scale three-dimensional structures in the photosphere and chromosphere. In this presentation, we will summarize the initial findings from SUNRISE III/SCIP.

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

X. Li, G. Valori, D. Calchetti, S. K. Solanki, J. Hirzberger, and J. Sinjan

Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

`contact e-mail:` *lixiang@mps.mpg.de*

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. Solar Orbiter (SO), and its onboard magnetograph (the Polarimetric and Helioseismic Imager, PHI), make it possible for the first time to refrain fromavoid 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. 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.

Interpretation of IFU spectropolarimetric observations of solar plage photosphere

G. Liu[1], J. Buttler[1], I. Milic[1,2,3], M. van Noort[4], J. M. Borrero[1], J. S. Castellanos Duran[4], and Christoph Kuckein[5,6]

[1] Institute for Solar Physics (KIS), Georges-Köhler-Allee 401A, 79110 Freiburg, Germany
[2] Faculty of Mathematics, University of Belgrade, Studentski Trg 16, 11000 Belgrade, Serbia
[3] Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
[4] Max-Planck Institute für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37079 Göttingen, Germany
[5] Instituto de Astrofísica de Canarias (IAC), Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain
[6] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

`contact e-mail:` *milic@leibniz-kis.de*

The development of the Microlensed Hyperspectral Imager (MiHI) prototype enabled an acquisition of high-spatial resolution, high-spectral fidelity, high-cadence spectropolarimetric data sampling the photosphere and chromosphere at visible wavelengths. Multiple datasets have been collected over the last decade, some of which contain magnetically sensitive spectral lines. In this contribution, we present the first efforts to invert these data using a depth-stratified spectropolarimetric inversion code with magnetohydrostatic (MHS) constraints - FIRTEZ. We focus on the two datasets that probe two different plage regions near the disk center and contain two distinct spectral regions: one around the Fe I 630 nm doublet, and the second around the Sodium D1 line. By inverting time-dependent, high-resolution data, we essentially obtain the magnetic and thermodynamic structure of the plage photosphere in 4D (x,y,z,t). We report the detection of persistent, very small-scale opposite polarities around the magnetic elements of the plage that manifest as low-lying loops and are revealed by the MHS inversions. We also present an observation of a collapsing granule and the spectropolarimetric signatures of the collapse, which we attempt to study through the comparison with the synthetic spectra from a very high-resolution (5 km) MHD CO5BOLD simulation.

A Detailed Polarimetric Study of a Type-II Solar Radio Burst with MWA

Puja Majee[1], Devojyoti Kansabanik[2,3], and Divya Oberoi[1]

[1] National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune, India
[2] University Corporation for Atmospheric Research, Boulder, CO, USA
[3] Hosted at Johns Hopkins University, Applied Physics Laboratory, Laurel, MD, USA

`contact e-mail:` *pujamajee@gmail.com*

Type-II solar radio bursts are plasma emissions generated by collisionless shocks in the corona and interplanetary space, typically driven by energetic solar eruptions such as flares and coronal mass ejections (CMEs). Their close association with such large-scale eruptions makes them relevant for space weather studies as well. The geoeffectiveness of a CME largely depends on the properties of the magnetic field it carries and how it interacts with the ambient solar magnetic field. Therefore, probing the magnetic field entrained in CMEs is crucial. The polarimetric properties of type-II bursts offer one of the few remote-sensing tools available for directly studying the strength and topology of magnetic fields in CME-driven shocks. However, reported polarization levels in the literature span a broad range, from negligible or weak polarization to strong circular polarization of several tens of percent. Most of the earlier studies are based on Sun-as-a-star observations, which provide spatially averaged measurements. Given the presence of multiple active regions and spatially varying polarized emission on the Sun, such integrated measurements are susceptible to beam depolarization, potentially leading to inaccurate results. To overcome these limitations, spatially resolved imaging is essential. The advent of new-generation instruments, like the Murchison Widefield Array (MWA), has made it possible to obtain high-dynamic-range, high-fidelity full-polar solar radio images with good temporal, spectral, and angular resolution. Leveraging these capabilities, we have conducted a detailed polarimetric imaging study of a type-II solar radio burst. Our analysis includes characterization of sources in both total intensity and polarized emission, along with an in-depth examination of their temporal and spectral evolution. This study represents an important step toward using polarimetric imaging to advance our understanding of type-II bursts and coronal propagation.

IRSOL: spectropolarimetry in solar flares

F. Vitali, A. F. Battaglia, R. Ramelli, and S. Berdyugina

IRSOL (Locarno) and Università della Svizzera Italiana (Lugano), Switzerland

contact e-mail: *francesco.vitali@irsol.usi.ch*

Spectropolarimetry has still much to offer in the study of solar flares, this is a possibility we are addressing with our IRSOL flare observation program. Specifically, we are running spectropolarimetric observations whose range includes the He I D3 5876 Åline, using the slit-spectrograph setup and occasionally the Fabry-Pérot.
Thanks to the high precision provided by the ZIMPOL polarimeter, we were able to clearly detect linear polarization in the He I D3 line during a solar flare event. Our analysis strongly suggests that this polarization originates from anisotropy in the radiation field. Although not yet observed, we think that He I D3 line could be used for the investigation of flare-accelerated particles and their impact in the lower atmosphere.

Magnetic field diagnostic of solar filaments with spectropolarimetric observations in He I 1083nm

D. Yamasaki[1], Y. Huang[2], Y. Hashimoto[2], S. Ueno[2], and K. Ichimoto[3]

[1] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

[2] Astronomical Observatory, Kyoto University, Kitashirakawaoiwake-cho, Kyoto, 606-8502, Japan

[3] College of Science and Engineering, Ritsumeikan University, 1-1-1, Nojihigashi, Kusatsu, Shiga, 525-0058, Japan

`contact e-mail:` *yamasaki.daiki@jaxa.jp*

Solar filaments are dense cool plasma in the solar corona. They are supported in a dip of coronal magnetic field. There are two classical models of magnetic field configuration of solar filaments; one is the normal polarity model proposed by Kippenhahn Schlueter (1957), and the other is the reverse polarity model proposed by Kuperus Raadu (1974). These two models are identified by the tilt direction between the magnetic field of the filament and polarity inversion line (PIL). To understand the mechanism that makes filaments unstable before their eruptions and/or solar flares, it is critical to confirm the magnetic field configuration of solar filaments. Previously, we have performed the He I 1083 nm spectropolarimetric observation targeting on quiet sun filaments with the Domeless Solar Telescope at Hida Observatory. We found that the magnetic field strength was 8-35 G and majority of the magnetic field configuration was reverse polarity (Yamasaki et al. 2023). In this study, we performed the same observation but targeting on an active region filament, which appeared in AR NOAA 13092 on September 5, 2022. The observation was carried out one hour after C class flare. As a result of our analysis of full Stokes profiles, we found the followings: deviation of the filament position from the PIL of about 10000 km, magnetic field strength of the filaments of 101 ± 33 G, and counter-streaming flow along the filament axis with about 10 km/s. By comparing the direction of the magnetic field in filaments and the global distribution of the photospheric magnetic field, we suggested that the magnetic field configuration of the filament was intermediate of the two classical models, i.e., magnetic field of the filament was almost parallel to the PIL. In our presentation, we will also discuss the interpretation of strong Zeeman-like Stokes profiles found in linear polarization, and disambiguation method in our Stokes inversion.

Penumbra formation: An observational study of the photosphere and chromosphere in three dimensions.

Jonas Zbinden and Lucia Kleint

Astronomical Institute, University of Bern

`contact e-mail:` *jonas.zbinden@unibe.ch*

The formation of sunspots is generally well understood, with the exception of penumbra formation. Two main mechanisms have been proposed to explain its onset: Flux emergence triggering the development of penumbral filaments, and a reconfiguration of the chromospheric magnetic field to a more horizontal orientation. During our observation campaign at the Swedish Solar Telescope (SST) in May 2022, we obtained high-resolution spectropolarimetric observations of a forming penumbral sector, covering both the photosphere and the chromosphere. To compute the magnetic field, we applied Milne-Eddington and weak field approximation techniques, as well as the multi-atom non-LTE inversion code STiC, to fit full Stokes profiles of FeI 6302 Å and CaII 8542 Å. We found that strong horizontal magnetic fields in the chromosphere, exceeding 500 G, are a key prerequisite for penumbra formation. At the site of initial filament development, we observed localized flux emergence accompanied by strong redshifts (2–3 km/s) throughout the atmospheric layers. We interpret these redshifts as field-aligned horizontal flows, possibly indicating a siphon flow evolving into the Evershed flow. The forming penumbral filaments were temporarily disrupted but reformed shortly after, with no significant change in the chromospheric horizontal magnetic field component. We conclude that a strong horizontal magnetic field in the chromosphere is a necessary boundary condition, while flux emergence initiates the growth of penumbral filaments. The interaction between the chromosphere and photosphere during penumbra formation remains not fully understood. We aim to address this with further observations during upcoming campaigns at SST to study this interplay in more detail.

DKIST resolves sub-arcsec photospheric scattering polarization

F. Zeuner[1], E. Alsina Ballester[2], R. Casini[3], D. M. Harrington[4], T. del Pino Alemán[2,5], J. Trujillo Bueno[2,5,6], and L. Belluzzi[1,7]

[1] IRSOL Istituto Ricerche Solari "Aldo e Cele Dacco", Università della Svizzera italiana, CH-6605 Locarno, Switzerland
[2] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[3] High Altitude Observatory, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307-3000, USA
[4] National Solar Observatory, Makawao, Hawaii, United States
[5] Departmento de Astrofísica, Facultad de Física, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
[6] Consejo Superior de Investigaciones Cientifícas, Spain
[7] Euler Institute, Università della Svizzera italiana (USI), CH-6900 Lugano, Switzerland

`contact e-mail:` *zeuner@irsol.ch*

The scattering polarization in the Sr I 4607 Å spectral line is a powerful diagnostic for probing microturbulent magnetic fields in the solar photosphere. However, measuring its spatial variations remains an observational challenge due to the weak polarization signals involved. In this talk, we present new high-resolution spectropolarimetric observations from ViSP@DKIST, capturing resolved scattering polarization maps in quiet Sun regions at various limb distances. Our observational approach enables the first direct identification of sub-arcsecond structures in the Sr I line's linear polarization. Power spectrum analysis confirms an effective spatial resolution of 0.2, pushing the observational limits of solar scattering polarization. These results highlight the potential of DKIST in advancing our understanding of small-scale magnetic structures and the turbulent surface dynamo in the solar photosphere.

Session 2

Observations and Data Analysis

Posters

Magnetic Field Vector Structure of a Sunspot During a Solar Flare

M. Benko and P. Gömöry

Astronomical Institute Slovak Academy of Sciences Tatranská Lomnica 059 60 Vysoké Tatry

contact e-mail: *mbenko@astro.sk*

This poster presents an analysis of spectro-polarimetric data of the sunspot in active region NOAA 13079, acquired on August 13, 2022, using the GREGOR Infrared Spectrograph (GRIS) and the High-resolution Fast Imager (HIFI). The observations targeted photospheric spectral lines (Ca I, Si I) and the chromospheric spectral line (He I). We aim to investigate the magnetic and dynamical properties in the atmosphere above the sunspot, spanning from the photosphere to the chromosphere. A spectral-line inversion technique was employed to infer the magnetic field vector from the full-Stokes profiles. Our objective was to calculate the magnetic properties of the sunspot throughout the solar flare event.

Challenges and Solutions for PUNCH Polarimetry

C. E. DeForest, S. E. Gibson, D. B. Seaton, R. Patel, and the Punch Team

Southwest Research Institute National Center for Atmospheric Research

`contact e-mail:` *craig.deforest@swri.org*

The PUNCH mission science requires exquisite linear polarimetry at the 1E-5 level compared to the background: while the science requirements only specify roughly 2% polarimetry to locate features in 3D, that is relative to the K signal from the corona (or solar wind) itself. The solar wind is observed against a background that is roughly 1,000 times brighter than the signal of intrest. The background, in turn, comprises three separate primary sources (instrument stray light, F corona, and the starfield) which are themselves polarized in different reference frames all in motion relative to one another. This challenge in background characterization and subtraction, together with the need to merge polarimetric data from four separate platforms with different, and changing, orientations in space, required rethinking the way we represent and manipulate the linear polarization state of light. Building on prior work with tri-polarizer systems, we developed the "MZP" system of virtual polarizer triplet channels as a useful representation of polarimetry. This representation allows us to apply conventional background-estimation methods that are inaccessible with the Stokes "IQU" system. It also highlights an analogy between systems of polarimetry and systems to represent color. We will present an overview of the MZP system and how we applied it to removing three separate polarized backgrounds to extract the polarization of the visible solar wind.

