Solar Polarization Workshop 10

abstract book

2022 Nov.7-11

Kyoto, Japan

Session List

Session 1: New facility and technology of solar polarimetry

Session 2: Solar phenomena revealed by polarimetry

Session 3: Theory and modeling of polarization

Session 4: Techniques for Stokes inversions and disambiguation

Session 5: Synergy to other fields
(stellar physics, planetary science, plasma physics)

Oral Session, 7 Nov.

Session 1

(Invited) EST: The future facility for accurate high-spatial resolution spectropolarimetry

M. Collados[1], C. Quintero Noda[1], M. Barreto[1], R. Schlichenmaier[2]
[1] IAC, [2] KIS
(Presented by L. Bellot Rubio)

Understanding the solar chromosphere represents one of the most difficult challenges in solar physics. The chromosphere is the thin layer in-between the plasma-dominated interior and photosphere and the magnetically-driven corona. Under a theoretical point of view, radiative transfer is dominated by the departure of LTE conditions. Deviations from classical magnetohydrodynamics may also appear as a consequence of its partially ionized nature. Chromospheric phenomena are, in turn, difficult to observe in its integrity because of the fast evolution of its fine structures and of the intrinsically weak polarization signals induced by the magnetic field. EST (European Solar Telescope) is intended to significantly improve our capabilities to observe the chromosphere and address fundamental questions such as:
(i) How does the magnetic field emerge to the surface, evolve and interact with its surroundings?;
(ii) how is the energy transported from the photosphere to chromosphere?;
(iii) how is the energy released and deposited in the upper atmosphere?; and
(iv) why does the Sun have a hot chromosphere?
To achieve these goals, EST includes the most innovative technology, with a simple, efficient and polarimetrically compensated telescope design, together with the most advanced instrumentation to simultaneously sample the physical conditions of the photosphere and chromosphere at the highest spatial and temporal resolutions and magnetic sensitivity that can give insight of the magnetic coupling of the different layers of the deep solar atmosphere. In this talk, the science, the adopted technical solutions and future perspectives of the project will be presented.

Session 1

Early laboratory testing of a photonic magnetograph

N. Hurlburt[1], G. Vasudevan[1], T. Kowalczyk[1], Humphry Chen[1,2], Lawrence Shing[1], Shelbe Timothy[1]
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We present early laboratory test results on the performance of a photonic magnetograph. This new class of magnetographs dispenses with traditional telescopes and mechanisms — replacing them with lasers and integrated circuits. We achieve this by using a patented combination of interferometric imaging, tunable lasers, and digital processing. Photonic magnetographs could scale from 2cm in diameter to 30cm on a single silicon wafer, with resolutions varying from 16 to 1 arc seconds respectively while retaining an essentially wafer-like profile that can easily be hosted on a variety of mission concepts.

Session 1

(Invited) Coronagraph-COronal Magnetism and Plasma ASsembled Scopes(COMPASS)

Zhi Xu and other CO-authors
YNAO

COMPASS, as a huge Lyot coronagraph, is developed from COSMO-LC proposed by Tomczyk et al., aiming at coronal magnetic field diagnostics in lower solar corona. It is featured by the simultaneous and independent polarimetry respectively combined with Integral Field Spectroscopy (IFS) at the green coronal line and tunable filtering observation at 1074.7nm. This talk details the configuration of the COMPASS and recent progresses in realizing the key techniques, including manufacture of a couple of fan-profiled Integral Field Unit (IFU) suitable for spatial scanning, as well as Integral Field Spectrograph (IFS) with multiple slits to promote the spectroscopic sampling efficiency.

Session 1

(Invited) The CLASP2 and CLASP2.1 missions for measuring chromospheric magnetic fields

Donguk Song[1], Ryohko Ishikawa[2], David E. McKenzie[3],
Javier Trujillo Bueno[4], Frédéric Auchère[5], Ryouhei Kano[2],
Laurel A. Rachmeler[6], Takenori J. Okamoto[2], Ken Kobayashi[3],
Christian Bethge[7],
and the CLASP2 and CLASP2.1 teams
[1] KASI, [2] NAOJ, [3] MSFC, [4] IAC, [5] IAS, [6] NOAA, [7] CU Boulder

One of the major remaining challenges in solar physics is to decipher the magnetic structure of the solar upper atmosphere, because it is key for understanding its activity and heating. To this end, we have developed an unprecedented ultraviolet (UV) spectropolarimeter called Chromospheric LAyer Spectro-Polarimeter (CLASP2), aimed at achieving high-accuracy measurements (<0.1% at 3σ) of the linear and circular polarization across the Mg II h & k lines (280 nm). On April 11, 2019, CLASP2 was launched by a NASA sounding rocket, and successfully demonstrated that two Mn I lines and the Mg II h & k lines can be used to directly measure magnetic fields at multiple atmospheric heights, from the lower to the upper chromosphere. CLASP2 was fully recovered after its flight, and we performed the second sounding rocket experiment on October 8, 2021 (hereafter, CLASP2.1). The purpose of CLASP2.1 is to map the solar magnetic field over a 2D field of view (FOV). During the CLASP2.1 flight, we scanned 16 positions in an active region plage, and successfully measured the four Stokes profiles within a FOV of 32”x196”. Recently, the team has developed the Tenerife Inversion Code (TIC) for inferring the magnetic field information from this type of data. In this talk, we present an overview of the CLASP2 and CLASP2.1 suborbital space missions.

Session 1

Multi-Application Solar Telescope (MAST) : Polarimeter and telescope polarization characterization

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Multi-Application Solar Telescope (MAST) is a 50 cm off-axis telescope installed on an island at Udaipur Solar Observatory (USO) and is operational since 2016. A narrow-band spectral imager constructed out of two tandem, Lithium niobate, voltage tunable Fabry-Perot etalons in two wavelengths, FeI 617.3 nm, and CaII 854.2 nm, is integrated with the telescope and is providing simultaneous photospheric and chromospheric spectral images. The images are currently being used for understanding the photospheric and chromospheric dynamics. Another important aim of the narrow-band imager is to measure the solar magnetic field, for which a polarimeter based on two liquid crystal variable retarders is installed. The characterization of the polarimeter along with the calibration unit is in progress. In order to obtain useful magnetic field measurements, it is important to remove the instrument polarization resulting from the primary and secondary reflections, the modeling and measurement of the instrumental polarization are being carried out. In this presentation, some of the results from MAST narrow-band imager will be presented, more specific details of the polarimeter, its calibration, and the efforts being undertaken to remove the telescope polarization will be presented.

Session 1

Recent Progresses in Shaping the FASOT

Zhongquan Qu, Yue Zhong, Zhi Xu, Hui Zhang, Guiwei Zhang,
Xiangming Cheng, Liang Chang
YNAO, CAS

The final version of FASOT experiences three stages. The prototype FASOT, acting as a precursor for testing the crucial techniques, had been constructed in 2012 and used for spectro-imaging polarimetry during solar eclipses, and the Reduced Polarimetric Optical Switching (RPOS) technique is successfully applied for it. The first generation of FASOT was mounted in Lijiang Observing Station, YNAO, Yunnan Province, China. It has just caught the first light. The second generation of FASOT, the final one, has been under construction and will be finished during the 25 solar activity summit. In this oral talk, the details of the above aspects will be reported.

Session 1

(Invited) The polarimetric and helioseismic imager of solar orbiter

D. Orozco Suárez, and the SO/PHI Team
IAA

On February 10, 2020, Solar Orbiter, the new ESA's Sun-exploring mission built in collaboration with NASA, was successfully launched atop an ULA Atlas 5 rocket from Cape Canaveral in Florida. Solar Orbiter has been the first to take the closest pictures ever of the Sun at EUV and visible wavelengths, and the first one that has directly imaged magnetic fields of the solar far side. Among their instruments, the Polarimetric and Helioseismic Imager (SOPHI), one of the remote-sensing suite of instruments aboard Solar Orbiter, aims at measuring the vector magnetic field and the line-of-sight velocity at the solar surface. SOPHI is a spectrometer and a polarimeter that measures the four Stokes profiles of the photospheric Fe I line at 617.3 nm. SOPHI is a genuine instrument of huge engineering importance, with the most cutting-edge and innovative technologies. It is the first instrument of its kind that works as a real tachograph and magnetograph because it delivers the solar physical quantities. Solar Orbiter is now in its nominal mission phase after its commissioning and cruise phases ended in December 2021. In this talk, I will briefly introduce Solar Orbiter and describe the PHI instrument and then review current science plans and highlight first SOPHI observations as well as show some of the first results coming from it.

Oral Session, 8 Nov.

Session 3

(Invited) Highlights of observational and theoretical high-precision spectropolarimetry

Javier Trujillo Bueno
IAC

The key observables for diagnosing magnetism from the photosphere to the corona are the polarization signals that the scattering of anisotropic radiation and the Hanle and Zeeman effects introduce in the spectral lines of the solar spectrum. Here I present a personal selection of high-precision spectropolarimetric measurements and their theoretical modeling, pointing out the underlying science and the improvements needed for facilitating new advances in our empirical understanding of solar magnetism.

Session 3

Non-symmetric Radiative Excitation of Polarized Lines in the Upper Atmosphere

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Forward calculations of polarized scattering in spectral lines formed in the chromosphere and corona often assume an incident radiation field that is unpolarized and cylindrically symmetrical about the radial direction. Treating symmetry-breaking introduced by spots or plage adds complexity to forward models and compounds the existing challenges faced in interpreting observations. Here we discuss recent work aimed at understanding symmetry-breaking effects on coronal forbidden lines, Thomson scattering, and the neutral helium triplet. We briefly introduce a new code called pyCELP that allows flexible calculations of forbidden line polarization, which is then used to model symmetry-breaking effects within a 3D MHD coronal model. We further present a spherical-tensor-based formalism for Thomson scattering that allows easy incorporation of symmetry-breaking in continuum scattering calculations near sunspots. Finally, we will discuss polarimetric observations of He I 1083 nm near sunspots and the role of symmetry breaking on both their intensity and polarized signatures.

Session 3

Formation of the polarized solar He I 10830 A line

Andrés Vicente Arevalo[1], Jiri Stepan[2], Tanausú del Pino Aleman[1]
[1] IAC, [2] ASCR

The He I 10830 A, line is among the most important lines for spectropolarimetric diagnostics of the outer solar atmosphere. Existing inversion methods assume that NLTE radiative transfer is negligible given the small optical thickness of the medium which is often of the order of one. The ongoing development of new inversion tools leads to the need to verify this assumption. We generalize the so-called multi-term picture of atomic levels and we derive a more general set of NLTE equations that can be used in case in which the radiation is not spectrally flat across the 10830 triplet profile. We show that already at optical thickness around tau=2 and in the simple 1D slab geometry, the NLTE transfer within the medium leads to polarization signals that are very different from those obtained using the so-called constant-property slab approximation that is being used today. We argue that neglecting NLTE radiative transfer in the 10830 line can lead to serious errors in the magnetic field diagnostics.

Session 3

(Invited) Modeling the polarization of the Na I and K I D lines

E. Alsina Ballester[1], L. Belluzzi[2], J. Trujillo Bueno[1]
[1] IAC, [2] IRSOL

The cores of the solar Na I and K I D lines provide information on the thermodynamic and magnetic properties of the middle chromosphere and of the region comprising the upper photosphere and lower chromosphere, respectively. Unlike the D1 lines, the D2 lines are intrinsically polarizable and are expected to present scattering polarization signals (i.e., the linear polarization signals produced by the scattering of anisotropic radiation) of sizable amplitude. These signals can be suitably modeled by considering two-term atomic systems with hyperfine structure (HFS). In this talk, we present a series of numerical investigations enabled by our recently developed non-LTE radiative transfer code, which can synthesize the intensity and polarization line profiles considering the aforementioned atomic systems, accounting for frequency correlations between incident and scattered radiation (partial frequency redistribution; PRD) as well as J- and F-state interference. The code can also account for the impact of magnetic fields in the incomplete Paschen-Back effect regime. The investigations presented here are split into two blocks. In the first block, we discuss the resolution of a long-standing paradox, in which the observed sodium D1 linear polarization signals could only be reproduced assuming that the solar chromosphere is practically unmagnetized. By accounting for HFS and PRD, we show that an appreciable D1 scattering polarization signal persists even in the presence of magnetic fields of strengths of tens of gauss. In the second block, we investigate the relevant physical mechanisms in shaping the intensity and polarization patterns of the potassium D lines as well as their magnetic sensitivity, paying particular attention to the D2 line. Our findings enhance the value of the scattering polarization of these lines for diagnostics of the magnetism of the solar chromosphere and upper photosphere, complementary to the information that is available via the circular polarization signals of the same lines.

Session 3

(Invited) Magnetic field diagnostics with UV spectropolarimetry

Tanausú del Pino Alemán
IAC

The electromagnetic radiation of the strongest atomic lines found in the UV solar spectrum comes from the solar chromosphere and thus encodes information about the physical properties of the emitting chromospheric plasma. However, exploiting this spectropolarimetric data is not easy, not only because those regions of the spectrum are out of reach for ground based facilities, but their modeling is also a computational challenge. Recently, the CLASP experiments have opened a new window to the diagnostic of the upper chromosphere and the base of the transition region, as well as the possibility to contrast the theory of atomic line formation with the observations. From the theoretical and computational point of view, these strong UV atomic lines form in a relatively rarefied region of the atmosphere, thus showing not only non-local thermodynamic equilibrium effects, but also the effect of atomic polarization and partially coherent photon scattering. In the last years, the community has significantly progressed on our capabilities to carry out radiative transfer modeling accounting for these physical ingredients, which take a heavy toll on the computational requirements. In particular, we have reached the point of being able to carry out the inversion of spectropolarimetric data, albeit under significant assumptions such as that of plane-parallel model atmospheres. This talk summarizes the main aspects of the UV spectropolarimetric modeling and shows some recents results on chromospheric diagnostics from spectropolarimetric inversions of the CLASP2 data.

Session 3

Exploring the UV solar spectrum: the polarization of Fe II lines between 250-280 nm.

David Afonso Delgado, Tanusú del Pino Alemán, Javier Trujillo Bueno
IAC

Spectropolarimetry of the solar ultraviolet spectrum has opened a new window to study the magnetism of the upper layers of the solar chromosphere. Theoretical investigations and the results of the CLASP (2015) and CLASP2 (2019) suborbital space missions demonstrated the diagnostic potential of the polarization produced by scattering processes and the Hanle and Zeeman effects in some ultraviolet spectral lines, such as Ly α, Mg II h & k, or the Mn I resonance lines to uncover the physics of the upper chromosphere and the transition region.

Although the near-UV spectral region between 250 and 280 nm also includes a significant number of Fe II lines, we lack theoretical and observational investigations about their polarization signals and magnetic sensitivity. In this work, we present the first detailed theoretical study about their intensity and polarization, including the effects of radiative transfer and the Hanle and Zeeman effects.

To this end, we have developed a comprehensive Fe II atomic model that includes all the potentially useful lines in this spectral region. The emergent Stokes profiles have been calculated by solving the problem of the generation and transfer of polarized radiation in a semi-empirical atmospheric model representative of the quiet Sun, and including or neglecting the contribution of arbitrary magnetic fields. We present a selection of Fe II spectral lines with significant linear and circular polarization signals and evaluate their diagnostic capabilities by studying their scattering polarization signals, formation heights, and magnetic sensitivity through the action of the Hanle and Zeeman effects. In addition, we include a detailed study of a weak Fe II emission line that is located in the far wings between the Mg II h & k lines, whose intensity and polarization has been recently observed by the CLASP2 mission.

Session 3

Simulating the Solar Corona in the Forbidden and Permitted Lines with Forward Modeling

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The magnetic field in the corona is important for understanding solar activity. However, routine observations of the linear polarization has only been achieved in the visible/IR which provides information about coronal magnetic direction and topology. To provide a constrain on the coronal magnetic field strength, the unsaturated, or critical regime of the magnetic Hanle effect which is potentially observable in permitted lines for example in the UV, is a promising candidate. To better understand how such observations might be used together in the future to diagnose the coronal magnetic field, a side-by-side comparison of forbidden versus permitted linear polarization signatures, which examines the transition from the unsaturated to the saturated regime, is investigated in this work. In addition, we use an analytic 3D flux rope model to demonstrate the Hanle effect for the line-of-sight versus plane-of-sky (POS) components of the magnetic field. As expected, the linear polarization in the unsaturated regime will vary monotonically with increasing magnetic field strength for regions where the magnetic field is along the observer's line of sight. The POS component of the field produces a linear polarization signature that varies with both the field strength and direction in the unsaturated regime. Once the magnetic field is strong enough that the effect is saturated, the resulting linear polarization signal is essentially the same for the forbidden and permitted lines.

Session 3

P-CORONA : A new forward modeling code to study the polarization of solar coronal lines

Supriya Hebbur Dayananda[2], Ángel de Vicente[2], Nataliia Shchukina[3,4], Tanausú del Pino Alemán[2], Javier Trujillo Bueno[2]
[1] IRSOL, [2] IAC, [3] Main Astronomical Observatory, [4] NASU

Over the last few years we have developed P-CORONA, a new parallel code to model the intensity and polarization of both forbidden and permitted lines in 3D models of the solar corona. For any coronal line of interest, P-CORONA computes the line-of-sight integrated Stokes profiles in any given 3D coronal model taking into account the symmetry breaking produced by the presence of magnetic fields and non-radial solar wind velocities. In this contribution, we first give an overview of P-CORONA (which will be made available as an open-source code to the astrophysical community in the near future). Secondly, we will present the results of an investigation of the effects of non-radial solar wind velocities on the polarization of the Fe XIII lines at 10747 and 10798 Å. Generally, these forbidden lines are assumed to be insensitive to the solar wind velocities because it is given for granted that the pumping radiation from the underlying solar disk is spectrally flat. However, there are strong photospheric lines of Si I at nearby wavelengths, separated in velocity by 72 km/s and 47 km/s, respectively, from the Fe XIII 10747 Å and 10798 Å lines. We present the results of our investigation of this problem in 3D models of the solar corona.

Session 3

Comprehensive data on atom+hydrogen and atom+electron collisions for spectroscopic and spectropolarimetric applications

M. Derouich
KSA

Without comprehensive knowledge of atomic collision data, efficient exploitation of polarimetric and spectroscopic observations becomes complicated. To contribute in overcoming this complication, we provide accurate variation laws leading to comprehensive determination of all depolarization and polarization transfer rates due to elastic collisions of hydrogen atoms with solar simple atoms, complex atoms, and atoms with hyperfine structure (e.g. Derouich 2020, The Astrophysical Journal Supplement Series, Volume 247, Issue 2, id.72). Then, we present general approach for calculating rates of excitation and polarization transfer due to collisions with electrons. Accuracy of our results is discussed. In addition, we extract new useful insights from the existing literature and suggest concrete ways of understanding, and correctly using, the available collisional data. Interesting open questions and misunderstandings will be pointed out and illustrated, especially regarding the case where magnetic fields effects are relevant during the collisions.

Oral Session, 9 Nov.

Session 2

(Invited) Hanle rotation finally revealed in Sr I 4607

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Measuring and interpreting small-scale magnetic fields in the solar atmosphere are crucial, yet challenging, tasks. Observations of scattering polarization and the Hanle effect in various spectral lines are increasingly used to complement traditional magnetic field determination techniques. One of the strongest scattering polarization signals in the photosphere is measured in the Sr I line at 4607.3 Å when observed close to the solar limb, that makes it a favourite line to observe since several decades. Despite many observations, one phenomenon clearly observed in several other scattering-sensitive spectral lines but turned out to be very elusive in Sr I is Hanle rotation.

In this talk I present the first observational evidence of Hanle rotation in the linearly polarized spectrum of the Sr I line at several limb distances. To achieve highly precise and unprecedentedly accurate polarization measurements needed to reveal the Hanle rotation signatures, we combined the fast modulating Zurich IMaging POLarimeter, ZIMPOL, at the IRSOL observatory in Locarno, Switzerland, with a novel technique based on a slow modulator installed in front of the telescope. With this setup, singly peaked linear polarization signals deviating from the expected scattering direction at the limb well above the noise level were detected. We carefully excluded instrumental or Zeeman origin of these signals. This suggests that the detected signals are the unambiguous signatures of Hanle rotation caused by spatially resolved, but weak magnetic fields.

Observing Hanle rotation signatures is an assisting tool to diagnosing these magnetic fields, which can be routinely applied on small spatial scales in the era of DKIST.

Session 2

Polarization measurement of the O V 121.83 nm intercombination line with CLASP

Y. Katsukawa[1], J. Trujillo Bueno[2], R. Manso Sainz[3], R. Ishikawa[1], J. Stepan[4], R. Kano[1], M. Kubo[1], N. Narukage[1], T. Bando[1], A. Winebarger[5], K. Kobayashi[5], F. Auchere[6]
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The Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) sounding rocket experiment provided precise polarimetric measurements of far ultraviolet (FUV) emission lines emanating from the solar chromosphere and transition region. The CLASP observation covered linear polarization not only at the optically thick H I Lyman-alpha 121.57 nm line but also at the weaker Si III 120.65 nm line as well as at the even weaker O V 121.83 nm line adjacent to H I Lyman-alpha. The Lyman-alpha wings and THE Si III line exhibit clear center-to-limb variation (CLV) of the fractional linear polarization Q/I, showing a negative increase toward the limb, with a fractional polarization signal of around 4% near the limb (Kano et al. 2017, Ishikawa et al. 2017). The negative Q/I corresponds to polarization perpendicular to the limb, which is consistent with the theoretical prediction where multiple scattering events create the linear polarization when the radiation propagates through the upper chromosphere and the transition region. The O V 121.83 nm line is weak because the line results from an intercombination transition. The CLASP observation indicates the possible existence of linear polarization perpendicular to the limb at the O V line. The fractional linear polarization Q/I is larger than the estimated noise only near the limb and is about 2% when we subtract the influence of the nearby continuum coming from the Lyman-alpha wing. If confirmed, polarization measurements of the OV line might provide a new tool to constrain the density as well as the magnetic field configuration in the upper chromosphere and the transition region.