Sunrise III early science - Exotic emission lines absent on the solar disk and remarkable chromospheric flows observed far beyond the limb

S. Castellanos Durán[1], S. Solanki[1], F. Iglesias[1], I. Milliç[2], A. Korpi-Lagg[1], A. Feller[1], J. Hölken[1], S. Narayanamurthy[1], T. Rietmüller[1], A. Gandorfer[1], and Sunrise team

[1] Max Planck Institute for Solar System Research, Germany
[2] Institute for Solar Physics (KIS), Germany

contact e-mail: *castellanos@mps.mpg.de*

This work analyzes spectropolarimetric limb observations taken by Sunrise III/SUSI around 409 nm. We uncovered some exotic lines that are absent in on-disk observations but visible in off-limb observations. We first identify all the lines that appear inside the limb and those that arise outside the limb. We found intriguing chromospheric emission lines, such as H-delta and Sr II, to be as far as 10 arcsecs away from the limb. We obtained the LOS velocity map off-limb lines. The velocities were determined directly and empirically from line shifts and line shapes. Emission maps show that these exotic lines cover the region of the opacity and emissivity gap.

Statistical properties of the emergence of magnetic flux sheets in the quiet Sun

S. M. Díaz-Castillo[1,2], C. E. Fischer[3,4], F. Moreno-Insertis[5,6], S. L. Guglielmino[7], R. Ishikawa[8], and S. Criscuoli[4]

[1] Institut für Sonnenphysik, Georges-Köhler-Allee 401 A, Freiburg i.Br., Germany
[2] Institute of Physics, Faculty of Mathematics and Physics, University of Freiburg, Freiburg i.Br., Germany
[3] European Space Agency (ESA) European Space Astronomy Centre (ESAC), Madrid, Spain
[4] National Solar Observatory, 3665 Discovery Dr., Boulder, CO 80303, USA
[5] Instituto de Astrofísica de Canarias, Avda. Vía Láctea S/N, 38200 La Laguna, Tenerife, Spain
[6] Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
[7] INAF – Osservatorio Astrofisico di Catania, Via Santa Sofia 78, 95123 Catania, Italia
[8] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

`contact e-mail:` *smdiazcas@leibniz-kis.de*

The emergence of small-scale magnetic flux in the quiet Sun plays a vital role in maintaining solar magnetic activity. Two emergence mechanisms have been observed within individual granules: compact magnetic loops and granule-covering magnetic flux sheets. While loops are frequently observed, evidence for flux sheet emergence is less abundant. This study statistically analyses these flux sheets, quantifying their frequency and potential contribution to the photospheric magnetic budget, and examining the associated plasma dynamics and granular phenomena. Using spectro-polarimetric data from the Hinode satellite's Solar Optical Telescope (Fe I 630.15 and 630.25 nm) and the Swedish Solar Telescope (Fe I 630.15, 630.25, and 617.3 nm), we developed a two-step method to identify flux sheet emergence. This involved detecting magnetic flux patches based on transverse and longitudinal magnetic flux density calculations and linking them to host granules via velocity field analysis. We identified 42 flux sheet emergence events, characterising their magnetic properties and the host granules' plasma dynamics. Our findings align with numerical simulations, showing a similar occurrence rate of approximately 0.3 events per day per Mm^2. Investigating the relationship between flux emergence and granular phenomena, we found that flux sheets often emerge in association with nascent granules, exploding granules, or granules with granular lanes. We highlight the potential role of recycled magnetic flux from downflow regions in facilitating flux sheet emergence. Our analysis suggests that these flux sheet events contribute to the overall distribution of small-scale magnetic flux that feeds the quiet Sun atmosphere.

On the magnetic connectivity of developing sunspots

N. Bello González[1], I. Chifu[2], M. García Rivas[3], J. Jurčák[3], R. Schlichenmaier[1], and M. Schmassmann[1]

[1] Institut für Sonnenphysik (KIS), Georges-Köhler-Allee 401A, 79110 Freiburg in Breisgau
[2] Institute for Astrophysics and Geophysics, Friedrich-Hund-Platz 1, 37077 Göttingen
[3] Astronomical Institute of the Czech Academy of Sciences, Fri˘cova 298, 25165 Ond˘rejov, Czech Republic

`contact e-mail:` *nbello@leibniz-kis.de*

While stable sunspots have been extensively studied and their global surface properties are well understood, their formation process and connectivity with its surroundings continue to elude definitive explanation. Here, we present further advancements on the mechanism(s) responsible for sunspot development through a comprehensive analysis spanning from observations of the photosphere and chromosphere, to magnetic field extrapolations, and state-of-the-art realistic 3D magneto-hydrodynamic simulations. Our findings provide clear evidence that penumbra formation begins with the emergence of sunspot magnetic flux through the solar surface, giving rise to transient penumbral filaments. As this magnetic flux continues to ascend through the solar atmosphere, a stable, low-lying magnetic canopy eventually forms. Once a sufficient amount of flux has emerged, its further rise is inhibited at the photospheric level, leading to the formation of stable penumbrae. This process is also accompanied by the formation of an enhanced magnetic network surrounding the spot, the nature of which will be further discussed.

Spectropolarimetric Diagnostics of the Solar Chromospheric Fibrils using DKIST/ViSP Observations

Sanjay Gosain

National Solar Observatory, 3665 Discovery Drive, Boulder CO 80303 USA

`contact e-mail:` *sgosain@nso.edu*

The chromosphere is a critical layer of the solar atmosphere situated between the photosphere and the corona. Studying its temperature structure is important to understand the complex dynamics and energy transfer process through these layers. We study the magnetic and thermal structure of chromospheric fibrils and an adjacent plage region using high-resolution DKIST/ViSP observations. In particular, we analyze the Ca II 854.2 nm spectral profiles of the observed region and infer the magnetic and thermal stratification with optical depth. We focus on the run of magnetic field strength, density and temperature along the length of the fibrils, as inferred with the NLTE inversion code NICOLE applied to our observations of very high spatial and spectral resolution.

Polarization Measurements of the White-Light Corona During the 2023 Total Solar Eclipse

Y. Hanaoka[1,2], Y. Sakai[2,3], and Y. Masuda[2]

[1] National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
[2] Solar Eclipse Digital Imaging and Processing Network, Tsukuba, Japan
[3] Chiba Prefectural Ichihara High School, Ichihara, Japan

contact e-mail: *yoichiro.hanaoka@nao.ac.jp*

Polarization of the white-light corona is key information for the quantitative study of the K-corona, and therefore, polarization measurements have been one of the principal topics of eclipse observations. We measured the polarization of the white-light corona during the total solar eclipse on April 20, 2023, which took place under high solar activity. Despite the short duration of totality, we were able to obtain high-accuracy polarization data. We derived the brightness and polarization of the K+F corona and estimated the brightness distributions of the K- and F-coronae using polarization information. The polarization of prominences in the continuum was also measured. We compared the eclipse data with those taken by LASCO-C2, and we found that the polarization measured by LASCO-C2 was systematically smaller (by about 30 %) than the results from the eclipse. This is the same trend that we found for the 2017 and 2019 eclipses, which took place around the solar minimum.

Metis detection of the helium D3 line polarisation in eruptive prominences

P. Heinzel[1,2], J. Štěpán[1], S. Jejčič[3], R. Susino[4], V. Andretta[4], G. Russano[4], and the Metis team

[1] Astronomical Institute, Czech Academy of Sciences, Czech Republic
[2] Center of Excellence, Wroclaw University, Poland
[3] University of Ljubljana, Slovenia
[4] INAF, Italy

`contact e-mail:` *pheinzel@asu.cas.cz*

Metis coronagraph on board of Solar Orbiter is detecting CME and eruptive prominences in hydrogen L-alpha line and in visible-light (VL) channel. VL channel between 580-640 nm provides Stokes measurements in I, Q and U. Interestingly, it contains the helium D3 emission line which is well know in prominences and its scattering polarisation provides the information about the magnetic field via the Hanle effect. We will report on the Metis VL detection of D3 emission and linear polarisation in a large eruptive prominence located very high in the corona. We will summarise theoretical aspects of the D3 line formation under prominence conditions and will outline the Metis capabilities to detect the magnetic fields in eruptive prominences.

The SUNRISE Ultraviolet Spectropolarimeter and Imager: Observations and Data Reduction

F. Iglesias[1,2], A. Feller[1], A. Gandorfer[1], T. L. Riethmüller[1], J. Hölken[1], A. Korpi-Lagg[1], J. S. Castellanos[1], K. Singh[1], M. Sanchez Toledo[2], S. K. Solanki[1], P. Bernasconi[3], J. C. del Toro Iniesta[4], Y. Katsukawa[5], and T. Berkefeld[6] . Sunrise Iii team

[1] Max Planck Institute for Solar System Research, Germany
[2] Grupo de Estudios en Heliofísica de Mendoza, CONICET, Universidad de Mendoza, Argentina
[3] Applied Physics Laboratory, Johns Hopkins University, USA
[4] Instituto de Astrofísica de Andalucía, Spain
[5] National Astronomical Observatory of Japan, Japan
[6] Kiepenheuer-Institut für Sonnenphysik, Germany

`contact e-mail:` *iglesias@mps.mpg.de*

Solar activity is fundamentally driven by its magnetic field, which is structured on small scales (10^4 - 10^5 times smaller than the solar diameter) and dynamically evolves throughout the solar atmosphere. Consequently, detailed measurements of the solar magnetic field and plasma at small spatial scales and multiple heights are required to answer some of the most difficult open questions in solar physics. Sunrise is a 1-m optical solar observatory carried aloft by a stratospheric balloon that studies magnetic fields and plasma flows with very high spatial resolution and sensitivity, by avoiding most of the seeing and absorption introduced by Earth's atmosphere. The third science flight of Sunrise took place in July 2024. The novel post-focus instrumentation includes three full-Stokes spectropolarimeters that cover wavelengths from $\approx$309 to 855 nm, to simultaneously probe the solar photosphere and chromosphere with remarkable height coverage. The Sunrise UV Spectropolarimeter and Imager (SUSI) is a scanning slit-spectrograph that operates in the 309-417 nm spectral range. SUSI includes a dual-beam polarimeter based on a rotating wave-plate and a synchronous phase-diversity, wide-band context channel used for image restoration. During the Sunrise III flight, SUSI acquired unprecedented high-spatial-resolution maps of the solar polarization in the near UV, observing hundreds of spectral lines that are not accessible from the ground. In this poster, we summarize the $\approx$ 87 h of observations, including $\approx$ 57 h of multiple science targets, recorded by SUSI with a constant full-stokes cadence of 0.256 s. We also detail the ongoing data reduction efforts and expected data products.

Highlights from the Sunrise III 2024 Campaign

Korpi-Lagg, Andreas[1], Gandorfer, Achim[1], Solanki, K. Sami[1], Feller, Alex[1], del Toro Iniesta, Jose Carlos[2], Orozco, David[2], Katsukawa, Yukio[3], Berkefeld, Thomas[4], Bernasconi, Pietro[5], Riethmüller, Tino[1], H. N. Smitha[1], and the Sunrise Iii Team

[1] MPI for Solar system Research, Göttingen, Germany
[2] Instituto de Astrofísica de Andalucía, Granada, Spain
[3] National Astronomical Observatory of Japan, Tokyo, Japan
[4] Institut für Sonnenphysik (KIS), Freiburg, Germany
[5] Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA

`contact e-mail:` *lagg@mps.mpg.de*

The Sunrise III 2024 flight was highly successful. Over the course of a 6.5-day journey in the stratosphere, departing from Kiruna, Sweden, and arriving in northwestern Canada, the balloon-borne solar observatory captured a diverse range of solar targets at the diffraction limit of its 1-meter telescope. Three instruments operated in synchronized mode to collect spectropolarimetric data in the near-UV (Sunrise UV Spectropolarimeter and Imager, SUSI), the visible (Tunable Magnetograph, TuMag), and the near-IR (Sunrise Chromospheric Imager and Polarimeter, SCIP). In this poster, we present a first glimpse into the high quality and variety of the data obtained: SUSI reveals 50-kilometer-sized structures in the solar photosphere, TuMag showcases a selection of the numerous targets observed, and SCIP demonstrates the high polarimetric sensitivity in generating maps of both the photosphere and chromosphere.