Session 2

Observational Evidence for the Hanle and Magneto-Optical Effects in the Polarization of the Mg II h & k Lines Observed by CLASP2

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[1] NAOJ, [2] IAC, [3] IRSOL, [4] NASA, [5] IAS, [6] NOAA, [7] KASI

Using the unprecedented observations across the Mg II h & k lines around 280 nm obtained by the Chromospheric LAyer Spectro-Polarimeter (CLASP2), we investigate how the linear polarization signals at different wavelengths (i.e., at the center, and at the near and far wings of the k line) vary with the longitudinal component of the magnetic field (B_L) at their approximate height of formation. Particular attention is given to the sign of the Stokes U signals, and the total linear polarization amplitude (LP) and its direction (χ), which are expected to be influenced by the presence of magnetic fields through the Hanle and magneto-optical (MO) effects. We find that at the center and near wings of the k line, the behavior of these quantities is significantly different in the observed quiet and plage regions, and that both LP and χ seem to depend on B_L. These observational results are indicative of the operation of the Hanle effect at the center of the k line and of the MO effects at the near wings of the k line. Hydrogen Lya at 121.6 nm is another spectral line sensitive to the Hanle and MO effects. We also show the 2D map of linear polarization in the Lya wings obtained by the CLASP2 slit-jaw imager, aiming at finding evidence of the operation of the MO effects.

Session 4

(Invited) Magnetic field diagnostic for the Solar Chromosphere

R. Centeno
HAO/NCAR

Sitting between the dynamically driven Photosphere and the magnetically dominated Corona, is the ever-elusive solar Chromosphere, which harbours the key to quantifying the state and the evolution of the Sun's outer magnetic envelope.

Our knowledge of the magnetic fields in the Sun's atmosphere relies, almost entirely, on our ability to interpret the intensity and the polarization of the light that it emits. While inferences of the photospheric magnetic field vector have been routinely carried out for decades now, chromospheric magnetometry is challenging at many levels. In particular, chromospheric spectral line polarization is theoretically complex and computationally demanding to model, let alone to interpret. In this talk I review the accuracy and limitations of approximate magnetic field inference tools applied to some chromospheric spectral lines of interest.

Session 4

Mapping the magnetic field azimuth in the chromosphere

J. Jurcak[1], J. Stepan[1], J. Trujillo Bueno[2]
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The Zeeman effect is of limited utility for probing the magnetism of the quiet solar chromosphere. The Hanle effect in some spectral lines is sensitive to such magnetism, but the interpretation of the scattering polarization signals requires taking into account that the chromospheric plasma is highly inhomogeneous and dynamic (i.e., that the magnetic field is not the only cause of symmetry breaking). Here we investigate the reliability of a well-known formula for mapping the azimuth of chromospheric magnetic fields directly from the scattering polarization observed in the Ca II 8542 A line, which is typically in the saturation regime of the Hanle effect. To this end, we use the Stokes profiles of the Ca II 8542 A line computed with the PORTA radiative transfer code in a three-dimensional (3D) model of the solar chromosphere, degrading them to mimic spectropolarimetric observations for a range of telescope apertures and noise levels. The simulated observations are used to obtain the magnetic field azimuth at each point of the field of view, which we compare with the actual values within the 3D model. We show that, apart from intrinsic ambiguities, the method provides solid results. Their accuracy depends more on the noise level than on the telescope diameter. Large-aperture solar telescopes, like DKIST and EST, are needed to achieve the required noise-to-signal ratios using reasonable exposure times.

Session 2

Synthetic Ca II 8542Å Stokes profile of chromospheric magnetic reconnection in emerging flux region

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Magnetic reconnection is an important driving mechanism of many chromospheric phenomena, e.g., UV bursts and chromospheric jets. Information of magnetic field is indispensable for analyzing chromospheric magnetic reconnection, which is mainly encoded in polarization signal. Previous studies suggested Ca II 8542Å chromospheric line as a good candidate for polarization signal studies. We aim to predict possible Stokes features of 8542Å related with chromospheric reconnection events, from realistic 2D MHD simulation and Stokes profile synthesis. Emerging magnetic flux sheet is imposed to imitate the emerging flux region, at the bottom boundary of well-relaxed unipolar atmosphere, which covers from convection zone to corona. The reconnection region is heated to ~8kK and the outflow velocity reaches ~35km/s. Through Stokes profile synthesis, several Stokes features related with reconnections and plasmoids are reproduced. We found direction switch on Stokes V and amplitude reduction on linear polarization at reconnection sites. Also, we report strong linear and circular polarization signals corresponding to huge and tiny plasmoids, respectively. Meanwhile, we discussed the differences of Stokes features between reconnections and shocks. We conclude that chromospheric reconnection could lead to several distinctive polarization features, which could be indicators to discriminate reconnections from other phenomena such as shocks in observation.

Session 2

(Invited) Chromospheric magnetic field in active regions

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Chromosphere is a dynamic layer in the solar atmosphere where various energetic events occur. Because the plasma beta becomes smaller than unity in the chromospheric layer, the dynamics is thought to be dominated by the magnetic field. It is crucial to infer the chromospheric magnetic field to understand the mechanisms of such energetic events. Recently, chromospheric magnetic field has been measured by spectropolarimetry with ground-based telescopes. We would like to summarize the previous studies focusing on chromospheric magnetic field observations in active regions.

We will report our recent study on the chromospheric magnetic field observations and nonlinear force-free field (NLFFF) extrapolation modeling. One of the assumptions in the NLFFF extrapolation is that the plasma beta is low, but this condition is considered to be incorrect in the photosphere. To evaluate the influence on the modeling due to the boundary condition inconsistency, the results of NLFFF extrapolation from the photosphere observed with Hinode are compared with the spectropolarimetric observations at He I 1083 nm. The comparisons allow quantitative estimation of the NLFFF uncertainty. We found that chromospheric magnetic field may have larger non-potentiality compared to the photospheric magnetic field and the large non-potentiality in the chromospheric height may not be reproduced by the NLFFF extrapolation from the photospheric magnetic field. We will also discuss the prospect of the future chromospheric magnetic field observations.

Session 2

Does the Hα Stokes V profiles probe the chromospheric magnetic field? An observational perspective

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The H α line is one of the most widely used spectral lines to study the solar chromosphere. However, polarimetric studies to infer the magnetic fields are sparse. One of the reasons could be that it has been shown using 1-D radiative transfer calculations that the photospheric magnetic fields have a significant contribution to the H α Stokes V profiles. Recent works, however, have revealed that 3-D radiative transfer is necessary to model the H α line core, though the works have only modeled the Stokes I. In this context, we explore the potential of the H α Stokes V profiles in inferring the chromospheric magnetic field using simultaneous spectropolarimetric observations of the H α and the Ca II 8542 Å lines obtained from the SPINOR instrument of the DST. We analyzed the topology and the strength of the LOS magnetic field (B) inferred from the weak field approximation (WFA) of the H α line and compared it with the inversions of the Ca II 8542 Å line. We found that the map of the B inferred from the WFA of the H α line core ($\pm$0.35 Å) shows morphology similar to that of at the chromospheric layers (log τ 500 = $-$4.5). The map of the B from the WFA about the line wings ([$-$1.5, $-$0.6] and [+0.6, +1.5] Å) and the full spectral range ($\pm$1.5 Å) shows morphology similar to that of at the photospheric layers (log τ 500 = $-$2). At the location of a pore we observed that the field strengths (|B|) inferred from the WFA about the H α line core are weaker than those obtained at log τ 500 = $-$4.5 through the inversions of the Ca II 8542 Å line. Our results suggest that |B| retrieved with the WFA applied to the H α line core is from higher chromospheric layers compared to that retrieved using the inversions of the Ca II 8542 Å line.

Session 2

Inference of the chromospheric magnetic field configuration of solar plage using the CaII 8542 angstrom line

A.G.M. Pietrow[1], D. Kiselman[2], J. de la Cruz Rodríguez[2], C.J. Díaz Baso[2], A. Pastor Yabar[3], R. Yadav[3]
[1] AIP, [2] SU, [3] SE

It has so far proven impossible to reproduce all aspects of the solar plage chromosphere in quasi-realistic numerical models. The magnetic field configuration in the lower atmosphere is one of the few free parameters in such simulations. The literature only offers proxy-based estimates of the field strength, as it is difficult to obtain observational constraints in this region. Sufficiently sensitive spectro-polarimetric measurements require a high signal-to-noise ratio, spectral resolution, and cadence, which are at the limit of current capabilities. We use critically sampled spectro-polarimetric observations of the Ca II 8542 Å line obtained with the CRISP instrument of the Swedish 1-m Solar Telescope to study the strength and inclination of the chromospheric magnetic field of a plage region. This will provide direct physics-based estimates of these values, which could aid modelers to put constraints on plage models.
We use a non-local thermodynamic equilibrium inversion code called STIC to infer the atmospheric structure and magnetic field of the region. In the plage we report an absolute field strength of $|B| = 440 \pm 90$ G, with an inclination of $10° \pm 16°$ with respect to the local vertical. This value for $|B|$ is roughly double of what was reported previously, while the inclination matches previous studies done in the photosphere.

Session 2

Velocity and Magnetic Field of Outflows from a Magnetic Reconnection Event

Krishnappa Nagaraju, K. Sankarasubramanian, and K. E. Rangarajan
Indian Institute of Astrophysics

Simultaneous multi-line spectropolarimetric observations of a magnetic reconnection event were carried out using the SPINOR instrument at the Dunn Solar Telescope. The magnetic reconnection took place when an emerging bipolar region interacted with the canopy fields of a pore resulting in a microflare. Several jets and multiple Halpha surges were produced during this event. The signatures of jets are observed as three lobed Stokes V profiles in the photospheric lines at 656.922 nm and 853.8 nm due to Fe I, and 853.6 nm due to Si I. The signatures of surges are observed as highly asymmetric intensity profiles of H alpha (656.28 nm) and Ca II 854.2 nm lines as well as in the Stokes V profiles of the photospheric lines. The H alpha surges are clearly seen in the slit-jaw images recorded with a narrow-band filter (UBF) tuned to five different wavelength positions within the H alpha line. We carried out two component inversion of Fe I 656.922 nm using the Stokes Inversion based on Response function (SIR) code to estimate the velocity and magnetic field of the jets and the surges. Further, we used bisector method to estimate the velocities from the intensity profiles of Halpha and Ca II 854.2 nm lines. In this presentation we will discuss in detail about the quantitative estimation of velocity and magnetic field of these reconnection outflows.

Session 5

(Invited) Electron temperature anisotropy explored by the impact polarization of the Lyman-alpha line in fusion plasma

M. Goto[1], N. Ramaiya[2], T. Oishi[2], Y. Kawamoto[2], T. Kawate[2]
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We have succeeded to detect polarization of the hydrogen Lyman-alpha line in the Large Helical Device, a heliotron type fusion experimental machine. With the help of an atomic model simulation, the anisotropy in the electron velocity distribution function in terms of the ratio of electron temperatures between parallel and perpendicular directions to the magnetic field is evaluated. The results show that the ratio of parallel to perpendicular temperatures takes value of roughly 0.1 while the Thomson scattering diagnostic gives the perpendicular temperature of 50 eV at the plausible Lyman-alpha emission location. This ratio increases to 0.5 when the Thomson scattering temperature decreases to 10 eV. On the other hand, no clear dependence of the ratio on the electron density is observed.

Session 3

Modeling scattering polarization accounting for angle-dependent PRD effects

L. Belluzzi[1], P. Benedusi[2], N. Guerreiro[1], G. Janett[1], S. Riva[3,4]
[1] IRSOL, [2] SIMULA Research Laboratory, [3] Università della Svizzera italiana, [4] USI

The correct modeling of the scattering polarization signals observed in many strong resonance lines of the solar spectrum requires accounting for coherent scattering processes with partial frequency redistribution (PRD). Modeling PRD effects is notoriously difficult from a computational standpoint, and simplifying approximations, such as angle-averaging the redistribution matrices, are frequently applied to lower the computational cost, but at the price of introducing hardly predictable artifacts and inaccuracies.

Starting from a suitable algebraic formulation of the problem, we devised a new parallel solution strategy for the non-LTE radiative transfer problem for polarized radiation. The approach is tailored for modeling PRD effects by applying the exact angle-dependent expression of the redistribution matrix. A code capable of solving the problem in both 1D and 3D models of the solar atmosphere, for the case of a two-level atom in the presence of arbitrary magnetic and bulk velocity fields, is operational. In the 1D geometry, it can be routinely applied to get scientific worthy results in a few minutes, using a couple of computing nodes.

Following a brief account of the physical and numerical approach to the problem, we explore a number of 1D applications of scientific interest, contrasting the results of angle-dependent and angle-averaged calculations, and we present first preliminary results of 3D calculations.

Session 3

(Invited) Multi-fidelity preconditioning of Krylov solvers for linear transfer problems of polarized radiation

G. Janett[1], P. Benedusi[2]
[1] IRSOL, [2] USI

The modeling of the transfer of polarized radiation gives rise to a large class of problems, which can be reframed as linear systems. Depending on the considered physical assumptions, these problems can be relatively lightweight from the computational point of view, or extremely complex and challenging for state-of-the-art iterative methods.
We propose a multifidelity approach, which leverages the strengths of different modeling assumptions and strategies, of variable accuracy and computational cost: we design efficient preconditioners, based on lightweight simplified (low-fidelity) models,
tailored to obtain accurate and fast solutions of specific computationally expensive (high-fidelity) problems.
We first apply a multifidelity preconditioned matrix-free GMRES iterative method
to the radiative transfer modeling of intensity and polarization of the solar CaI 4227A spectral line, considering a two-level atom in a 1D atmospheric model, taking angle-dependent PRD effects into account. The proposed strategy shows near-optimal strong and weak scaling and converges in a few iterations, thus suggesting its suitability for realistic 3D applications. Subsequently, we apply and analyze the performance of the same solution strategy to model the Mg II h & k lines by considering a two-term atom.

Session 3

Scalable Matrix-free Solver for 3D Polarized Radiative Transfer in Stellar Atmospheres

P. Benedusi [1], S. Riva [2], P. Zulian [2], J. Štěpán [3], L. Belluzzi [4], R. Krause [2]
[1] Simula, [2] USI, [3] Astronomical Institute of the Czech Academy of Sciences, [4] IRSOL

We present an efficient and massively parallel solution strategy for the transfer problem of polarized radiation. We consider a 3D medium out of local thermodynamic equilibrium, accounting for partial frequency redistribution effects in scattering processes. Such a setting results in one of the most challenging problems in radiative transfer modelling. The discrete ordinate method alongside an exponential integrator are used for discretization. Efficient solution is obtained with a Krylov method equipped with a tailored multi-fidelity 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 with more than one billion of degrees of freedom in less than half an hour on massively parallel machines, always converging in a few iterations for the proposed tests.

Session 3

Influence of Thomson Scattering Redistribution on Resonance Line Polarization

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Thomson scattering of line photons by electrons at rest is frequency coherent. However, when thermal motion of electrons is accounted for the scattered line photons get redistributed in frequency according to the Thomson electron scattering redistribution function. In this talk we present a recent investigation on influence of Thomson electron scattering redistribution on resonance line polarization formed in spherically symmetric extended and expanding atmospheres. The concerned polarized transfer equation is solved in the comoving frame using the accelerated lambda iteration technique. We highlight the importance of including the Thomson electron scattering redistribution effects in polarized spectral line formation problems relevant to stellar atmospheres.

Oral Session, 10 Nov.

Session 2

(Invited) The impact of He I 1083 nm spectropolarimetry in solar physics

T. Anan
NSO

He I 1083 nm is a unique spectral line in the solar spectra. The line appears strongest in chromospheric temperature plasma that is irradiated by strong coronal EUV emission, which plays an important contribution in how energy levels in neutral helium atoms are populated. In addition, the line is very sensitive to the magnetic field in the chromosphere through the Zeeman and Hanle effects. In this talk, I am going to present some studies utilizing the unique features of this line to address some important science questions in solar physics. The line has been used to measure expansion of magnetic flux tubes (Orozco Suárez et al. 2015), investigate (de)coupling of neutral atoms from plasma (Schad et al. 2013), track heating in plage regions and the corona (Anan et al. 2021; Solanki et al. 2003), measure the magnetic fields in corona via coronal rain (Schad 2018), as well as address the global energetic of solar flares (Anan et al. 2018), and so on. Since DKIST will have two instruments with He I 1083 nm spectropolarimetric capabilities, the improved cadence and spatial resolution will lead to new discoveries using this line.

Session 2

Investigation of the magnetic field structure of dark filaments by using a spectro-polarimetric observation with He I 1083 nm

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Solar filaments are the dense cool plasma clouds in the solar corona. They are supported by the helical coronal magnetic field. However, the models are still under argument; one is the normal polarity model proposed by Kippenhahn & Schlueter (1957), and the other is the reverse polarity model proposed by Kuperus & Raadu (1974). To understand the mechanism that the filaments become unstable before the eruption, it is critical to confirm the magnetic structure of solar filaments. In this study, we performed the spectro-polarimetric observation with the He I 1083 nm line to investigate the magnetic field structure of dark filaments. The observation was carried out with the Domeless Solar Telescope at Hida Observatory which achieves a polarization sensitivity of 3.0×10^-4. We obtained 9 samples of quiet sun (QS) filaments and 10 samples of active region (AR) filaments. As a result of the analysis of full Stokes profiles of QS filaments, we found that the linear and circular polarization signals of 1.6 - 3.0×10^-3 and 0.4 - 1.8×10^-3, respectively. By comparing with the synthetic Stokes profiles calculated with HAZEL (Assensio Ramos & Trujillo Bueno 2008), we confirmed that the observed linear and circular polarization signals were caused by the Hanle effect and the Zeeman effect, respectively. For the QS filaments, the field strengths were estimated as 20 - 50 G. We also estimated the directions of the transversal components of the magnetic field on dark filaments. We found that the direction was roughly along the direction of the main body of the filaments. In our presentation, we will also discuss the field strengths and the magnetic field structures of AR filaments based on our observation.

Session 2

Superstrong magnetic fields in bipolar light bridges

J. S. Castellanos Duran, N. Milanovic, A. Korpi-Lagg, B. Loeptien, M. van Noort, S. K. Solanki

MPS

The strongest magnetic fields on the Sun were long thought to appear in umbrae of large sunspot groups. However, recent spectropolarimetric observations have identified superstrong magnetic fields that are well beyond typical umbral fields, but in bright regions. One of these observations detected superstrong fields up to 8.2 kG in one bipolar light bridge (BLB). These regions appear in between two umbrae with opposite polarity. In this work, we present the first statistical analysis of BLBs. We analyzed spectropolarimetric data taken by Hinode/SOT-SP. These data were analyzed using the 2D coupled inversions that account for the point-spread function of the telescope during the minimization procedure. We found 48 BLBs hosted in 37 different sunspot groups. The 48 BLBs were seen in ~400 different Hinode/SOT-SP scans. Consistently similar characteristics were found in BLBs: superstrong magnetic fields, bi-directional velocity flows, and bipolar magnetic structures with the polarity inversion line commonly appearing along the long axis of the light bridge. In addition, visual inspection of the continuum images combined with the magnetic azimuth information suggests that BLBs are highly sheared regions. Our findings point to the shear being an important common mechanism to enhance the magnetic field to superstrong levels inside BLBs.

Session 2

The strongest magnetic fields in sunspots and their statistical properties

Joten Okamoto
NAOJ

Sunspots are concentrations of magnetic fields on the solar surface. Then, where is the strongest field in each sunspot? It is generally located in an umbra, but sometimes stronger fields are found outside umbrae, such as a penumbra and a light bridge. The formation mechanism of such strong fields outside umbrae is still puzzling. Now we have numerous high-quality datasets taken with the Hinode/Spectro-Polarimeter over 10 years, which motivate us to address this question via a statistical analysis of strongest fields in sunspots. Hence, we complied a ranking list of active regions by their largest field strengths and investigated conditions for appearance or formation of strong magnetic fields. In this talk, we will discuss the key features to produce strong fields in a statistical sample.

Session 4

(Invited) An Overview of Disambiguation Techniques

Graham Barnes
NWRA

Typical Stokes inversion codes can only infer the transverse component of the magnetic field up to an ambiguity of 180 degrees in its direction. To take full advantage of the information returned by the inversion, it is necessary to resolve this ambiguity. I will give an overview of existing disambiguation methods, focusing on some recent approaches that incorporate either the temporal evolution of the magnetic field, or its variation with optical depth to provide an additional constraint on the direction of the field, as well as the use of machine learning to directly infer the disambiguated components of the magnetic field from Stokes spectra.

Session 2

Unipolar and bipolar magnetic flux appearance in the quiet Sun internetwork

Luis Bellot Rubio [1], Milan Gošić[1,2,3], Mark Cheung[2], David Orozco Suárez[1], Yukio Katsukawa[4], and Jose Carlos del Toro Iniesta[1]
[1] IAA-CSIC, [2] LMSAL, [3] BAERI, [4] NAOJ

Small-scale internetwork magnetic fields are considered to be the main building blocks of the quiet Sun magnetism. Thus, it is important to understand how they appear on the solar surface. In this work we employ long-duration Hinode/NFI magnetogram sequences to analyze the appearance modes and temporal evolution of individual internetwork magnetic elements inside a supergranular cell at the disk center. We identify bipolar features by examining the properties of the footpoints and assessing their magnetic connectivity through a magnetofrictional simulation. The rest of features are considered to be unipolar. Magnetic bipoles appear at a faster rate than unipolar features (68 as opposed to 55 Mx cm-2 day-1), and provide about 70% of the total instantaneous internetwork flux detected in the interior of the supergranule. Bipolar features tend to be bigger and stronger than unipolar features. They also live longer and carry more flux per feature. Both types of flux concentrations appear uniformly over the solar surface. However, bipolar features represent new flux on the solar surface, while unipolar features are probably formed by the coalescence of background flux. This may solve the problem posed by studies that reported most of internetwork features to be unipolar.