Multi-height Probing of Horizontal Flows in Solar Photosphere Using High-resolution Spectropolarimetry

T. Kostić[1], I. Milić[1,2,3], M. Rempel[4], B. Welsch[5], M. Kazachenko[6,7,8], A. Asensio Ramos[9,10], and B. Tremblay[4,11]

[1] Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
[2] Institute for Solar Physics, Georges Khöler Allee 401a, 79110 Freiburg, Germany
[3] Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski Trg 16-20, 11000, Belgrade, Serbia
[4] High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA
[5] University of Wisconsin - Green Bay, Green Bay, WI, USA
[6] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA
[7] Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Boulder, CO, USA
[8] National Solar Observatory, University of Colorado Boulder, Boulder, CO, USA
[9] Instituto de Astrofísica de Canarias (IAC), Avda Vía Láctea S/N, 38200 La Laguna, Tenerife, Spain
[10] Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
[11] Environment and Climate Change Canada, Satellite Data and Data Assimilation Research Section, Dorval, Québec, Canada

`contact e-mail:` *teodor@aob.rs*

Probing of horizontal flows refers to the ability to infer horizontal plasma motion from successive maps of photospheric intensity and/or line-of-sight magnetic field. The most commonly used method for tracking features and calculating velocities is *Local Correlation Tracking* (LCT), and its derivative FLCT (F stands for Fourier). FLCT calculates the relative displacement vector in the x, y plane between two images that makes the patterns of the two features best match each other. In this work, we test the feasibility of recovering plasma flows at multiple atmospheric heights using FLCT. Our work is based on the premise that different spectral lines probe different depths of the solar atmosphere. Namely, spectral line opacity rapidly increases as we approach the line center, with substantial changes occurring at picometer scales. Different wavelengths, experience different opacities and thus sample different layers of the solar atmosphere. In our work, multi-height diagnostic is achieved by tracking synthetic magnetograms obtained through a robust inversion of synthetic spectropolarimetric observables in two spectral lines: Fe I 525.0 nm and Mg I b2. These two lines probe the low/mid photosphere and upper photosphere/temperature minimum, respectively. We synthesized the polarized spectra of the two lines and then obtained synthetic magnetograms using Milne-Eddington inversion for the Fe I line and weak field approximation for the Mg I line. Tracking vertical magnetic fields inferred from synthetic observations of the Fe I 525.0 nm and the Mg I b2 spectral line yields satisfactory inference for the horizontal velocities in the mid photosphere and temperature minimum ($\log \tau = -1$ to $\log \tau = -3$), respectively.

Spectropolarimetric Observations of Solar Flares in the Lower Atmosphere

Noah Messerli

Astronomical Institute of the University of Bern

`contact e-mail:` *noah.messerli@unibe.ch*

Despite their importance for space weather, the physical mechanisms that trigger solar flares are still not fully understood. Polarimetric measurements offer a unique window into the evolving magnetic environment during flares, enabling us to observe rapid changes in magnetic structures and energy release. These observations play a crucial role in testing theoretical models and improving our capability to predict solar activity. Leveraging the diffraction-limited capabilities of the Swedish Solar Telescope on La Palma, we have acquired unprecedented high-resolution observations of multiple solar flares with varying intensities. Our data reveals intricate fine-scale dynamics and complex ribbon structures in the lower solar atmosphere. Spectropolarimetric data were obtained in the chromospheric CaII8542Å line, which is sensitive to magnetic fields and plasma conditions in the chromosphere, as well as the photospheric FeI6302Å line, a crucial diagnostic of the magnetic field in the lower atmosphere. Additionally, spectroscopic observations were taken in the CaIIK line to provide further chromospheric diagnostics. By applying codes such as STiC, the line profiles can be inverted under non-LTE conditions. This makes it possible to derive the height-dependent profiles of Doppler velocities, temperature, and magnetic field vectors across the field of view throughout the evolution of the flare. Polarimetric data may provide key insights into the still poorly understood aspects of flare activity, including the mechanisms that trigger flares, and may help clarify the role of the lower solar atmosphere in the processes leading up to and occurring during flares.

Recent Spectropolarimetric Observation of a Filament with THEMIS

A. W. Peat[1], A. Berlicki[1,2], B. Schmieder[3,4], and P. Heinzel[1,2]

[1] University of Wrocław, Centre of Scientific Excellence - Solar and Stellar Activity, Kopernika 11, 51-622 Wrocław, Poland
[2] Astronomical Institute, Czech Academy of Sciences, 25165 Ondřejov, Czech Republic
[3] LIRA, Observatoire de Paris, Université PSL , CNRS, Sorbonne Université, Université Paris-Diderot, 5 place Jules Janssen, 92190 Meudon, France
[4] Centre for mathematical Plasma-Astrophysics, Celestijnenlaan 200B, 3001 Leuven, KU Leuven, Belgium

`contact e-mail:` *aaron.peat@uwr.edu.pl*

The Télescope Heliographique pour l'Etude du Magnétisme et des Instabilités Solaries (THEMIS) at the Mt Teide observatory in the Canary Islands in Spain, has been fitted with a new spectropolarimeter. We wish to showcase a recent spectropolarimetric observation of a large filament viewed near the north eastern solar limb with this instrument. We also wish to present some preliminary analyses.

Dual observations of a decaying sunspot: Hinode/SP vs. SDO/HMI in magnetic field analyses

M. García Rivas[1], J. Jurčák[1], and N. Bello González[2]

[1] Astronomical Institute of the Czech Academy of Sciences, 251 65, Ondřejov, CZ
[2] Institut für Sonnenphysik (KIS), 79110 Freiburg, DE

`contact e-mail:` *marta.garcia.rivas@asu.cas.cz*

Several studies in the last few years have focused on the analysis of the magnetic properties on umbra-penumbra (UP) boundaries of sunspots (e.g. Jurčák et al. 2018, Schmassmann et al. 2018, Benko et al. 2018). Jurčák et al. 2018, using Hinode data, and Schmassmann et al. 2018, using HMI data, found a critical vertical magnetic field on UP boundaries of stable sunspots, with a different absolute value. In order to find shared characteristics between magnetic structures, solar pore boundaries have been included in the sample (e.g. García-Rivas et al. 2021). Since solar pores are more heavily affected by light contamination from quiet Sun regions than umbrae, a new dataset was employed: SDO/HMI maps corrected for scattered light (HMI_{dcon}). With the aim of running a comparison between the datasets above-mentioned (Hinode, HMI, and HMI_{dcon}), we study the continuum intensity and magnetic temporal evolution of a decaying sunspot that eventually loses its penumbra and transforms into naked spots. Spot boundaries have historically been defined by a continuum intensity threshold even though intensity maps from different instruments exhibit different intensity contrasts that affect the boundary position. The studied spot allows us to look for general dissimilarities in the selected datasets, and the influence of the nature of the spot (umbra surrounded by a penumbra / umbra without penumbra) on the derived UP boundary properties.

On the interaction of magnetic field with granular morphological properties

J. I. Campos Rozo[1,2], J. Jucak[1], and M. Van Noort[3]

[1] Astronomical Institute of the Czech Academy of Sciences, Czech Republic
[2] Observatorio Astronomico Nacional, Universidad Nacional de Colombia
[3] Max Planck Institute for Solar System Research, Germany

`contact e-mail:` *rozo@asu.cas.cz*

We perform a statistical study of the solar granulation properties, focusing on the morphological characteristics and how they are affected by the presence of magnetic fields. The dataset used in the present work is a high-resolution observational data of the active region NOAA 11768 obtained by the 1-m Swedish Solar Telescope (SST). We analyze blue-continuum filtergrams acquired with a temporal cadence of 5.6-second as well as spectropolarimetric data from the Crisp Imaging Spectropolarimeter (CRISP) with a temporal separation between images of 30 seconds. For the study we apply a two-step segmentation algorithm: the first step applies an initial local minima threshold to identify the solar granules, followed by the application of the second step which performs most of the capabilities included in the Multi-Level Tracking (MLT-4) algorithm for more accurate granulation segmentation, including erosion and expansion to fit the granular shapes. Statistical analysis shows that granulation sizes and shapes are strongly influenced by the presence of magnetic field, i.e. with granules exhibiting reduced dimensions in regions of higher magnetic strengths. These results provide a better look into the relationship between photospheric convective cells and magnetic field properties, improving our understanding of solar plasma dynamics.

Averaging active regions: Is it a viable concept?

Michal Švanda[1,2], Jan Jurčák[1], and Markus Schmassmann[3]

[1] Astronomical Institute of the Czech Academy of Sciences, Fričova 298, CZ-25165, Ondřejov, Czech Republic

[2] Astronomical Institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, CZ-18200, Prague, Czech Republic

[3] Institut für Sonnenphysik (KIS), Georges-Köhler-Allee 401A, D-79110 Freiburg im Breisgau, Germany

`contact e-mail:` *svanda@asu.cas.cz*

Solar active regions (ARs) are fundamental manifestations of magnetic activity, yet their diversity complicates efforts to extract general evolutionary patterns. We test whether ensemble averaging can provide such insight by constructing an "average" bipolar AR from observations of the Helioseismic and Magnetic Imager and Atmospheric Imaging Assembly on board SDO. The selected ARs were normalized in space and time to ensure comparable polarity orientation, emergence conditions, and disk position before computing ensemble averages of magnetograms, Dopplergrams, and multi-wavelength intensity maps. The average AR reproduces the canonical picture known from individual case studies: flux emergence, peak activity, and decay, with the leading polarity retaining coherence longer than the trailing one. Flow maps show diverging outflows preceding clear magnetic signatures, and coronal diagnostics reveal enhanced heating above the AR. These agreements validate ensemble averaging as a robust method. We show convincingly that bipolar ARs are scale-invariant: after linear spatial and temporal normalization, their evolution follows the same pattern irrespective of size. Thus, ensemble averaging not only confirms known features of AR development but also demonstrates that their evolution can be universally described once appropriately scaled. We believe this methodology opens a new window into AR research.

Session 3

Origin and Evolution of Stellar Magnetic Fields: Theories and Observational Constraints

Talks

The variability of magnetic white dwarfs

Stefano Bagnulo[1] and John D. Landstreet[1,2]

[1] Armagh Observatory and Planetarium, Armagh BT61 9DG, Northern Ireland, UK
[2] University of Western Ontario, London, Ontario N6A 3K7, Canada

`contact e-mail:` *stefano.bagnulo@armagh.ac.uk*

Most white dwarf stars do not show any variability - in fact, they are often considered flux standard stars. Because of flux stability, it is generally impossible to observe their rotation, except when they pulsate or when they have a magnetic field. Indeed, many magnetic white dwarfs exhibit a polarised spectrum that periodically varies as the star rotates because the magnetic field is not symmetric about the rotation axis. The polarisation variability comes often with subtle photometric variability. Past studies have suggested that a few old magnetic white dwarfs have extremely long rotational periods, showing at most quite small variations even on timescales of decades. This lack of obvious polarimetric (and photometric) variability has been explained by the assumption that such rare, non-varying magnetic white dwarfs have very long rotation periods of the order of centuries. Here we present a different interpretation: the lack of variability is practically the rule in old and strongly magnetic white dwarfs, and is not due to a long rotational period, but to the fact that, with time, strong magnetic fields become symmetric about the stellar rotation axis. We will present the observational evidences of this phenomenon, and discuss the mechanisms that may cause the magnetic field to align with the stellar rotation axis.

Magnetic fields in white dwarfs and neutron stars

Lilia Ferrario

Mathematical Sciences Institute, The Australian National University, ACT 2601, Canberra, Australia

`contact e-mail:` *Lilia.Ferrario@anu.edu.au*

Magnetic fields are a ubiquitous feature of compact stars, from white dwarfs to neutron stars and magnetars. Magnetic field strengths are in the range $10^3 - 10^9$G in magnetic white dwarfs (MWDs), $10^8 - 10^{13}$G in ordinary neutron stars, and up to 10^{15}G in the ultra-magnetic neutron stars known as magnetars. These fields are typically inferred through spectral modelling in MWDs and from spin-down rates in neutron stars, under the assumption of magnetic dipole radiation. Despite decades of observational and theoretical work, the origin of such fields remains a major unresolved problem in stellar astrophysics. The long-standing fossil field hypothesis suggests that magnetic fields are inherited from earlier evolutionary stages and survive stellar collapse. However, this explanation struggles to account for the observed absence of MWDs in detached binaries with non-degenerate companions. This inconsistency has led to increasing support for an alternative scenario: that many MWDs—and possibly some magnetars—form through stellar mergers. In this framework, differential rotation during a merger or common envelope phase drives dynamo action, amplifying weak seed fields to the observed strengths. Compelling observational support for the merger hypothesis comes from the population of hot and warm DQ white dwarfs, which are carbon-rich, dynamically old, and magnetic in over 70% of cases. Their surface composition and magnetic properties point strongly to a merger origin, offering a direct link between binary evolution and the formation of compact stars with extreme magnetic fields.