Session 2

Traits of a quiet Sun Ellerman Bomb

Anjali J. Kaithakkal[1], J. M. Borrero[2], A. Pastor Yabar[3],
J. de la Cruz Rodríguez[3]
[1] ARIES, [2] KIS, [3] ISP, Stockholm U.

The focus of this investigation is to quantify the conversion of magnetic to thermal energy initiated by a quiet Sun cancellation event and to explore the aspect of current dissipation resulting from the interaction of the opposite polarity magnetic features. Using a quiet Sun disk center observation acquired with the Swedish Solar Telescope (SST), we studied a reconnection-related cancellation and the appearance of a quiet Sun Ellerman bomb (QSEB). The data has imaging spectroscopy in the Balmer H α line at 656 nm, along with spectropolarimetry in the Fe I 617 nm, Ca II 854 nm lines. The event that we studied involves a pre-existing magnetic feature of positive polarity reconnecting with an emerging negative polarity feature of a relatively smaller size. In addition to enhancements in the wings of H α, and both the core and the wings of the Ca II line profile, we also observe an increase in both the wings and core of the Fe I spectral line as well. To the best of our knowledge, this is the first time a QSEB leaving its imprint in the Fe I 617 nm spectral line is reported. From FIRTEZ-dz inversions of the spectropolarimetric data, we obtained a flux cancellation rate of 5.9 × 1014 Mx/s which is comparable to that reported for EBs, and a temperature enhancement of 882.0 K at the photospheric height (log τ = -1.5) and that of 854.3 K at the chromospheric height (log τ = -5.0). We also derived total magnetic energy within the height between log τ = −1.5 and log τ = −5.0 and found it to be in the range of [1019 − 1022] erg and thermal energy in the range of [1018 − 1021] erg, implying that the magnetic energy released during the flux cancellation event can support heating in the range of heights covering photosphere and chromosphere. The inversion results also showed the presence of a current sheet between the cancelling magnetic features and it points to a significant contribution of current dissipation to heating from the photosphere to the chromospheric heights.

Session 2

(Invited) Spectropolarimetry of flaring active region

D. Kuridze
Aberystwyth University

The structure and dynamics of flaring active regions are controlled by the magnetic field. Therefore, measurements of the magnetic field are key to our understanding of flare physics. It is well known that flare activity increases the signal-to-noise of the polarimetric signals in optical and near infrared spectral regions at energy deposition sites such as ribbons and kernels. This makes flares well-observable with large aperture, high-resolution ground-based telescopes, providing a unique chromospheric diagnostic for measuring the magnetic field. However, intense heating of the chromosphere during flares leading to a deepening of the monochromatic optical depth via ionisation, which is an example of the multi-variable effects that make sophisticated tools such as inversions critical in the careful interpretation of flare spectropolarimetry. Furthermore, flare material evaporates from the chromosphere and becomes part of the corona and subsequently condensate and form loops with high density and lower temperature. Such loops also permit the use of chromospheric diagnostic as the plasma falls and traces magnetic field lines. In my talk I will discuss recent advances, basic methods, and specific aspects of flare polarimetry.

Session 2

Stratification of physical parameters in a C-class solar flare using multi-line observations

R. Yadav[1,2], J. de la Cruz Rodríguez[2], C. J. Díaz Baso[2], F. Calvo[2],
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[4] Catholic Univ. of America

We present high-resolution and multiline spectropolarimetric observations of a C2-class solar flare (SOL2019-05-06T08:47). The rise, peak, and decay phases of the flare were recorded continuously and simultaneously in the Ca II K, Ca II 8542 Å, and Fe I 6173 Å lines with the CRISP and CHROMIS instruments at the Swedish Solar Telescope. The observations in the chromospheric Ca II lines exhibit intense brightening near the flare footpoints. At these locations, a non-LTE multiline inversion code (STiC) was employed to infer the stratification of temperature, magnetic field, line-of-sight velocity, and microturbulent velocity at the flare footpoints. We also estimated radiative losses in the lower limited chromosphere from the Ly-alpha, singly ionized Ca and Mg atoms using the semi-empirical model atmosphere inferred from the inversion of the CRISP and CHROMIS datasets. The stratification and temporal analysis of the inferred parameters shows the evidence of chromospheric heating, the presence of both chromospheric evaporation and condensation at the flare footpoints. Moreover, we have also obtained a high spatial-resolution map of integrated radiative losses around the flare peak time. The stratification of the net cooling rate suggests that the Ca IR triplet lines are responsible for most of the radiative losses in the flaring atmosphere. The maximum value of integrated radiative losses is reached around the flare peak time, and can go up to 175 kW m−2 for a single pixel located at footpoint. The obtained radiative losses values are also compared with the RADYN flare simulations. Our analysis illustrates that even a less intense C-class flare can heat the deeper layers of the solar chromosphere, mainly at the flare footpoints.

Session 2

A new view into flaring sunspots

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The solar magnetic field in the Sun reveals itself in different structures, being sunspots one of the most wonderful ones. They are the oldest known manifestations of solar activity and appear on the solar surface as single entities or in groups associated with magnetic bipoles (known as active regions). Sunspots are large magnetic field concentrations that inhibit the normal convection observed on the solar surface. This inhibition makes these structures cooler and darker than the surrounding photosphere. Moreover, the sunspots are frequently associated with one of the most energetic events in the Sun: solar flares. These events, and associated eruptions, if strong enough, may cause damage to the Earth. This is why it is important to better understand the behavior of sunspots, particularly the behavior of the magnetic field associated with them. Such knowledge would improve our understanding of the Sun and would also help prevent possible damage to our technology. An interesting and still open question in Solar Physics concerning solar flares is their ability to produce local heating, and if so, the mechanism(s) underlying this heating. One possible source of local heating is the ohmic dissipation, whose determination requires the evaluation of electric currents. We are in a sweet opportunity as the newly developed Stokes inversion code (FIRTEZ-dz) is able to perform the inference in the x, y, z domain and thus it allows the determination of, among other physical parameters, electric currents. This way, combining these new properties of this inversion code with the very good spatial resolution data observed by SP/SOT/Hinode, we have studied a flare event that led to important photospheric heating and we have estimated the contribution to this heating by ohmic dissipation.

Session 2

Recent Developments in Low-frequency Spectro-Polarimetric Snapshot Imaging Studies of the Radio Sun

Devojyoti Kansabanik[1], Divay Oberoi[2], Surajit Mondal[3], Soham Dey[2], Puja Majee[2]

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Meter-wavelength radio emissions are generated by the different physical processes in corona. All of these processes are governed by the magnetic field of the solar corona. The emission mechanism, magnetic field, and propagation effect imprint some of their signatures on the polarization of these radio emissions. The circular polarization fraction of these emissions vary by two orders of magnitude, while their brightness temperature varies by about nine orders of magnitude. To observe both the faint and bright radio sources, which also show dramatic spectro-temporal variability, one needs high dynamic range spectro-polarimetric snapshot imaging. Despite its importance, this has not been possible until recently due to instrumental and technical limitations. With the new technology instrument, the Murchison Widefield Array (MWA), and our recently developed polarisation calibration and imaging pipeline (P-AIRCARS; Kansabanik et al. 2022), it has now become possible to make high-fidelity polarimetric solar radio images at high temporal and spectral resolution. This has led to several interesting discoveries and results in the field of radio polarimetric studies of the Sun. These include the measurement of the magnetic field of CMEs, the measurement of the magnetic field of the quiet solar corona at mid and higher coronal heights, and detailed polarization studies of different solar radio bursts. We have also made progress in making full heliospheric magnetic field measurements using the Faraday rotation measurement of the background radio sources. Here I will present glimpses of all of these discoveries, results, and the current status of solar polarimetry at radio wavelengths with the MWA. I will also briefly describe the key science objectives, which can be accomplished with spectro-polarimetric radio imaging using the future Square Kilometre Array.

Session 2

The formation and disappearance of penumbra

M. Murabito[1], S. L. Guglielmino[2], I. Ermolli[3], P. Romano[2], S. Jafarzadeh[4,5], L. H. M. Rouppe Van der Voort[5]
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Unique high-resolution spectropolarimetric observations of the SST/CRISP ground-based instrument, complemented with data from the SDO/HMI and Hinode/SP space-borne instruments and from potential field extrapolations and data inversion, are used to investigate the formation and decay of penumbral regions.
Here we report the magnetic and velocity properties of the solar plasma during the formation and decay of a penumbra observed from the lower photosphere to the upper chromosphere in AR NOAA 12585. We show that the penumbra only appears in a photospheric region that lacks an overlying magnetic canopy. We then show that the penumbra disappears progressively both in time and space. This process seems to be linked with the presence of overlying canopies as well. Noticeably, we also show the detection of Evershed flows and horizontal fields after the apparent disappearance of the penumbral sectors.

Session 5

(Invited) Magnetism in isolated white dwarfs

S. Bagnulo[1] and J.D. Landstreet[1,2]
[1] AOP, [2] UWO

The presence of a strong magnetic field is a feature common to a significant fraction of degenerate stars, and several theories have been proposed to explain it. We will review literature data, and explain how observational biases have hidden the correlations between the incidence of magnetic field and other stellar parameters. We will present the results of a volume-limited spectropolarimetric survey of white dwarfs, which strongly support the idea that at least two different mechanisms are responsible for the presence of a surface magnetic field. In high-mass white dwarfs, which are probably the results of mergers, magnetic fields are extremely common and very strong, and appear immediately in the cooling phase. These fields may have been generated by a dynamo active during the merging. The origin of magnetic fields in white dwarfs that are result of single star evolution is totally different. Lower mass white dwarfs are rarely detectably magnetic at birth, but fields appear very slowly in about a quarter of them. What we may see is an internal field produced in an earlier evolutionary stage that gradually relaxes to the surface from the interior, eventually amplified by a dynamo generated during the crystallisation of the stellar core.

Session 4

(Invited) Novel framework for the three-dimensional NLTE inverse problem

J. Stepan
AI ASCR

The inversion of spectropolarimetric observations of the solar upper atmosphere is one of the most challenging goals in solar physics. If we account for all relevant ingredients of the spectral line formation process, such as the three-dimensional (3D) radiative transfer out of local thermodynamic equilibrium (NLTE), the task becomes extremely computationally expensive. Instead of generalizing 1D methods to 3D, we have developed a new approach to the inverse problem. In our meshfree method, we do not consider the requirement of 3D NLTE consistency as an obstacle, but as a natural regularization with respect to the traditional pixel-by-pixel methods. This leads to more robust and less ambiguous solutions. We solve the 3D NLTE inverse problem as an unconstrained global minimization problem that avoids repetitive evaluations of the λ ~operator. Apart from the 3D NLTE consistency, the method allows us to easily include additional conditions of physical consistency such as the zero divergence of the magnetic field. Stochastic ingredients make the method less prone to ending up within the local minima of the loss function. Our method is capable of solving the inverse problem faster by several orders of magnitude than by using grid-based methods. The method can provide accurate and physically consistent results if sufficient computing time is available, along with approximate solutions in the case of very complex plasma structures or limited computing time.