Properties and origin of Sun-as-a-star magnetic field

K. Nagaraju and M. Vishnu

Indian Institute of Astrophysics Bengaluru, India

contact e-mail: *nagarajuk@iiap.res.in*

The line-of-sight component of Sun-as-a-Star Magnetic Field (SSMF) exhibits a prominent periodicity of 27 days with its amplitude as low as ± 0.1 gauss during solar minimum period to ± 2.5 gauss during solar maximum period. This dependency of amplitude on solar cycle may imply that the observed non-zero SSMF represent the magnetic flux imbalance associated with the sunspot activity across the visible disk of the Sun. While this may be true of the larger amplitude variation, what contributes to the persistent non-zero SSMF, though with the reduced amplitude, observed during solar cycle minimum is still an open question. Closer look at the SSMF variation shows that the smaller amplitude variation is present even during solar maximum period. This may suggest the presence of a constant magnetic structure whose magnitude (the LOS component) is modulated by the solar rotation and hence contributing to the persistently observed low amplitude SSMF variation. In this context we present the analysis of the synoptic (Carrington) magnetic field maps of SOHO/MDI and SDO/HMI, particularly during the minima periods between solar cycles 23-24 and 24-25. The magnetic fields are averaged over a selected range of Carrington latitudes and compared them with the observed SSMF towards the goal of identifying the region contributing the SSMF. The time history of thus identified region in Carrington maps will help in addressing the above stated enigma. In addition to presenting this analysis, we will give a brief description about the instrument and laboratory characterization of a sun-as-a-star vector magnetometer.

A Neural Network and Optimization Framework for the Inversion of Multiline Full-Stokes Stellar Spectropolarimetric Data

J. M. Raygoza-Romero[1], J. C. Ramírez-Vélez[2], and I. H. López-Nava[1]

[1] Dept. of Computer Science, Center for Scientific Research and Higher Education at Ensenada (CICESE), Tijuana-Ensenada Highway, km 107, 22860 Ensenada, Baja California, Mexico

[2] Institute of Astronomy, National Autonomous University of Mexico (UNAM), Tijuana-Ensenada Highway km 107, 22860 Ensenada, Baja California, Mexico

`contact e-mail:` *jraygoza@cicese.edu.mx*

We introduce a novel framework for the inversion of stellar magnetic fields, combining neural network-based synthesis of Stokes profiles with an optimization algorithm for parameter retrieval. This approach aims to reconstruct the global magnetic geometry of stars—particularly dipolar configurations—by fitting synthetic Stokes profiles to observed multiline profiles. The synthesis model is trained on radiative transfer simulations that include full-Stokes (IQUV) polarization, enabling flexible adaptation to different observational setups. A key advantage of this method lies in its efficiency: the neural network facilitates rapid generation of synthetic profiles while substantially reducing the need for extensive retraining when applied to different stellar targets. This is especially beneficial given the high computational cost associated with polarized radiative transfer. We assess the performance of the inversion across a range of scenarios, demonstrating that the inclusion of linear polarization significantly improves the performance and robustness of the inferred magnetic parameters, both for the target star and for other stellar cases. The results shed light on the relationship between polarization profiles and underlying magnetic field structures, paving the way for more precise interpretations of spectropolarimetric data. Furthermore, the framework supports scalable investigations of magnetic field morphologies and their links to stellar structure and activity, helping to connect theoretical models with observational constraints in stellar magnetism.

Before the Compact Stage: Magnetic Fields in Stars of All (St)Ages

Gregg A. Wade

Queen's University, Kingston, Canada Royal Military College of Canada, Kingston, Canada

contact e-mail: *gw33@queensu.ca*

From their births to their final phases, stars advect, amplify, and sculpt magnetic fields through interactions of those fields with the dynamic, ionized stellar plasma. Cooler stars with convective envelopes near their surfaces exhibit ubiquitous magnetic activity resulting from dynamos powered by the conversion of convective and/or rotational mechanical energy into magnetic energy, generating and sustaining highly structured and variable magnetic fields in their outer envelopes whose surface properties generally correlate strongly with stellar mass, age, and rotation rate. Strong magnetic fields are also frequently detected at the surfaces of stars with radiative envelopes. The characteristics of these fossil fields differ fundamentally from those of cool stars: they are intense, long-lived, and organized on global scales, and show no clear correlations with stellar rotational properties. Understanding the characteristics and relationships of these fundamental modes of stellar magnetism has important implications for our basic knowledge of every star in the Galaxy (and beyond). While hot stars, white dwarfs, and neutron stars exhibit radiative zones near their surfaces, many cool stars exhibit analogous regions in their deep interiors. On the other hand, the strong convection characterizing the exteriors of cool stars also occurs in the cores of hot stars. As a consequence, understanding envelope dynamos of cool stars informs our understanding of interior dynamos of hotter stars. Similarly, the study of surface fossil magnetism of hot stars (and degenerate remnants) informs us about analogous fundamental physics occurring deep below the observable surfaces of cool stars, including the Sun. This talk will review our current understanding of the magnetic fields of non-degenerate stars across the HR diagram, with a focus on connections between the structure of stars and their magnetic fields, and the coupled evolution of magnetic fields and their stellar hosts.

Session 4

Modeling Polarization: Theory and Methods

Talks

Spectropolarimetric synthesis of forbidden lines in MHD models of coronal bright points

E. Alsina Ballester[1,2]

[1] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

`contact e-mail:` *ernest.alsina@iac.es*

The inference of the magnetic field vector from spectropolarimetric observations is essential for understanding the physical processes governing the solar corona. In this talk, we explore which information on the magnetic fields of coronal bright points (CBP) can be obtained from the intensity and polarization of several forbidden lines of interest. We show the results of syntheses with the P-CORONA code, applied to a model of a CBP obtained with the Bifrost MHD code. The enhanced density within the CBP produces an intensity brightening and circular polarization signals close to 0.1% of the intensity, but suppresses the linear polarization. Moreover, we study the impact of the outer coronal material along the line of sight (LoS) by carrying out P-CORONA syntheses for a larger global MHD model. We also apply the weak field approximation (WFA), showing that it provides information on the longitudinal magnetic fields from the strongest-emitting spatial intervals along the LoS, and that it is more reliable in the regions of the CBP where the field does not change sign. Finally, accounting for the time evolution of the CBP model, we find that its signals are slightly attenuated but are still clearly identifiable, and the area where the WFA can be suitably applied remains substantial. We identify the circular polarization of the Fe XIV 5303 Å and especially Fe XIII 10747 Å lines as valuable diagnostics for the magnetic fields in the higher-temperature regions of the CBP. This could be exploited with future coronagraphs with similar capabilities to Cryo-NIRSP/DKIST, but designed to observe below 0.05 solar radii from the base of the corona.

Javier Trujillo Bueno: a Life in the Science of Solar Spectropolarimetry

Luca Belluzzi[1,2]

[1] Istituto ricerche solari Aldo e Cele Daccò (IRSOL), Faculty of Informatics, Università della Svizzera italiana (USI), CH-6605, Locarno, Switzerland
[2] Euler Institute, Faculty of Informatics, Universita della Svizzera italiana (USI), CH-6900 Lugano, Switzerland

`contact e-mail:` *luca.belluzzi@irsol.usi.ch*

I briefly retrace the scientific activity of Javier Trujillo Bueno in the fields of solar spectropolarimetry and magnetic field diagnostics, during his nearly 40 years long career. Given the great extent of his research, I focus on a selection of studies that had a crucial impact in the field and highlight the scientific challenges he has been most fascinated with. At the same time, I outline his role within the broader solar (and stellar) physics community, emphasizing his enterprising spirit, catching enthusiasm, and his invaluable dedication in training new generations of young scientists.

Efficient 3D radiative transfer modeling of scattering polarization

P. Benedusi[1,2], S. Riva[1,2], G. Janett[1,2], and L. Beluzzi[1,2]
[1] Istituto ricerche solari Aldo e Cele Daccò (IRSOL), Faculty of Informatics, Università della Svizzera italiana, Locarno, Switzerland[2] Euler Institute, Faculty of Informatics, Università della Svizzera italiana, Lugano, Switzerland

`contact e-mail:` *pietro.benedusi@usi.ch*

We present an efficient and massively parallel solution strategy for the transfer problem of polarized radiation, for a 3D stationary medium out of local thermodynamic equilibrium. Scattering processes are included accounting for partial frequency redistribution effects. Such a setting is one of the most challenging ones in radiative transfer modeling. The problem is formulated for a two-level atomic model, which allows linearization. The discrete ordinate method alongside an exponential integrator are used for discretization. Efficient solution is obtained with a Krylov method equipped with a tailored physics-based preconditioner. A matrix-free approach results in a lightweight implementation, suited for tackling large problems. Near-optimal strong and weak scalability are obtained with two complementary decompositions of the computational domain. The presented approach made it possible to perform simulations for the Ca I line at 4227Å with more than 40 billions degrees of freedom in few hours on massively parallel machines, always converging in a few iterations for the proposed tests.

The magnetic sensitivity of the Ca II resonance and subordinate lines in the solar atmosphere

I. Juanikorena Berasategi[1,2], E. Alsina Ballester[1,2], T. del Pino Alemán[1,2], and J. Trujillo Bueno[1,2,3]

[1] Instituto de Astrofísica de Canarias, E-38205 La Laguna (Tenerife, Spain)
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna (Tenerife, Spain)
[3] Consejo Superior de Investigaciones Científicas, (Spain)

contact e-mail: *ijuanikorenab@gmail.com*

Over the last two decades, novel theoretical investigations have allowed to decipher the key physical mechanisms that control the polarization of strong chromospheric lines, such as hydrogen Ly-α and Mg II h k around 280 nm, as well as to develop advanced plasma diagnostic techniques for their radiative transfer modeling and interpretation. The polarization signals of the resonant H and K lines and of the infrared triplet of Ca II are also of great interest for probing the magnetism of the solar chromosphere, as well as its thermal and dynamic conditions. Recently, the Sunrise III stratospheric telescope has provided high- quality spectropolarimetric observations in most of these chromospheric lines, thanks to its SUSI and SCIP instruments, and GRIS at the GREGOR telescope is now ready for unprecedented observations in the Ca II 854.2 nm line. However, a reliable modeling and interpretation of such observations is not an easy task. The polarization of solar chromospheric lines results from complex physical mechanisms: radiative transfer under non-equilibrium conditions in a plasma (the solar chromosphere) that is highly inhomogeneous and dynamic, anisotropic radiation pumping and the Hanle and Zeeman effects, partial frequency redistribution (PRD) in the scattering events, and quantum-mechanical interference between magnetic sublevels pertaining to different atomic levels. An important first step for a reliable interpretation of the Sunrise III and GRIS/GREGOR observations is to solve the problem of the generation and transfer of polarized radiation in the Ca II spectral lines, taking into account the joint action of scattering processes with PRD and J-state interference and the Hanle and Zeeman effects, but using one dimensional models of the solar atmosphere. We show the results of such an investigation, presenting the dominant physical mechanisms that control the polarization signals in each of the Ca II chromospheric lines and their magnetic sensitivity

Modeling of the scattering polarization of strong resonance lines: forward and inversion problems

G. Janett[1,2], F. Riva[1,2], P. Benedusi[1,2], S. Riva[2,1], and L. Belluzzi[1,2]

[1] Istituto ricerche solari Aldo e Cele Daccò (IRSOL), Faculty of Informatics, Università della Svizzera italiana, Locarno, Switzerland

[2] Euler Institute, Faculty of Informatics, Università della Svizzera italiana, Lugano, Switzerland

`contact e-mail:` *gioele.janett@irsol.usi.ch*

The measurement of the magnetic field in the chromosphere and transition region remains a formidable challenge. Frontier research in this field combines the diagnostic potential of the Zeeman and Hanle effects in strong resonance lines. The practical application of this diagnostic approach has been hampered by the complexity of its modeling, which must account for non-LTE effects, scattering polarization, PRD, and the impact of bulk velocities. Here, we expose an efficient solution strategy for this radiative transfer problem, presenting results in 1D atmospheric models for different spectral lines of interest for chromospheric magnetic field diagnostics, such as Ca I 4227, Mg II h&k, H I Ly-α, and He II 304. We also expose preliminary forward modeling calculations carried out in 3D atmospheric models extracted from state-of-the-art R-MHD simulations of the solar atmosphere. Furthermore, we leverage our efficient solution strategy to tackle the inversion problem, presenting the successful retrieval of height-dependent magnetic and bulk velocity fields in 1D models by inverting synthetic scattering polarization signals of Ca I 4227.

EUV polarimetry of coronal E1 transition lines: Potential, Challenges and Future

R. Khan[1,3], S. E. Gibson[2], R. Casini[2], and K. Nagaraju[1]

[1] Indian Institute of Astrophysics, Bangalore, India
[2] High Altitude Observatory, Boulder, USA
[3] Smithsonian Astrophysical Observatory, Cambridge, USA

`contact e-mail:` *drraveenak@gmail.com*

Coronal magnetism lies at the heart of many long-standing questions in solar physics, such as million-degree energization of the solar corona, initiation and acceleration of the solar wind, massive eruption of energetic particles through solar flares and coronal mass ejections (CMEs). The lack of routine measurements of the vector magnetic field has limited our understanding of the occurrence of these physical processes in the corona. An ad hoc observation of the linear polarization of O VI at 1032 Å– achieved by rotating the Solar and Heliospheric Observatory (SOHO) satellite– helped in deriving the coronal magnetic field by utilizing the instrumental polarization and the Hanle effect. This unoptimized measurement of resonance scattering induced linear polarization in an extreme-ultraviolet (EUV) line demonstrated that EUV linear polarization measurements from space has the potential of probing the vector magnetic field in the corona. To measure the coronal magnetic fields, we need to measure the observables– the linear polarization signals (Stokes I, Q, U)– which are sensitive to the magnetic fields via the Hanle effect. In a series of studies exploring the potential and challenges of EUV polarimetry, we have identified several magnetically sensitive lines in the 100 to 1000 Å spectral range, which form at similar coronal plasma temperatures and lie close to each other in wavelength. At the SPW11 meeting, I will present on the analysis of synthesized scattering polarization for one of these EUV permitted (electric-dipole transition) lines, examining how the polarization varies across different phases of a solar cycle under the influence of electron collisional excitation and magnetic fields. I will also discuss the challenges and future prospects of EUV polarimetry, in tandem with the Hanle effect, as a powerful diagnostic tool for mapping the vector magnetic field of the solar corona.