Oral Session, 11 Nov.

Session 4

(Invited) Spectropolarimetric inversions including magneto-hydrostatic constraints

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The interpretation of solar spectropolarimetric observations are, arguably, the most insightful tool into the physical conditions of the solar atmosphere and specially the magnetic field that permeates it. This process relies on the assumption of some radiation-matter interaction model (radiative transfer equation –RTE) that, prescribed with some model parameters for the solar atmosphere, characterizes the outgoing radiation polarimetric properties. The inference of the model parameter from a set of observations is known as inversion, and some of the most advanced inversion codes (SIR, SPINOR, SNAPY, STiC, DESIRE, TIC) consider a thermodynamic and magnetic depth stratified atmosphere. An important issue that these inversion codes have to deal with is the fact that spectral lines are hardly sensitive to the gas pressure stratification, i.e. additional constraints are required in order to solve the thermodynamics of the model atmosphere. The most common one is to simplify the magneto-hydrodynamic (MHD) equation of motion to its simplest form, i.e., hydrostatic-equilibrium (HE), or consider only the term related to gravity. This approach leads to some limitations, among others, the inferred gas pressure stratification is as good as HE is representative of the real gas pressure and the physical properties of each pixel are retrieved independently of the neighbouring ones, i.e. there is no horizontal consistency.

It is possible to overcome some of these limitations using a less simplified MHD equation of motion than in HE, for instance by including the magnetic terms (magneto-hydrostatic approximation). In doing so, the inferred gas pressure is more consistent with the prediction from MHD and, for example, the Wilson-effect is retrieved in a consistent manner. In this invited contribution we will present the current status in the development of an spectropolarimetric inversion code (FIRTEZ-dz) that includes magneto-hydrostatic constraints in order to evaluate the gas pressure, validating its performance and application to real data.

Session 4

A fast approach to calibrate the vector magnetic field from the polarization measurement in Huairou Solar Observing Station

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A fast approximate method is proposed to calibrate the polarization measurement through Lyot filter. In this method, we only need the measurements at four wavelengths: Stokes parameters in the symmetry position around the line center, intensity at the line center and the continuum. Firstly, we use the synthesis stokes profile based on Milne-Eddington atmosphere model to obtain the fitting coefficients in the weak field approximation. Then we use the intensity at the four wavelength points to calculate the correction ratio caused by the bias of atmosphere model. We compared the polarization data of Huairou Solar Observing Station (HSOS) with the inversion data of HMI and Hinode/SP based on the heavy computation or time-consuming wavelength scanning. The linear correlation coefficient after calibration is better than 0.9 and the difference of mean current helicity(H c =< J z B z >) is even less than 3% (1%) than that of smoothed Hinode (SDO/HMI) data. Such method perfectly removes the so-called saturation effect of the sunspot's umbra measured through Lyot-type filter. The effectiveness reflects that the high order differentials of profile at the measured、wavelength probably play an important role to calibrate the vector magnetic field. Our method will tremendously reduce the difficulty of the design and control of Multiple-Channel Technique (MCT) of HSOS which obtain the polarization signal simultaneously at several wavelengths. The strong correlation between the correction ratio and the magnetic field strength shows a potential to improve the accuracy of stellar or cosmic magnetic field measurement as long as the Zeeman effect and polarized light transfer exists there

Session 4

Comparison of polar magnetic fields derived from MILOS and MERLIN inversion for Hinode/SOT-SP data

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The detailed investigation of the polar magnetic field and its time evolution is one of the important achievements of Hinode. The precise measurements of the polar magnetic field are essential for understanding the 11-year solar cycle, and they provide important boundary conditions for identifying the source regions of the solar wind. In this study, we compare the polar magnetic field derived by the MILOS inversion code used in Shiota et al. 2012 with the Hinode/SOT-SP Level-2 data provided by the HAO. The Hinode/SOT-SP Level-2 data are derived by the HAO MERLIN inversion code. Both MILOS and MERLIN are Milne-Eddington inversion codes. The method of converting the magnetic field vector to the local vertical and the method of disambiguation of the magnetic field azimuth are also applied for the results with the two inversion codes in the same way. A date set used in this study was taken in the North polar region of the Sun in HOP 206 on August 23, 2021. We found that the magnetic flux density with respect to the local vertical tends to be about 1.2 times larger in the results with the MERLIN inversion than those with the MILOS inversion and this is due to the fact that the result with the MERLIN inversion tends to have a larger magnetic filling factor. The difference in the magnetic filling factor between the MILOS and MERLIN inversion is larger compared with the other magnetic field parameters (field strength, inclination, and azimuth). When we run MILOS with the fixed filling factor to equal the HAO MERLIN values, the flux density derived from the MILOS and HAO inversion codes is almost same. The discrepancy of the filling factor is most probably related to the difference in the assumptions of the stray light profile.

Session 4

The reliable noise reduction method for the Stokes spectral profiles

Yu Liang
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The Stokes profiles inversion technology based on the spectra-polarimetry of the magnetic sensitivity spectrum has become the most mainstream tool to obtain the magnetic field and thermodynamic information in the solar atmosphere (refer to the classic monograph of Stenflo, del Toro Iniesta, and Landi Degl'Innocenti & Landolfi). The core idea of Stokes profiles inversion is to fit the synthetic Stokes spectrum which is generated based on the polarization radiation transfer(PTE) process under a certain atmospheric model with the observation data. Then adjust the input physical parameters (including vector magnetic field, dynamics, thermodynamics, etc.) in turn, and iterate until the optimal solution of each physical parameter is reached.

Magnetic field inversion assumes ideal spectral profiles for fitting, but the actual data will be affected by noise. The noise level of the Stokes spectrum will directly affect the inversion accuracy of the vector magnetic field. This problem is more serious when processing weak magnetic field regions. It is an ingenious, feasible, and low-cost solution to seek a reliable noise reduction method adapted to the Stokes spectrum in the inversion (fitting) process, and then to improve the inversion accuracy of the vector magnetic field.

In this presentation, the deviations(statistical error) between the physical parameter inversion results (the theoretical Stokes spectrum, the noised Stokes spectrum, and the denoised Stokes spectrum) and the original input physical parameters under the ME atmospheric model have been compared. The noise reduction results of spectral noise reduction algorithms such as frequency domain, spatial domain, convolution, wavelet, and data rank reduction have been analyzed. We aim to find one or more reliable noise reduction methods for the Stokes spectrum in inversion.

Session 4

(Invited) Unlocking the potential of deep learning for the analysis of spectropolarimetric observations

C. J. Díaz Baso
RoCS UiO

The solar magnetic field is responsible for most of the physical processes in the solar atmosphere and their many manifestations. It can be inferred by analyzing polarimetric observations of spectral lines. Outside strong active regions, these signals are particularly weak, and in most cases very close to the detection limit of the current instrumentation. In addition, the modeling of the intensity and polarization signatures in spectral lines that form in the upper atmosphere prevents the use of inference techniques in large observed fields or in time-evolution analyses due to the extensive computational time. This, combined with the fact that the volume of data collected nowadays is unprecedentedly large, shows that these observations cannot be reasonably analyzed with conventional methods. In the last decade, machine learning and neural networks have emerged as powerful tools to extract the relevant information from these massive collections, analyze the data, and in short improve and accelerate the whole process. In this contribution, I will present several successful deep learning-based solutions for recovering weak polarization signals under complex noise corruption, robust image deconvolution, acceleration of spectropolarimetric inversions, and Bayesian uncertainty quantification. I will discuss their implications and provide an outlook for future research.

Session 2

SO/PHI-HRT SDO/HMI Cross-Calibration and the True Solar Magnetic Flux

J. Sinjan[1], D. Calchetti[1], J. Hirzberger[1], S. K. Solanki[1], J.C. del Toro Iniesta[2], J. Woch[1], A. Gandorfer[1], A. Alvarez-Herrero[3], T. Appourchaux[4], R. Wolkmer[5], D. Orozco Suárez[2], and the SO/PHI team.

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Onboard the Solar Orbiter spacecraft is the Polarimetric and Helioseismic Imager (SO/PHI), which has two telescopes, a high resolution telescope (HRT) and the full disk telescope (FDT). The instrument is designed to infer the photospheric magnetic field through differential imaging of the polarised light emitted from the Sun. It is the first magnetograph to move out of the Sun-Earth Line, providing excellent stereoscopic opportunities with other ground and space based instruments. Of particular interest is the correlation between SO/PHI and SDO/HMI, since they probe the same magnetically sensitive line of Fe1: 6173Å. Here a cross correlation between HMI and HRT is presented using conjunction data from the Cruise and Nominal Mission Phase(s).

Secondly, a possible contributor to the Open Flux problem is the underestimation of polar magnetic flux. As a pre-study to investigating this with stereoscopic data from PHI, simulations were carried out to understand the underlying physics when viewing the magnetic field at highly inclined viewing angles ($\mu = \cos(\Theta)$). MuRAM simulations together with SPINOR inversions were used to generate Stokes Profiles over a range of μ. Results from these simulations into the μ dependence of the magnetic flux will be shown.

Session 2

(Invited) Spectro-polarimetry of the sun from space and ground: What we learned and issues for the future

K. Ichimoto
Kyoto U.

Spectro-polarimetry is an indispensable tool for the modern solar physics. Its highest priority is to determine the magnetic fields that govern the dynamics of the outer solar atmosphere, while fascinating engravings of quantum physics found in the polarization signals in solar spectra also attract our attentions. For these reasons, a significant progress has been achieved in past decades thanks to the development of opto-sensing technology. Distinctive instruments are currently in operational in a number of ground facilities with large or small telescopes and in space. Development of advanced instruments are also under progress for the next generation, especially towards the measurement of 3D magnetic fields penetrating in low beta regions. In this talk, after a brief review of the solar spectro-polarimetry in Japan, I will present what we learned and issues for future step.

Poster Session

Session 1

Development of DST Spectro-Polarimeter at Hida Observatory

Y. Huang [1], K. Ichimoto [1], D. Cabezas [1], D. Yamasaki [1], G. Kimura [1], S. Ueno [1], T. Kawate [2]
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Magnetic field is the key to understand and explore the intrinsic properties of solar atmosphere and activities. Polarimeter is the mandatory tool to infer the solar magnetic fields through the Zeeman and Hanle effects. Currently a new spectro-polarimeter is developed on DST (Domeless Solar Telescope) at Hida observatory. The polarization modulator consists of a continuously rotating 50 mm diameter waveplate with a retardation that is nearly constant at around 127 ◦ in 500–1100 nm, and a PBS (Polarization Beam Spliter) with an extinction ratio higher than 1:300. The main upgrades to our spectro-polarimeter includes (1). a 3D printed modulator case; (2). a coude mirror based slit scan system; (3). an infrared InGaAs camera (Allied Vision) with a maximum read-out speed of 301 FPS; (4). a combined use of the AO system; (5). a standardized data calibration pipeline. With the new polarimeter, a sensitivity of 0.02% could be achieved in 4-5 seconds (on disk) or 6-10 seconds (off limb) for 500-1100 nm, making it possible to obtain one set of full Stokes map in at least 8 minutes with a maximum FOV (Field-of-View) of 127” × 240” and a scan resolution of 2”. The polarimeter could be installed either on the vertical spectrograph for high dispersion observation, or on the horizontal spectrograph for simultaneous multi-wavelength observation. We will present some interesting results obtained by this new Ipolarimeter.

Session 1

Calibration and Data Analysis Pipeline of the Infrared Spectro-Polarimeter at NAOJ/Mitaka

T. Sakurai and the IRSP Team
NAOJ

We have been operating the Infrared Spectro-Polarimeter (IRSP) since 2010 at the Mitaka campus of NAOJ. This instrument produces full-disk polarization maps at two wavelength bands (Fe 1564.8 nm and He 1083.0 nm/Si 1027.0 nm). The overview of the instrument and the derivation method of magnetic field parameters were described in Sakurai et al. (2018, DOI: 10.1093/pasj/psy050) and the data are open at https://solarwww.mtk.nao.ac.jp/en/db_cal.html#irmag.

Here we will describe more in detail the calibration procedure. The polarization modulator we are using is a rotating waveplate (taking eight frames per half rotation), and its retardation and the direction of the axis are determined by inserting a calibrator package made of a polarizer and a nearly achromatic quarter-waveplate. Both the calibration polarizer and the waveplate are rotatable, and by rotating them by 90 degrees and take extra measurements, we are able to eliminate errors caused by inaccurate setting of the polarizer and waveplate axes. The effects of the scattered light are estimated by using the data taken off the limb and are corrected by using the Moffat function as a model for the scattered light distribution (Chae et al. 1998, DOI: 10.1023/A:1005012509071). The conversion from the Stokes IQUV spectra to the magnetic field parameters is not by a full Stokes inversion but by adopting look-up tables (based on the Unno-Rachkovsky formula) that connect the magnetic field parameters and the observed QUV polarization degrees integrated over a wavelength range in the line wing. In the case of the Fe 1564.8 nm line, because of its large Zeeman splitting, we also use look-up tables to utilize the Zeeman splitting and the polarization degrees at the wavelength of the split Zeeman components.

Session 1

Building an efficient compression method for solar spectro-polarimetry data accumulated by Hinode/SP

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Solar spectra contain physical information that allows astronomers to broaden their knowledge about our sun. We have spectro-polarimetry data accumulated by the Hinode satellite for more than a decade. However, it is difficult to process such large amount of high dimensional data even with the present methods of informatics, including machine learning techniques. To this end, we aim to obtain a compressed representation of solar spectral data which is an important step for further detailed analysis of the polarimetric spectra, such as flare prediction, automatic categorization of spectra, detection of anomalous spectra, and so on.

We used Solar Optical Telescope-Spectropolarimeter (SOT-SP) data in this study. The spectro-polarimeter (SP) covers wavelength range between 630.1 and 630.3 nm, including Fe I line pair at 630.15 nm and 630.25 nm. The observation period of the data corresponds to 2021-08-03 and the field-of-view (FoV) of the 2D spatial spectro-polarimeter is 75.6″ ×81.2″ with a sampling slit of ~0.15″ . The data was selected concerning its capture at near the disk center (not around the solar limb) and inclusion of both regular surface and sunspot regions.

We built an autoencoder, an encoder-decoder model based on deep learning techniques, for compressing Stokes I and V polarization parameters. The model gets polarization data as input and encodes and decodes it to output data which should be similar as possible to the input data. Output of the encoding part is our feature vector, namely the compressed representation of Stokes I and V parameters.

For the model training we constructed a customized loss function as the sum of mean absolute error (mae) of Stokes I and weighted mae of Stokes V. The weight value is determined as 0.1 which is the variance ratio of Stokes I and V continuum. We analysed the model performance from the correlation between raw and reconstructed spectra. Our study resulted in standard deviation (std) of 2.71~3.16% at the line centers and less than 0.7% at the continuum for Stokes I, and 4.46~4.79% at the line cores for Stokes V. The result shows that by using the customized loss function our model performed with smaller std values for reconstruction of the Stokes parameters.

Session 4

SpIn4D: Spectropolarimetric Inversion in Four Dimensions with Deep Learning

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The National Science Foundation's Daniel K. Inouye Solar Telescope (DKIST) will provide high-cadence, high-resolution, and multi-line measurements of the solar photosphere. New algorithms are required to meet the demand of the large data volume and to exploit the spatiotemporal information encoded in the polarized spectra. Here, we describe an NSF-funded project that aims to perform spectropolarimetric inversion in four dimensions with Deep Learning (SpIn4D). We first perform realistic magnetohydrodynamic (MHD) simulations of the solar photosphere, and forward synthesize a large library of DKIST-like spectra. Using these spectra as the input and the known MHD ground-truth as the target, we then train, validate, and benchmark a set of convolutional neural networks that can rapidly infer the physical variables of interest. Finally, as DKIST data become available, we will apply adversarial domain adaptation techniques to reduce the systematic differences between simulated and real data.

Session 5

A tabletop device for investigating spectropolarimetric responses to anisotropic/magnetized plasmas

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Spectropolarimetry is a popular tool for investigating the dynamics of magnetized plasmas. The population density of atomic sublevels represents the strength of anisotropic collisions and electromagnetic interactions to atoms. On the other hand, atomic structure is determined by many-body systems consisting of electrons and a nucleus in addition to the fields/colliding particles to be considered. Furthermore, non-equilibrium plasmas in three dimensions dynamically create non-uniform anisotropic field structures. How we have interpreted such complex systems is to develop quasi-equilibrium models of atomic structure, population density structure, plasma structure, and radiative transfer. These models need to be verified experimentally in a simpler system by controlling atomic interaction with external fields and particles.
We set up a tabletop plasma device designed especially for spectroscopic measurements of plasmas interacting with external lasers, particle beams, and magnetic fields. The device consists of a quartz pipe coupling an antenna and of a vacuum chamber made of stainless steel. A radio-frequency (RF) power supply of 13.56MHz with a forward RF power of 5kW at maximum is used for plasma production. Density of neutral particles is controlled by vacuum pumps and a mass-flow controller, while it is monitored by pressure gauges. Electron temperature and density are measured by Langmuir probes, and these typical values are Te ~ 1e4 K and Ne ~ 1e12 cm-3. We performed experiments by setting the device in front of the focal plane of the Horizontal Spectrograph of the Domeless Solar Telescope at Hida Observatory of Kyoto University. By using the spectropolarimetric system with high spectral resolution and high polarimetric sensitivity, we directly compared helium spectra emitted from the laboratory plasmas and solar prominences. In the presentation, we introduce the apparatus, obtained spectra, and results of the comparison with solar spectra.

Session 2

Polarization of the Corona Observed During the 2017 and 2019 Total Solar Eclipses

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Polarization measurements of the white-light corona has been one of the principal topics in the solar polarimetry, because it gives the electron density distribution of the corona regardless of the temperature. Such measurements have been conducted in space and on the ground, but among various observations, solar eclipses are particularly good chances to perform precise polarimetry because of the low scattered light level down to the limb.
We carried out polarimetric observations of the white-light corona during the total solar eclipses on 2017 August 21 and 2019 July 2, and derived the brightness, polarization brightness, and degree of the polarization of the K+F corona from just above the limb to approximately 4 Rsun.
Comparison of our results with other observations exhibits that there is systematic discrepancy in some cases. The eclipse observations can provide a good calibration source of the brightness and polarization of the white-light corona, not only for existing space coronagraphs but also for future missions.

Session 2

Spectral line broadening associated with the turbulence in fading granules

R.T. Ishikawa, Y. Katsukawa
NAOJ

In the quiet region in the solar photosphere, turbulent convective motions of the granular flows play important roles in driving subgranular-scale flows via turbulent cascade from the energy injection at granular scales. Such subgranular-scale flows are critical in creating small-scale magnetic structures through a local dynamo mechanism. We found that the spectral line width broadens significantly when granules fade out (Ishikawa et al. 2020a). We performed radiative transfer calculations to interpret this line broadening and found that there are two solutions: one explains the broadening with a microturbulence term of about 1 km/s, and the other explains it with a large velocity gradient and temperature gradient without the microturbulence term. We cannot distinguish between the two scenarios only with the Fe I lines observed by Hinode-SOT/SP. To discuss the possibility of turbulence development associated with fading granules, we analyzed MURaM simulation data. Numerical calculations were performed with a horizontal grid size of 10.4 km, and spectral line profiles were calculated using the SIR code. The spectral lines obtained were used to investigate the correspondence between changes in atmospheric structure and changes in spectral line shape during the fading of granules. The turbulent velocity of the photosphere was defined by using the response function for FWHM and the point-spread function of Hinode-SOT. As a result, the line broadening accompanying the fading granules was reproduced. The turbulent motion was found to originate from the granulation boundary when a granule fades out. These turbulent flows can interact with small-scale magnetic fields in the intergranular lanes and they are predicted to be observed with the Fe I 15654 nm line.

Session 2

The stability of sunspots and pores related to the magnetic field properties

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We will summarize the recent observational results that show the key role played by the vertical component of the magnetic field ($B_{||}$) in the inhibition of convection in the solar photosphere. In sunspots and pores, only regions with $B_{||}$ stronger than a critical value of approximately 1.8 kG are stable against convection and the intensity boundaries of stable umbrae and pores match boundaries based on $B_{||}$. In regions with $B_{||}$ weaker than the critical value, more vigorous modes of magneto-convection take over. This behavior is observed during the formation of penumbra and light bridges and during the decay of sunspots and pores. Current case studies of pore evolution indicate that also areas defined by the critical value of $B_{||}$ decay rapidly in the final stages of pores lifetime. However, we observe a clear relation between the decay rates of areas defined by intensity threshold and by $B_{||}$: the evolution of areas defined by $B_{||}$ precede by approximately four hours the evolution of areas defined by intensity threshold.