The Hα line as a probe of chromospheric magnetic fields

Harsh Mathur[1,2], Jayant Joshi[1], Thore Espedal Moe[3,4], Tiago M. D. Pereira[3,4], and K. Nagaraju[1]

[1] Indian Institute of Astrophysics, II Block, Koramangala, Bengaluru 560 034, India
[2] The Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune, Maharashtra 411007, India
[3] Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway
[4] Rosseland Centre for Solar Physics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway

`contact e-mail:` *harsh.mathur@iucaa.in*

The Hα line is a cornerstone diagnostic for probing the solar chromosphere, but its potential for magnetic field inference via spectropolarimetry remains underutilized. One contributing factor is that previous studies—based on simplified 1D radiative transfer (RT) models—suggested a dominant photospheric origin for the Hα Stokes V signal, casting doubt on its chromospheric sensitivity. Moreover, until now, no polarimetric studies have employed full 3D RT modeling to reassess this interpretation in a more realistic atmospheric context. In this work, we present the first comprehensive 3D RT polarimetric synthesis of the Hα Stokes profiles under the field-free approximation, using a state-of-the-art 3D rMHD model of the solar atmosphere. For context and comparison, we also synthesize the Ca II 8542 Å and Fe I 6173 Å lines. Line-of-sight (LOS) magnetic fields are inferred from the Hα and Ca II 8542 Å lines using the weak-field approximation, while Milne-Eddington inversion is employed for the Fe I 6173 Å line. Our results show that the core of the Hα line forms significantly higher in the chromosphere—approximately 500 km above the Ca II 8542 Å line—with peak magnetic sensitivity at $\log \tau_{500} = -5.7$, compared to $\log \tau_{500} = -5.1$ for Ca II 8542 Å line. These findings are consistent with recent observational evidence (Mathur et al. 2023, 2024) confirming that Hα line core probes magnetic fields at higher atmospheric layers than the Ca II IR triplet lines. This study supports the argument that spectropolarimetric observations of the Hα line provide complementary insights into magnetic field stratification at greater chromospheric heights, particularly when recorded simultaneously with widely used diagnostics such as the Ca II 8542 Å line.

Title: He I 1083 as a unsaturated Hanle diagnostic of the magnetic field in CMEs

Momchil Molnar[1], Roberto Casini[2], Bibhuti Jha[1], and Yuhong Fan[2]

[1] Southwest Research Institute, Boulder, CO, 80301, USA
[2] High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, 80301

`contact e-mail:` *momchil.molnar@swri.org*

The He I 1083 is an important atomic multiplet commonly observed in the active chromosphere and solar prominences. In eruptive prominences observed at large coronal heights, when the magnetic field drops below a few gauss, the linear polarization of He I 1083 becomes sensitive to the magnetic field via the unsaturated Hanle effect. This work shows how linear polarization observations of He I 1083 can be used to infer the direction of the longitudinal magnetic field in CMEs. To accomplish this goal, we developed a numerical framework capable of computing the polarization signals of the He I 1083 from realistic MHD models of prominence eruptions. The code can treat general magnetic regimes, ranging from zero field strength to the complete Paschen–Back effect, and can accept any atomic structure satisfying the Russell–Saunders (LS) coupling scheme, including atoms with nonzero nuclear spin (hyperfine structure). We use the prominence MHD eruption models from Fan (2018) as the basis for this study, where we show how the derived integrated linear polarization signals from different vantage points could be used for inferring the magnetic field of the eruption. We further discuss the observability of these diagnostics, following the work of Molnar and Casini (2024).

Polarization Signatures and Coronal Magnetic Memory During the April 8 2024 Great North American Eclipse

Shaonwita Pal[1], Soumyaranjan Dash[3], Soumitra Hazra[4], and Dibyendu Nandy[1,2]

[1] Center of Excellence in Space Sciences India, Indian Institute of Science Education and Research Kolkata, Mohanpur 71246, West Bengal, India

[2] Department of Physics, Indian Institute of Science Education and Research Kolkata, Mohanpur 71246, West Bengal, India

[3] Institute for Astronomy, University of Hawaii at Manoa, Pukalani, USA

[4] Lowell Center for Space Science and Technology, University of Massachusetts Lowell, USA

`contact e-mail:` *shao.physics@gmail.com*

The total solar eclipse of April 8, 2024, provided a rare opportunity to investigate the Sun's corona at the peak of Solar Cycle 25. In this study, we employ a data-driven global MHD model to predict the coronal magnetic field and compare our postdictions with observed large-scale structures. While solar maximum presents challenges for forecasting coronal activity, the integration of a surface flux transport model enables meaningful predictions. Our model, initiated one week prior to the eclipse, successfully reproduces multiple complex streamer-like structures that closely match features seen in white-light eclipse images and SDO/AIA observations. We also compute the magnetic squashing factor to examine the spatial complexity of the separatrix web (S-web), identifying regions prone to magnetic reconnection. Additionally, we perform forward synthesis of the coronal emission's polarization by modeling the Stokes I, Q, U, and V parameters for key spectral lines, thereby shedding light on the Sun's coronal magnetic structure. The results further reveal signs of dynamical memory in the global coronal configuration, persistent over one Carrington rotation. This work contributes toward advancing coronal magnetometry, with relevance for current and future missions such as the Daniel K. Inouye Solar Telescope, Coronal Multichannel Polarimeter (CoMP), Solar Orbiter, and ISRO's Aditya-L1 mission.

Effects of angle-dependent partial redistribution on linear polarization profiles from a spherically symmetric medium

M. Sampoorna[1] and H. D. Supriya[2]

[1] Indian Institute of Astrophysics, Koramangala, Bengaluru 560 034, India
[2] Instituto de Astrofisica de Canarias, E-38205, La Laguna, Tenerife, Spain

contact e-mail: *sampoorna@iiap.res.in*

Linear polarization of resonance lines, produced via scattering of limb-darkened radiation field in a stellar atmosphere, sensitively depends on the form of the partial redistribution (PRD) function used in the polarized line transfer computation. For computational simplicity angle-averaged PRD functions are usually preferred over the more exact angle-dependent functions. However, from earlier studies in planar atmospheres it is clear that angle-dependent PRD effects cannot always be neglected. In this talk we present the angle-dependent PRD effects on linear polarization profiles emanating from spherically symmetric extended and expanding medium. We consider angle-dependent PRD effects in scattering on both atoms and free electrons. After discussing the numerical methods of solution, we illustrate the significant differences between linear polarization profiles computed with angle-dependent and angle-averaged PRD.

Coronal Magnetometry with EUV Permitted Line

Nataliia G. Shchukina

Main Astronomical Observatory, National Academy of Sciences, 03143 Kyiv, Ukraine

`contact e-mail:` *shchukin@mao.kiev.ua*

A major challenge in solar physics is to obtain empirical information on the magnetic field of the million-degree plasma of the solar corona. To this end, we need observables of the solar radiation sensitive to the coronal magnetic field. The most familiar observables are the polarization signals of visible and near-infrared forbidden lines of highly ionized species and some ultraviolet permitted lines, like hydrogen Lyman-alpha. While the coronal radiation in these spectral lines can only be detected for off-limb line of sights, the coronal radiation from permitted extreme ultraviolet (EUV) lines can be observed also on the solar disk. These coronal lines are mainly collisionally excited; however, in 2009, Manso Sainz and Trujillo Bueno pointed out that some permitted EUV lines can actually be linearly polarized if their lower level carries atomic alignment, and that their linear polarization is sensitive to the orientation of the coronal magnetic field. Here we theoretically investigate the linear polarization in permitted EUV lines of a variety of ions: Fe X, Fe XI, Fe XIII, Fe XIV, Si IX, and Si X. To this end, we have developed a numerical code, which we have applied to investigate the linear polarization and magnetic sensitivity of many permitted EUV lines in a one-dimensional model of the solar corona, providing a list of the most promising lines to be further investigated for polarimetry with future space telescopes. Our next step will be to extend this work by using state-of-the-art three-dimensional coronal models.

3D Radiative Transfer Modeling of the Scattering Polarization in the Wings of Mg II k and h

Andrii V. Sukhorukov[1,2,3,4], Javier Trujillo Bueno[2,3,5], Luca Belluzzi[6,7,8], and Jiří Štěpán[9]

[1] Institute for Solar Physics, Dept. of Astronomy, Stockholm University, AlbaNova University Centre, SE-106 91 Stockholm, Sweden
[2] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[3] Dpto. de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
[4] Main Astronomical Observatory, National Academy of Sciences of Ukraine, 27 Akademika Zabolotnoho str., UA-03143 Kyiv, Ukraine
[5] Consejo Superior de Investigaciones Científicas, Madrid, Spain
[6] Istituto ricerche solari Aldo e Cele Daccò (IRSOL), Faculty of Informatics, Università della Svizzera italiana (USI), CH-6605 Locarno, Switzerland
[7] Leibniz-Institut für Sonnenphysik (KIS), D-79104 Freiburg i. Br., Germany
[8] Euler Institute, Università della Svizzera italiana (USI), CH-6900 Lugano, Switzerland
[9] Astronomical Institute ASCR, Fričova 298, 251 65 Ondřejov, Czech Republic

`contact e-mail:` *andrii.sukhorukov@astro.su.se*

The CLASP2 rocket experiment was performed on April 11, 2019. It observed the solar chromosphere in the Mg II resonant doublet near 280 nm for three targets: the quiet Sun at the disk center, at the limb, and an active plage at midway. Slit spectra in all four Stokes parameters were obtained in the UV. The limb target revealed profile shapes for the linear polarization caused by quantum interference in the upper term ^{2}P. Additionally, the linear polarization exhibited spatial variations on the mesogranular scale. This confirmed the theoretical prediction of Stenflo (1980), recently thoroughly investigated by Belluzzi and Trujillo Bueno (2012). We have developed two numerical modules for the PORTA radiative transfer code to interpret these data through forward modeling. We have numerically solved the transfer problem, taking into account the effects of 3D geometry, partial redistribution of scattered photons, and quantum interference in a two-term atom. We will describe the observational experiment, complexities of the theoretical method, computational demands, and our approximations. We will compare synthetic and observed data to show the importance of various effects: spatial symmetry breaking, quantum interference, magneto-optical sensitivity, and instrumental limitations.

Spectropolarimetry of Coronal Lines: Forward Modeling Tools and Their Applications

H. D. Supriya[1,2], T. del Pino Alemán[1], J. Trujillo Bueno[1,3], A. de Vicente[1], N. Shchukina[1,4], and G. del Zanna[5]

[1] Instituto de Astrofisica de Canarias, E-38205, La Laguna, Tenerife, Spain
[2] Astronomical Institute of the Czech Academy of Sciences, Fričova 298, Ondřejov, Czech Republic
[3] Consejo Superior de Investigaciones Cientıficas, Spain
[4] Main Astronomical Observatory, National Academy of Sciences, 03143 Kyiv, Ukraine
[5] DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK

`contact e-mail:` *supriyahd@gmail.com*

Forward modeling is a powerful method for studying the behavior of spectral lines under various physical conditions. In this talk, I will review some of the available forward modeling tools for coronal lines, with a focus on P-CORONA, a recently developed, publicly available code. P-CORONA models the intensity and polarization of both forbidden and permitted lines using three-dimensional magnetohydrodynamic simulations of the corona. It accounts for the spectral line polarization caused by anisotropic radiation pumping, magnetic fields through both the Hanle and Zeeman mechanisms and incorporates the influence of non-linear solar wind velocities. I will present key results obtained with P-CORONA for a range of lines from ultraviolet to infrared, including those observed by the Daniel K. Inouye Solar Telescope (DKIST). Finally, I will discuss how such forward modeling tools can support various applications, including exploring how different physical parameters affect coronal emission, testing theoretical models by comparing them with observations, and guiding the design of instruments by predicting which spectral lines and polarization signals are most useful for specific science goals.

Session 4

Modeling Polarization: Theory and Methods

Posters

Experimental Simulation and Model Validation of the Hanle Effect in Solar Atmosphere Using a Laboratory Plasma

T. Kawate[1,2,3], K. Ichimoto[4], and M. Goto[2,3]

[1] National Institutes for Quantum Science and Technology, Naka 311-0193, Japan
[2] National Institute for Fusion Science, Toki 509-5292, Japan
[3] Graduate Institute for Advanced Studies, SOKENDAI, Toki 509-5292, Japan
[4] Ritsumeikan University, Kusatsu 525-8527, Japan

`contact e-mail:` *ichimoto.kiyoshi.34j@st.kyoto-u.ac.jp*

Magnetic structures in the solar atmosphere provide fundamental information for investigating heat and particle transport phenomena. The Zeeman-Hanle effect has been widely used to study the fine magnetic structures through spectropolarimetric measurements. While the accuracy and precision of spectropolarimetric and inversion methods have been improved, validation of these techniques relies on theoretical models or on the solar atmosphere itself in most cases. Our motivation is to verify and validate these techniques experimentally in a simplified laboratory system, where plasma parameters can be controlled and results can be cross-validated with independent diagnostics.

We developed an inductively coupled plasma (ICP) system[1], and installed it in front of the focal plane of the Horizontal Spectrograph of the Domeless Solar Telescope at Hida Observatory of Kyoto University. The spectrograph is equipped with a spectropolarimetric system with high spectral resolution and high polarimetric sensitivity[2], and it is usually operated for solar observations. In the ICP system, anisotropic radiation fields are generated intrinsically at the observation port, and we observed scattering polarization in the helium plasma. By applying weak magnetic fields up to 20 G using external Helmholtz coils, we experimentally measured Zeeman-Hanle signals. The magnetic field was independently measured by a Hall sensor. We compared the experimentally obtained spectropolarimetric signals with theoretical Zeeman-Hanle profiles. In the presentation, we discuss the results of the helium triplet lines at 1083 nm and 587 nm using the ICP system.

[1] T. Kawate et al., Plasma Fusion Res. 18, 1401037 (2023)
[2] K. Ichimoto et al., Tech. Rep. Astron. Obs. Kyoto Univ. 6, 3 (2022)

Bi-directional & Evershed flows in penumbral filaments of sunspot simulations

M. Schmassmann[1], M. Rempel[2], R. Schlichenmaier[1], J. Jurčák[3], and N. Bello González[1]

[1] Institut für Sonnenphysik (KIS), Freiburg, Germany
[2] High Altitude Observatory, NSF National Center for Atmospheric Research, Boulder, CO, USA
[3] Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic

`contact e-mail:` *schmassmann@leibniz-kis.de*

There are many observations of sunspots, but few attempts at sunspot simulations. Rempel (2012) presented realistic magneto-hydrodynamic (MHD) sunspot simulations, where the horizontal magnetic field at the top boundary is artificially increased, and which show Evershed flows in all filaments. Jurčák et al. (2020) showed that the magnetic field of such simulations differs from observations; in particular, the B_{ver} at the umbral boundary is too low, and the horizontal field in the penumbra is too strong.
Using the MURaM MHD code and a potential field top boundary condition, we simulated a sunspot using potential field initial conditions. Our simulations give B_{ver} at the umbral boundary consistent with observations and show ongoing flux emergence in the penumbra. When running the simulation with these initial and boundary conditions and a 96 (32) km horizontal (vertical) resolution, the penumbral filaments show bi-directional flows: in- & down-flows in the inner penumbra and outflows in the outer penumbra. However, when using a 32 (16) km resolution, some filaments show the same behavior, whereas others show the typical Evershed (radially outward) flow.
The bi-directional flows are observed in high-resolution observations of penumbra formation by García-Rivas et al. (2024), whereas the Evershed flow is observed in the stable phase of sunspots. We investigate penumbral filaments with these different flow regimes within our high-resolution simulation, and with those in a lower resolution simulation and a simulation with a different top boundary condition. We compare the different 3D flow structures in these penumbral filaments.

Electron-impact excitation data for modeling polarized line emissions from the solar atmosphere

A. F. Sekkal-Haddouche, M. K. Inal, and M. Benmouna

Dept. of Physics, Faculty of Sciences, Abou-Bekr Belkaid University, 13000 Tlemcen, Algeria

`contact e-mail:` *mokhtar.inal@univ-tlemcen.dz*

Analysis of the polarized line emission from hot plasmas requires knowledge of the multipole rate coefficients for collisional excitation of highly charged ions by electrons in the isotropic or cylindrical symmetry conditions. For isotropic electrons, these collision data are involved in lines formed by photoexcitation due to an external anisotropic radiation, in addition to excitation by local isotropic thermal electrons. This scenario can occur in line emission from the solar corona irradiated anisotropically by the photosphere. In the case of electrons with a cylindrically symmetric velocity distribution, the multipole rate coefficients are needed for plasmas such as those found in solar flares and active regions where beams of energetic electrons may be generated. Relatively little attention has been paid to the multipole rate coefficients. We previously reported their calculations for isotropic collisions considering transitions in the Fe XIII ion, assuming a Maxwellian electron distribution [1]. These calculations are useful in analyzing the coronal lines at 1074.7 and 1079.8 nm. More recently, we provided results of the multipole rate coefficients for excitation of the O V ion from its metastable 2s2p triplet levels, using an anisotropic Maxwellian distribution with two temperatures along the parallel and perpendicular directions to the symmetry axis [2]. Such results may be relevant to active regions. In this communication, we present some data to illustrate how the excitation program used to compute the multipole collision strengths [3] opens new prospects for the field of solar polarization spectroscopy. References [1] A. F. Sekkal-Haddouche, M. K. Inal and M. Benmouna, Eur. Phys. J. D 77, 148 (2023). [2] A. F. Sekkal-Haddouche, M. K. Inal and M. Benmouna, Phys. Rev. A 111, 042814 (2025). [3] M. Belabbas, M. K. Inal and M. Benmouna, Phys. Rev. A 104, 042818 (2021).

Session 5

Inverse Problem: Methods and Applications

Talks

Exploring Chromospheric Magnetism: Polarization Diagnostics from Mg II and Fe II Spectral Lines

D. Afonso-Delgado, R. Centeno, and R. Casini

High Altitude Observatory, 3080 Center Green Drive, Boulder, CO, USA

`contact e-mail:` *dadelgado@ucar.edu*

The polarization of ultraviolet spectral lines is a powerful diagnostic tool for probing the magnetic field in the upper solar chromosphere. Observations from the Chromospheric LAyer Spectropolarimeter missions (CLASP2 and CLASP2.1) have demonstrated the diagnostic potential of the MgII h k resonant doublet for constraining the chromospheric magnetic field. Recent studies have advocated for the inclusion of the Fe II lines within the 250-270 nm spectral range as an optimal complement to the Mg II h and k spectral window lines to obtain a more detailed mapping of the magnetic field stratification through the solar chromosphere. In this context, the Chromospheric Magnetism Explorer (CMEx) mission is being developed to exploit the full diagnostic capabilities of this ultraviolet spectral region. We conducted radiative transfer modeling of MgII and FeII polarization signals using magneto-hydrodynamic simulations of different solar active regions. These synthetic observations allow us to test inversion techniques for recovering the magnetic field's stratification throughout the whole solar chromosphere. Our results demonstrate that a CMEx-like mission could distinguish between magnetic structures such as magnetic flux ropes (MFR) and sheared magnetic arcades (SMA), confirming the validity of existing models of solar eruption formation.

3D inversion of a solar prominence

A. Vicente Arevalo[1] J. Stepan[2] T. del Pino Aleman[3]

[1] KIS Institute fur Sonnenphysik
[2] ASU Astronomical Institute of the Czech Academy of Science
[3] IAC Instituto de Astrofisica de Canarias

`contact e-mail:` *andres.vicente.arevalo@gmail.com*

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 imposing 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.

Full Stokes inversions with scattering polarization: 1D and 3D

T. del Pino Alemán[1,2], J. Štěpán[3], and H. Li[4]

[1] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[2] Departamento de Astrofísica, Univ. de La Laguna, La Laguna, Tenerife E-38200, Spain
[3] Astronomical Institute of the Czech Academy of Sciences, 25165 Ondřejov, Czech Republic
[4] State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing, 100190, Peoples Republic of China

`contact e-mail:` *tanausu@iac.es*

Inversion techniques are widely applied in the analysis of spectropolarimetric observations to infer the thermal and magnetic properties of the solar atmosphere. Over the past decades, these techniques have become increasingly more sophisticated, building up in complexity and scope. In this talk, I will highlight some of these latest advances, with a particular focus on the exploitation of scattering polarization and the Hanle effect for magnetic field diagnostics. Since these effects are intrinsically sensitive to the geometry of the radiation field, their proper treatment requires going beyond one-dimensional modeling. I will discuss development in both one-dimensional and three-dimensional approaches and the challenges they still present for quantitative inference.

Electric field diagnostics with the H-epsilon line

T. Anan[1], R. Casini[2], H. Uitenbroek[3], K. Yang[4], H. Socas-Navarro[5], T. Schad[1], J. Reep[4], S. Tiwari[6], L. Tarr[1], J. Qiu[7], K. Ichimoto[8], S. Jaeggli[1], Y. Katsukawa[9], A. Asai[10], K. Reardon[3], A. Tritschler[3], F. Wöger[3], and T. Rimmele[3]

[1] National Solar Observatory, Makawao, Hawaii, 96768, USA
[2] High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, 80301, USA
[3] National Solar Observatory, Boulder, Colorado, 80303, USA
[4] Institute for Astronomy, University of Hawai'i at Manoa, Pukalani, HI, 96768, USA
[5] Institute de Astrofísica de Canarias, La Laguna, Tenerife, Spain
[6] Lockheed Martin Solar and Astrophysics Laboratory, Palo Alto, California, 94304, USA
[7] Department of Physics, Montana State University, Bozeman, MT, 59717, USA
[8] College of Science and Engineering, Ritsumeikan University, Kusatsu, Shiga, 525-8577, Japan
[9] National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
[10] Astronomical Observatory, Kyoto University, Sakyo, Kyoto 606-8502, Japan

`contact e-mail:` *tanan@nso.edu*

Electric fields experienced by atoms play a central role in magnetic diffusion, magnetic energy dissipation, and moreover particle accelerations. Using the newly commissioned US National Science Foundation's Daniel K. Inouye Solar Telescope (DKIST), we observed NOAA active region 12995 on February 23rd, 2022, in three spectral ranges, i.e., 397 nm, 630 nm, and 854 nm, using the Visible SpectroPolarimeter (ViSP). We successfully obtained Stokes spectra of Ellerman bombs, transient brightening in the lower chromosphere associated with magnetic reconnection. At the Ellerman bomb, we discovered a broadband circular polarization in a Balmer line of the neutral hydrogen at 397 nm, H epsilon, that is consistent with the presence of an electric field. To infer the electric field, we made a database of synthesized Stokes profiles, using a numerical code that implements a formalism of scattering for the hydrogen lines in the presence of magnetic and electric fields (Casini 2005). In this presentation, we will describe the details of the database and discuss future perspectives for developments of inversion codes.

Magnetic Field Reconstruction via Neural Field Assisted Spectropolarimetric Inversions

C. J. Díaz Baso

Rosseland Centre for Solar Physics, University of Oslo, Norway

`contact e-mail:` *carlos.diaz@astro.uio.no*

Spectropolarimetric observations provide valuable information about the physical conditions in the solar atmosphere, particularly the magnetic field. However, traditional pixel-by-pixel inversion techniques fail to capture the inherent spatial and temporal coherence of the solar atmosphere. To address this limitation, we propose a novel approach that utilizes neural fields (NFs) to perform spectropolarimetric inversions. NFs leverage compact neural network parameterization to represent continuous physical quantities. This allows us to impose spatio-temporal constraints on the inferred magnetic field, improving the fidelity of the reconstruction compared to the standard pixel-wise approach, especially in noisy scenarios. We demonstrate the superior performance of NFs in performing spectropolarimetric inversions in different spectropolarimetric observations from the Swedish 1-m Solar Telescope (SST). Moreover, the NF framework seamlessly integrates external constraints, such as alignment with the orientation of the chromospheric fibrils or similarity to pre-computed magnetic field extrapolations, further improving the fidelity of the inferred magnetic field. This work showcases the potential of NFs for future instruments with large fields of view, thanks to their compact representation and the ability to impose spatio-temporal constraints to improve the magnetic field reconstruction in the solar atmosphere.

A Transformer-Based Approach to Spectropolarimetric Regression

R. Campbell[1], M. Mathioudakis[1], and C. Quintero Noda[2,3]

[1] Queen's University Belfast[1]
[2] Instituto de Astrofisica de Canarias[2]
[3] Dept. Astrofisica, Universidad de La Laguna[3]

contact e-mail: *rjcampbell.research@outlook.com*

Inverting the Stokes vector to retrieve physical conditions in the solar atmosphere is a fundamental tool for probing solar magnetism. However, traditional inversion methods remain computationally expensive and can suffer from convergence issues, especially when applied to complex, multi-line, full-Stokes datasets. We present the first implementation of a Transformer-based model for spectropolarimetric inversion. Transformer architectures, which have revolutionised natural language processing through their ability to capture long-range dependencies in sequences, are well suited to handling spectropolarimetric data. Our model takes full-Stokes spectra across multiple spectral lines as input and predicts stratified atmospheric parameters—temperature, magnetic field strength, inclination, azimuth, and line-of-sight velocity—as a function of optical depth. It incorporates an attention mechanism that enables the inversion to dynamically focus on the most informative spectral regions for each parameter, and uses positional embeddings to preserve spectral ordering. We benchmark its performance against a multilayer perceptron (MLP) baseline using synthetic spectra from realistic 3D MHD simulations spanning 15 photospheric and chromospheric lines. The Transformer achieves both lower absolute errors and higher correlations with the ground truth than the MLP, while producing physically bounded and regularised atmospheric profiles. Performance remains robust across noise levels typical of real observations. This approach provides a fast, accurate, and interpretable method for full-Stokes, multi-line inversion, and we outline plans to apply the method to datasets from DKIST and SUNRISE III. Our open-source Transformer-based model can also be adapted for other inversion codes.

Towards solar many-line inversions

J. Hölken[1], M. van Noor[1], A. Feller[1], H.-P. Doerr[2,1], S.-K. Solanki[1,3], W. Cao[4,5], N. Gorceix[4,5], J. Kang[6], K. Ahn[4], and J. Chae[6]

[1] Max-Planck-Institut für Sonnensystemforschung (MPS), Göttingen, Germany
[2] Thüringer Landessternwarte, Tautenburg, Germany
[3] School of Space Research, Kyung Hee University, Yongin, Republic of Korea
[4] Big Bear Solar Observatory, Big Bear City, USA
[5] New Jersey Institute of Technology, Newark, USA
[6] Astronomy Program, Seoul National University, Seoul, Republic of Korea
[7] Korea Astronomy and Space Science Institute, Daejeon, Republic of Korea

`contact e-mail:` *hoelken@mps.mpg.de*

Currently established practical noise values for unrestored spectro-polarimetric data are ranging from 10^{-3} to 10^{-5} of the continuum intensity (For instance: van Noort 2012, Iglesias et al. 2016). At the highest spatial resolution and after the application of spectral image reconstruction, the absolute noise number typically resides more in the 10^{-2} regime. In this contribution we discuss how the increased absolute noise numbers can be mitigated.
In contrast to stellar physics, for the analysis of spatially highly resolved solar spectra the simultaneous observation and inversion of only a few (often only one) spectral lines is still the norm. In this contribution we present the first diffraction-limited spectro-polarimetric data from FISS-SP, a slit-scanning instrument at the 1.6m Goode Solar telescope, and for the first time we combine the simultaneously observed information of more than 80 lines. In comparison to the results from an inversion using only a line doublet, we find more fine-structure and a better constrained atmospheric configuration (i.e., in terms of consistency and physicality).
The line-selection process and the interpretation of the fit results is not straight forward. We will discuss some of the issues, implications, and findings.

3D Coronal Magnetic Field Inversion: from UCoMP toward DKIST

M. Kramar[1,3], S. Tomczyk[2], and H. Lin[3]

[1] DKIST Science Support Center, National Solar Observatory, Pukalani, HI 96768, USA
[2] Solar Scientific LLC, Boulder, CO, USA
[3] Institute for Astronomy, University of Hawaii at Manoa, Pukalani, HI 96768, USA

`contact e-mail:` *mkramar@nso.edu*

Due to the low optical density of the coronal atmosphere, the inference of the physical properties of the corona are constrained by the entanglement of coronal signals due to the integration over line of sight (LOS), except for localized emission sources (bright loops in active regions). To disentangle the LOS integrated signals, the tomographic inversion is needed. Tomography is the determination of the structure of a 3D object using measurements of line-of-sight integrated signals obtained from many different viewing directions. The reliability of the vector field tomographic inversion has been investigated by numerical experiments that showed that the vector tomography can recover the orientation and, with less accuracy, amplitude of the field vector with only linear polarization (LP) data and photospheric magnetic field boundary conditions, and with higher accuracy than the PFSS model. We applied the vector tomography inversion to the Upgraded Coronal Multi-channel Polarimeter (UCoMP) which observes linear polarization (LP) of the Fe XIII 10747 A coronal emission line (CEL) with a wide field of view (FOV) covering almost the whole lower solar corona. The additionally required 3D coronal electron density and temperature were obtained by scalar field tomographic inversion of STEREO/EUVI observations. Therefore, we have obtained 3D vector magnetic field, electron density, and temperature which will allow us to plot 3D maps of free magnetic energy, plasma beta, and current (curl B). Particularly, the preliminary inversion result shows a larger value the magnetic field strength than for MHD model used as the starting conditions for the inversion. As supplementary to LP data, the circular polarization (CP, Stokes-V) provide information about the LOS projected field strength. We demonstrate that the CP observations by the DKIST Cryo-NIRSP and DL-NIRSP will further constrain the solution and provide a more realistic coronal magnetic field than PFSS models.

Inferring the Solar Magnetic Field from the Stokes Profiles of the Mg I 12.32-micron Emission Line: Seares' approximation and Non-LTE inversion

Wenxian Li

State Key Laboratory of Solar Activity and Space Weather, National Astronomical Observatories, Chinese Academy of Sciences

`contact e-mail:` *wxli@nao.cas.cn*

Due to its large Zeeman sensitivity, the Mg I line at 12.32 micron is an important diagnostic tool for solar magnetism. Therefore, the development of a rapid and effective inversion strategy from Stokes observations is essential. To accomplish this, we first synthesized the Stokes profiles from the FAL-C model atmosphere under different magnetic field geometries. Then, we inferred the magnetic field vectors based on the Seares approximation. Furthermore, we utilized the inferred magnetic field parameters from the Seares approximation as initial estimates for a non-LTE inversion procedure. We examined the fits and inversions for various combinations of Stokes parameters, namely (I), (I, V), and (I, Q, U, V). The comparisons between the inferred field and the model field confirm the effectiveness of the inversion strategy. Finally, we applied this inversion strategy to full-Stokes spectro-polarimetric observations made by the Infrared System for the Accurate Measurement of Solar Magnetic Field (AIMS).

Inference of magneto-hydrostatic equilibrium in the chromosphere

A. Meissner, A. Pastor Yabar, and J. de la Cruz Rodriguez

Institute of Solar Physics, Stockholm University, 11421 Stockholm, Sweden

contact e-mail: *aaron.meissner@astro.su.se*

One of the major open questions in solar physics is the coronal heating problem, which refers to the fact that from the chromosphere upwards the temperature is higher than what can be expected if radiation was the main heating process. The inference of depth-stratified atmospheric models from spectropolarimetric data through inversion methods provides the most detailed characterization of the physical conditions of the solar atmosphere. However, most of the methods, with a few exceptions for the photosphere, use the assumption of hydrostatic equilibrium in a 1D (where each pixel is treated independently of the others) when calculating the gas pressure and density, which leaves out the magnetic forces in the force balance Including these in the balance requires the estimation of electric currents, which relies on spatial derivatives of the magnetic field. In this contribution we present the implementation of a magneto-hydrostatic equilibrium equation solver into the inversion code STiC in order to account for the magnetic forces in the photosphere and chromosphere. We consider some ideal cases in which we avoid the intricacies of the solution of the radiative transfer equation. Using finite differences for the derivatives, we can solve the magneto-hydrostatic equation by solving a system of linear equations. We then use an iterative approach including an equation of state in order to converge to a stable solution. We then test this method taking parameters from r-MHD simulations. In doing so, we assess the accuracy to which this approach can retrieve electric currents as well as some heating terms such as ohmic or ambipolar dissipative terms. Finally, we will present the impact that this approach in the estimation of the gas pressure and the density has on the final ability to estimate accurate radiative losses in some of the main spectral lines of atoms that usually contribute to the radiative losses: CaII, MgII and HI.

Neural machine translation for solar atmospheric modeling

A. Asensio Ramos

Instituto de Astrofisica de Canarias

`contact e-mail:` *aasensio@iac.es*

We present a novel approach to Stokes inversion by framing it as a language translation task. Solar full Stokes parameters and corresponding atmospheric models are represented as sequences of discrete tokens using Vector Quantized Variational Autoencoders (VQ-VAE). An encoder-decoder Transformer architecture is then employed to learn the mapping between the token sequences of the observed Stokes parameters and the latent representation of the atmospheric models. By training the Transformer to translate from the "language" of Stokes parameters to the "language" of atmospheric models, we leverage the sequence-to-sequence capabilities of this architecture for inversion. Furthermore, the inherent generative nature of the Transformer decoder allows for the estimation of uncertainties in the retrieved atmospheric stratifications. This work demonstrates the potential of applying neural machine translation techniques to complex astrophysical inversion problems.

Transfer technique applied to polarized spectral lines

J. Ramirez Velez[1], J. Raygoza Romero[2], and H. Lopez Nava[2]

[1] Instituto de Astronomia, UNAM, Ensenada, Mexico
[2] Ciencias de la computación, CICESE, Ensenada, Mexico

`contact e-mail:` *jramirez@astro.unam.mx*

We present a new approach to produce polarized spectra in the four Stokes profiles using a deep Artificial Neuronal Network (ANN) model. The novelty of our approach is that we employ the so-called transfer learning technique, where one pre-trained ANN is used to train other ANNs to perform a similar task –as for example, for the synthesis of the Stokes profiles at different wavelengths and/or with a different atmospheric model–. For the training of the original ANN were required millions of instances, each one corresponding to different magnetic configurations over the stellar surface. This could be very time consuming particularly if one is interested in the analysis of several spectral lines. However, once the original ANN is trained, and thanks to the transfer learning technique, for the training of the subsequent ANNs only few thousands of instances are required to obtain a comparable performance as the original ANN. This approach has the great advantage that many ANNs can be trained with small databases, a key aspect in machine learning. This approach can be implemented in the solar (local profiles) or stellar (surface integrated) domains. We present the performance of our approach using as test study the inversion of multi-line profiles form a star, finding excellent results to determine the stellar surface magnetic configuration.

Robustness of the transition probability of atomic lines inferred from solar spectra

D. Vukadinović[1], H. N. Smitha[2], A. Korpi-Lagg[2,3], and S. K. Solanki[2]

[1] Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria
[2] Max Planck Institute for Solar System Research, Justus-von-Liebig Weg 3, Göttingen
[3] Department of Computer Science, Aalto University, PO Box 15400, FI-00076 Aalto, Finland

`contact e-mail:` *dusan.vukadinovic@uni-graz.at*

Atomic parameters are an essential ingredient in modelling the observed spectral lines and extracting meaningful physical information about the observed astrophysical object. The atomic line parameters can be determined with different approaches from observed solar and stellar spectra. Our focus here is on the transition probability of spectral lines, usually denoted as $\log(gf)$. We use the spectropolarimetric inversion method implemented in the `globin` inversion code where atomic parameters are spatially coupled and allowed to vary in the whole field of view simultaneously (the coupled method). We use quiet-sun disc-centre observations at $1.56\,\mu$m from the GRIS/GREGOR spectrograph to test the reliability of the inferred atomic parameters. The observed spectral lines are modelled assuming local thermodynamic equilibrium. We find that the $\log(gf)$ values inferred using the coupled method from `globin` are robust against any local contamination to the observed line profiles, such as, gray stray light, and are unbiased in a chosen parametrisation of the atmospheric model and observation dataset. We determine the uncertainties in the inferred $\log(gf)$ values with the Markov chain Monte Carlo method. For the strongest lines in the analysed spectral region, the uncertainty in the $\log(gf)$ is 12 %, comparable to the uncertainties achieved in experiments. The uncertainty increases to more than 30 % for weaker and blended lines. The inferred $\log(gf)$ values differ mainly for blended lines from those reported in a recent study that uses the same observations but a different approach for the retrieval of the $\log(gf)$ values.

Non-LTE synthesis and inversion of the Mg I 12.32 µm line

Yuchuan Wu[1,2], Wenxian Li[1,3], Xianyong Bai[1,2,3], Feng Chen[4,5], Hao Li[3], and Yuanyong Deng[1,2,3]

[1] State Key Laboratory of Solar Activity and Space Weather, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China
[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, China
[3] State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, Chinese Academy of Sciences
[4] School of Astronomy and Space Science, Nanjing University, Nanjing, China
[5] Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing, China

`contact e-mail:` *wuyc@bao.ac.cn*

Magnetic field is one of the most important physical quantities in solar physics. Mg I 12.32 µm line is very sensitive to magnetic field, thus is suitable for measuring solar magnetic field. We employed the radiative transfer code RH 1.5D to synthesize the spectra of Mg I 12.32 µm line based on a model atmosphere computed with the magnetohy drodynamic numerical code MURaM. We analysed Mg I 12.32 µm line's features at various locations and the relationships between these features and physical parameters in model atmosphere. We also use an inversion code STiC to inverse synthesized spectra of Mg I 12.32 µm line and get physical parameters of the atmosphere.

Spectropolarimetric inversions including physical constraints

A. Pastor Yabar[1], A. B. Grinon Marin[1], A. Asensio Ramos[2,3], and J. M. Borrero[4]

[1] Institute for Solar Physics, Stockholm University, AlbaNova University Center, 106 91, Stockholm, Sweden
[2] Instituto de Astrofísica de Canarias (IAC), Avda Vía Láctea S/N, 38200, La Laguna, Tenerife, Spain
[3] Departamento de Astrofísica, Universidad de La Laguna, 38205, La Laguna, Tenerife, Spain
[4] Institut für Sonnenphysik, Schöneckstr. 6, 79104, Freiburg, Germany

`contact e-mail:` *adur.pastor@astro.su.se*

Depth-stratified spectropolarimetric inversions are one of the most insightful approaches to the characterization of the solar atmosphere. These have been performed, almost exclusively, under the assumption of hydrostatic equilibrium in a pixel by pixel basis. This is required as spectral line sensitivity to any other thermodynamic property than temperature is low. Thus, the ability to infer the 3D thermodynamic and magnetic topology of the solar atmosphere is strongly limited. This scientific goal is further hindered by the fact that spectral line is sensitive to the stratification of physical parameters in optical depth rather than geometrical scale, required to address the 3D topology. In recent years, there have been some attempts to overcome these limitations, for instance neural network mappings, radiative magnetohydrodynamic (MHD) assisted inversions, inversions under the assumption of the magnetohydrostatic approximation.
Here we present an alternative approach: use a Physics-Informed Neural Networks to represent the atmosphere in an N-dimensional space (three spatial coordinates and time). This is a different approach to classical deep learning techniques as the neural network provides the atmosphere at the required space-time grid, which feeds a radiative transfer solver (FIRTEZ-dz). The output spectra is then compared to the observations driving the minimization of a likelihood function. In the process, the the atmosphere representation is modified in order to best explain the observations. We explore the benefits (mainly related to the inclusion of soft penalty of un-physical solutions, in the sense of deviations from MHD predictions) and drawbacks of this approach over a synthetic observation. We will specifically consider the case of the magnetic field vector, divergence free solutions, and accuracy on the estimation of electric currents and the three components of the Lorentz force.

Global inversions using multi-resolution solar data

Jaime de la Cruz Rodriguez . Adur Pastor Yabar

Institute for Solar Physics, Stockholm University, Sweden

`contact e-mail:` *jaime@astro.su.se*

Diagnosing the physical state of chromospheric plasmas from observational data is best done through inversion techniques. However, not so many chromospheric diagnostics are available in the solar spectrum in comparison with the photosphere. Therefore, in order to set proper constraints on the inversion process, we usually need to include data from remarkably different instruments and telescopes, operating at different spatial resolutions. The inversion process can struggle to process such datasets because the different spectral windows resolve different spatial scales per resolution element. In this review talk I will present a technique that allows processing such complex datasets with minimal blurring effects induced by the lowest resolution data in the set. I will also present early results from the application of this technique to high resolution spectropolarimetric data.

Session 5

Inverse Problem: Methods and Applications

Posters

Spherical Spectropolarimetric Inversions with PINNs Enable Novel Magnetograms from SDO/HMI

Robert Jarolim[1], Momchil Molnar[2], Matthias Rempel[1], and Rebecca Centeno[1]

[1] NSF National Center for Atmospheric Research, High Altitude Observatory, Boulder, 80302, CO, USA
[2] Southwest Research Institute, Boulder, 80301, CO, USA

`contact e-mail:` *momchil.molnar@swri.org*

Spectropolarimetric inversions are fundamental for the inference of the solar magnetic fields. A set of assumptions used for inverting photospheric spectral lines is that they form under the Milne-Eddington (ME) conditions, which allow for fast spectropolarimetric inversions, nowadays used routinely in most inversion pipelines. Our method performs spectropolarimetric inversions of solar data under the ME approximation with Physics Informed Neural Networks (PINNs). Building on synthetic spectral line profiles, we demonstrate that our approach can reliably solve complex magnetic configurations in a computationally-efficient way. Our method intrinsically enables spatially and temporally coupled inversions that can improve the accuracy of the inferred plasma parameters. We apply our method to observations from SDO/HMI in a spherical geometry and compare our results the VFISV pipeline inversions. Our approach improves the accuracy of the magnetic field inversions by the implicit spatio-temporal regularization, and we present an outlook for reducing the noise levels in the faster cadence HMI magnetic field data products. The spherical projection inherent of the method reduces the projection effects close to the limb, which allows us to study the polar magnetic fields. This study highlights the ability of PINNs to smoothly integrate complex data products into a unified representation, achieving state-of-the-art magnetic field estimates and advancing our existing full-Sun observations.

Equipartition field strength on outer sunspot boundary

J. Jurčák[1], M. Schmassmann[2], D. Korda[1], and N. Bello González[2]

[1] Astronomical Institute of the CAS, Ondřejov, Czech Republic
[2] Institute of Solar Physics (KIS), Freiburg, Germany

`contact e-mail:` *jurcak@asu.cas.cz*

The outer boundary of sunspots, specifically the penumbra-quiet Sun transition, has not been studied in detail. Prior observations hinted at specific magnetic field strengths but did not derive a definitive conclusion on its nature. Our studies investigate the magnetic properties of this outer boundary by analyzing SDO/HMI data of a long-lived sunspot and statistically large sample of sunspots observed by SDO/HMI where the intensity maps and inversion results are deconvolved by neural network trained on Hinode SP data. Observational analysis revealed a strong correlation between the continuum intensity boundaries of sunspots (defined as 0.9 of the quiet-Sun continuum intensity) and iso-contours of magnetic field strength. The mean absolute magnetic field strength at this outer boundary was found to be approximately 650 G. This value match the typical value of equipartition field strength in the solar photosphere, but this key physical parameter cannot be reliably determined through inversions of observables. This observational finding is strongly supported by the sunspot simulations. Simulations clearly demonstrate that the total magnetic field strength is approximately equal to the equipartition field strength at the outer penumbral boundary, thereby defining the sunspot's border. Vertical cuts through simulated sunspots show that the magnetopause – the boundary between the sunspot and the surrounding plasma – precisely coincides with the transition from super-equipartition to sub-equipartition field strength. Based on the convergence of observational evidence and simulation results, we conclude that the outer boundary of sunspots is fundamentally defined by the equipartition field strength.

Inversion of the Solar Mg II h and k Lines

Hao Li[1], Tanausú del Pino Alemán[2,3], and Javier Trujillo Bueno[2,3]

[1] State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing, 100190, Peoples Republic of China
[2] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[3] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

contact e-mail: *lihao01@nssc.ac.cn*

The polarization of the Mg II h and k resonance lines is the result of the joint action of scattering processes and the magnetic field–induced Hanle, Zeeman, and magneto-optical effects, thus holding significant potential for the diagnostic of the magnetic field in the solar chromosphere. The Chromospheric LAyer Spectro-Polarimeter sounding-rocket experiment, carried out in 2019, successfully measured the four Stokes parameters in the spectral region of this doublet around 280 nm, both in an active-region plage and in a quiet region close to the limb. We apply to some of the Stokes profiles the recently developed HanleRT Tenerife Inversion Code, which assumes a one-dimensional model atmosphere for each spatial pixel under consideration (i.e., it neglects the effects of horizontal radiative transfer). We find that the nonmagnetic causes of symmetry breaking, due to the horizontal inhomogeneities and the gradients of the horizontal components of the macroscopic velocity in the solar atmosphere, have a significant impact on the linear polarization profiles. By introducing such nonmagnetic causes of symmetry breaking as parameters in our inversion code, we can successfully fit the Stokes profiles and provide an estimation of the magnetic field vector.

Probing solar polar magnetic fields: a spatially-coupled approach with disambiguation

Đ. Mijović[1], I. Milić[2], and R. Centeno[3]

[1] Faculty of Mathematics, University of Belgrade, Studentski Trg 16-20, 11000 Belgrade, Serbia
[2] Institute for Solar Physics, Georges Khöler Allee 401a, 79110 Freiburg, Germany
[3] High Altitude Observatory, Center Green Drive 3090, CO 80301 Boulder, United States of America

contact e-mail: *djordje.mijovic@matf.bg.ac.rs*

In the solar polar regions, the inclined limb geometry and limited spatial resolution of spectropolarimetric instruments introduce significant biases in the retrieval of vector magnetic fields. Near the limb, the Zeeman linear signals, proportional to the square of the transversal magnetic field, contain information on the radial component of the field, which is crucial for studying so-called open polar flux. Furthermore, resolving 180° ambiguity becomes crucial, as it directly influences the inference of the open flux.
In this study, we synthesize full Stokes profiles $\{I, Q, U, V\}$ from a 3D MHD atmosphere model (polar geometry effects are included) and apply spatial degradation to mimic the effects of the telescope's PSF. We perform both traditional pixel-to-pixel inversion and the spatially-coupled approach. By comparing (i) the *ground truth* magnetic field vector ($\boldsymbol{B}$) and line-of-sight (los) velocity (v_{los}) from the original atmosphere, with the results of different inversion approaches (traditional pixel-to-pixel inversion and spatially-coupled inversion) we investigate the improvements in recovering underlying magnetic field structures. After quantifying these improvements, we address the inherent 180° ambiguity in transverse azimuth. To resolve it, we apply a robust minimum energy disambiguation procedure to the ambiguous magnetic field inferred by different inversion approaches.
Our results indicate that combining spatially-coupled inversion and minimum energy disambiguation yields more accurate and reliable reconstructions of photospheric magnetic structures and line-of-sight velocities in polar regions. These improvements are most pronounced within particular ranges of $|\boldsymbol{B}|$ and v_{los}. Intervals differ for various cases we examined.

Non-LTE Inversion of the H-Beta 4861Å Line for Chromospheric Magnetic Field measurement

Wang, Jiasheng[1], Li, Wenxian[2], Bai, Xianyong[2], Tian, Hui[1], Sun, and Yingzi[2]

[1] School of Earth and Space Sciences, Peking University, Beijing, 100871, People's Republic of China
[2] Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Beijing 100101, People's Republic of China

contact e-mail: *jiasheng.wang@pku.edu.cn*

The chromosphere is a complex solar atmosphere that hosts variety of dynamic transients and transports a critical amount of free energy to heat the corona, with mechanisms such as magnetoacoustic wave heating and small-scale transients (nano-flares and spicules) proposed by observational evidence. However, due to the limited sensitivity of polarization measurement and the influence of spectral line broadening, the basic magnetic field configuration in chromosphere has not yet been fully revealed to correspond with the observed phenomena. In this work, we investigated the validity and application of the magnetic field inversion method for the H-beta 4861 Å spectral line with non-local thermodynamic equilibrium (NLTE) approximations. The formation height of H-beta line in the chromosphere is 1200 km, with a stratification of 200 km. We generated synthetic spectra by incorporating magnetic fields into semi-empirical VAL models for quiet Sun and sunpots, and then performed inversions to obtain the magnetic fields, which were then compared with the magnetic fields in the models. In addition, we evaluated the accuracy of the magnetic fields obtained using the weak-field approximation (WFA) and the impact of using these WFA results as the initial guess model for NLTE inversion on the final results. Our work validates the effectiveness of the inversion method applied to the measurement of line-of-sight magnetic field components in both weak-field (0-1200 Gauss) and strong-field (>2000 Gauss) regions, while maintaining accuracy of WFA in the field range of 1000-2000G. This demonstrates that the inversion techniques we employed are capable of resolving Zeeman-sensitive spectral lines in the chromosphere, which can be applied to the H-beta observational data from the Solar Magnetism and Activity Telescope at the Huairou Solar Observing Station to provide full-disk chromospheric magnetic field information.

First results from 3D inversion of the solar chromosphere using CLASP2.1 data

J. Štěpán[1], T. del Pino Alemán[2], and CLASP2. 1 Team

[1] Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic
[2] Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain

`contact e-mail:` *jiri.stepan@asu.cas.cz*

The CLASP2.1 mission has provided unprecedented spectropolarimetric observations of the solar chromosphere through a raster of multiple slit positions, enabling imaging spectropolarimetry across a two-dimensional field of view. We have applied our 3D NLTE inversion code, POLARIS, to these data to infer the physical conditions of the chromosphere. Here we present the first results of this analysis, including the derived thermal and magnetic structure of the observed region.