Session 1

SUNRISE III: The Solar Atmosphere in 3D and High Resolution

Andreas Korpi-Lagg[1], Sami K. Solanki[1], Thomas Berkefeld[2], Pietro Bernasconi[3], Alex Feller[1], Achim Gandorfer[1], Yukio Katsukawa[4], Valentin Martinez Pillet[5], Smitha Narayanamurthy[1], Tino Riethmüller[1], Jose Carlos del Toro Iniesta[6], Alberto Alvarez-Herrero[7], María Balaguer Jiménez[6], Luis Bellot Rubio[6], Julián Blanco Rodríguez[8], Juan Manuel Borrero[2], Hirohisa Hara[4], Ryohtaroh T. Ishikawa[4], Yusuke Kawabata[4], Takuma Matsumoto[9], Takayoshi Oba[4], Nour-Eddine Raouafi[3], David Orozco Suárez[6], Isabel Pérez Grande[10], Basilio Ruiz Cobo[11], Esteban Sanchis[8]

[1] MPS, [2] KIS, [3] JHUAPL, [4] NAOJ, [5] NSO, [6] IAA, [7] INTA, [8] Univ. Valencia, [9] U. Nagoya, [10] UPM, [11] IAC

The balloon-borne solar observatory SUNRISE III will provide a three-dimensional picture of the physical processes in the solar atmosphere. Its novel instrumentation will deliver the details of the physical processes from the deepest photospheric layers up to chromospheric heights with special emphasis on the coupling between the various height layers. The 1-meter solar telescope will resolve structures down to a size of 70 km and deliver the light to a suite of scientific instruments, simultaneously covering a spectral range between 309 and 900 nm. The conditions in the stratosphere will result in constant-quality, seeing-free observations of spectral lines not easily accessible with ground-based observatories. The pointing stability of the observatory will be in the range of milli-arcseconds, corresponding to only a few kilometers on the solar surface. This stability, achieved by combining the gondola pointing (JHUAPL) with an image stabilization system (KIS) is required for high-precision polarimetric measurements, allowing to obtain the magnetic vector in addition to the temperature and velocity information.

The scientific payload of SUNRISE III consists of three instruments: Two slit-based spectro-polarimeters for the near ultra-violet (SUSI / MPS) and the near-infrared (SCIP / NAOJ, IAA, UV, UPM), and an imaging spectro-polarimeter (TuMag / IAA, INTA, UPM, UV, IAC). SUNRISE III has been extensively tested during during hang tests with Sun pointing at the MPI for Solar System Research (November 2021, Göttingen, Germany), and at Esrange, Sweden, in preparation for the first launch attempt in summer 2022. We present the status of the observatory and the options for a flight in the near future.

Session 1

Tackling the unique challenges for low-frequency solar polarimetric calibration and imaging for Sun with the Murchison Widefield Array

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Polarization properties of the various solar emissions have long been known to be a rich source of information for understanding the emission mechanisms and the magnetic field topology. Nonetheless, largely due to technical challenges, polarimetric solar observations at low radio frequencies have remained perhaps the least explored regime. The brightness temperature and degree of polarization of the solar radio emission varies dramatically depending on the type of the emission. The strong radio bursts are very bright, approaching up to 10^12 K and show moderate to high degree of circular polarization, while with brightness temperature as low as 10^4 K the non-thermal gyrosynchroton emissions are many orders of magnitude weaker, and the quiet sun thermal emissions at a 10^5 K show very little degree of circular polarization (~<1%). The coronal magnetic field is extremely hard to measure, and the degree of circular polarization from the quiet Sun is the only known remote sensing tool which can estimate the average coronal magnetic fields. To the best of our information, such a measurement is yet to be done. Perhaps the most rewarding, and also challenging, of polarimetric observations will be the measurements of Faraday rotation of linearly polarised light from background sources as it passes through the magnetised plasma of the coronal mass ejections (CMEs) on its way to the observer. Such measurements will enable us to estimate the vector CME magnetic field, the holy grail of space weather and in the fullness of time will have enormous societal impact. Towards meeting these aims we have initiated the effort to build a solar high fidelity spectro-polarimetric snapshot imaging capability at low radio frequencies. This pipeline is being designed to work with data from the Murchison Widefield Array (MWA), one of the SKA-Low precursors. I will briefly summarise the various challenges which need to be overcome for polarimetric calibration due to reasons ranging from the nature of the wide field-of-view aperture arrays like the MWA to the issues specific to solar imaging. I will then present the strategies developed to address these challenges and conclude by sharing the preliminary but very interesting results which our efforts are yielding.

Session 2

First detailed polarimetric study of a group of type-III solar radio bursts with the Murchison Widefield Array

Soham Dey, Devojyoti Kansabanik, Divya Oberoi
NCRA-TIFR

Magnetic reconnection is a well-known process for acceleration of electrons in the solar corona. When streams of semi-relativistic electrons travel through the hot magnetized coronal plasma along open magnetic field lines, it can result in type-III solar radio bursts by plasma emission mechanism. These radio emissions are among the most widely studied solar phenomenon at meter-wavelength. However, most of these studies are limited to the analysis of their dynamic spectra, which do not provide any information about the structure and location of these sources. The emergence of new generation telescopes like the Murchison Widefield Array, and our recently developed full Stokes calibration and imaging pipeline (P-AIRCARS, Kansabanik et al. 2022), now enables us to produce spectro-polarimetric snapshot solar radio images with high fidelity and dynamic range. This allows us to obtain polarimetric properties of these bursts in unprecedented detail and has already led to a few interesting discoveries. Circular polarization of type-III radio bursts are well reported in the literature. Theoretically one expects any linear polarization, even if present, should get washed out due to the large differential Faraday rotation in the corona. On the contrary, we have found the first convincing image-based evidence of linearly polarized emission from these bursts. We note that the linear polarization fraction is greater than the circular polarization fraction and they are anti-correlated throughout the burst duration. This suggests the possibility of the conversion of circular to linear polarization while the radio wave is travelling through the magnetized and inhomogenous corona. Here we will present our findings about the polarization of these type-III solar radio bursts.

Session 2

First detailed polarimetric study of a type II solar radio burst with the Murchison Widefield Array

P. Majee, S. Dey, D. Kansabanik, D. Oberoi
National Centre for Radio Astrophysics

Type II solar radio bursts are well known to be predominantly associated with the more energetic and fast coronal mass ejections (CMEs). These CMEs are expected to drive shocks in the coronal medium and play a dominant role in giving rise to energetic particles which are the biggest concern for Space Weather. The type II radio bursts arise from plasma emission mechanisms and occur at fundamental and harmonic levels of the local plasma frequency. The emission at both the fundamental and harmonic is often found to be split in two sub-bands or lanes. A commonly accepted interpretation is that the electrons accelerated at the shock front moving both ahead of and behind the shock, give rise to these two lanes of emission. This suggests that these sources must lie close to each other. The vast majority of studies of type II bursts, however, rely on dynamic spectra which do not provide any spatial information. High fidelity and dynamic range solar radio images with good temporal and spectral resolution from instruments like the Murchison Widefield Array (MWA) now enable such imaging studies. Interestingly, a recent MWA imaging study of the harmonic emission from a type II burst (Bhunia et al., 2022 A&A, submitted) finds evidence that, the sources from the two lanes are not only located rather far apart in the radio images, but they are also moving in different directions and with different speeds. Making use of the recently developed spectro-polarimetric snapshot imaging pipeline (P-AIRCARS, Kansabanik et al., 2022), we have extended the study of Bhunia et al. 2022 to include polarimetric imaging and also improved upon some of the analysis procedures used by them. Here we summarize the preliminary results about the polarization properties of this type-II radio burst.

Session 3

Suitability of the CRD approximation for the RIII redistribution matrix in the RT modeling of scattering polarization

S. Riva[1], N. Guerreiro[2], P. Benedusi[3], L. Belluzzi[2]
[1] USI, [2] IRSOL, [3] Simula

The correct modeling of the scattering polarization signals observed in several strong resonance lines of the solar spectrum requires taking partial frequency redistribution (PRD) effects into account. These effects are conveniently described through the formalism of the redistribution matrix. For a resonance line, this is given by the sum of two terms, RII and RIII, which describe coherent and completely incoherent scattering processes in the atomic reference frame, respectively. The expressions of RII and RIII become particularly involved in the observer's reference frame, where the Doppler effect introduces a strong coupling between the frequency and propagation direction of the incident and scattered radiation, making the problem very demanding from a computational standpoint.

For simplicity's sake, approximate versions of RII and RIII are often applied. Complete frequency redistribution (CRD) has been widely used to approximate RIII in the observer's frame. This approximation proved very successful for modeling the intensity spectrum, but its suitability for scattering polarization has been questioned. Sampoorna et al. (2017) studied this approximation through radiative transfer (RT) calculations in an isothermal medium, demonstrating its applicability for modeling scattering polarization, particularly in optically thick media.

Here we generalize their work, and we analyze the suitability of the CRD approximation for RIII in 1D models that better represent the solar atmosphere, accounting for both magnetic and bulk velocity fields. Our results, based on the modeling of both photospheric (SrI 4607 A) and chromospheric (CaI 4227A) lines, firmly confirm the applicability of this approximation in the RT modeling of scattering polarization.

Session 3

Depolarization of solar molecular lines by collisions with neutral hydrogen atoms and with electrons

M. Derouich & S. Qutub
KSA

The topic of scattering molecular polarization and its interpretation in terms of solar magnetic fields faces serious problem due to the lack of collisional data. In fact, rigorous interpretation of scattering molecular polarization requires the calculation of the rates of (de)polarizing collisions occurring during the formation of the polarized molecular lines. In this context, we present our recent results and projects concerned with elastic depolarizing collisions of MgH, CN and C2 molecules with hydrogen atoms (e.g. Qutub et al., 2021, The Astrophysical Journal, Volume 915, Issue 2, id.122). In addition, our quantum polarization transfer rates due to inelastic collisions of CN and C2 molecules with electrons will be presented and discussed (e.g. Derouich et al., 2020, Research in Astronomy and Astrophysics, Volume 20, Issue 12, id.210).

Session 3

Theoretical modelling of the scattering polarisation signal of the Ca I 4227 A line accounting for angle-dependent PRD effects and bulk velocities

N. Guerreiro[1], G. Janett[1], L. Belluzzi[1], S. Riva[2] and P. Benedusi[2]
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The scattering polarisation signals observed in several lines of the solar spectrum are highly sensitive to the dynamics of the solar plasma and, particularly, to velocity gradients. Modelling of scattering polarisation in strong chromospheric lines requires taking partial frequency redistribution (PRD) effects into account, and if velocities are included, the exact angle-dependent expression of the redistribution matrix has to be used. The ensuing numerical problem is notoriously challenging from a computational standpoint, but due to recent algorithmic advances it can currently be routinely solved.
We explore the polarisation of the chromospheric CaI 4227 A line by solving the non-LTE radiative transfer problem for polarised radiation in one-dimensional models of the solar atmosphere, accounting for angle-dependent PRD effects. We consider both semi-empirical models with academic bulk velocity fields, as well as models extracted from MHD
simulations, which include realistic values and variations of the bulk velocity and the magnetic field. The inclusion of bulk velocities into the modelling translates into shifts, asymmetries, and enhancements of the scattering polarisation profiles, which may also represent distinctive signatures of the concerted interaction of hydrodynamics and magnetic forces.

Session 3

3D RT Modeling of the Scattering Polarization in the Wings of Mg II h&k

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We aimed to investigate the spectro-polarimetric measurements of quiet solar chromosphere targets in the wings of Mg II h&k, observed by the CLASP2 rocket experiment on April 11, 2019. To interpret these data through forward modeling, we developed two numerical modules for the radiative transfer (RT) code PORTA (Stepan & Trujillo Bueno, 2013). Both modules solve the polarized transfer equations in 3D for a two-term atom considering the J-state interference as well as partial redistribution in scattering (PRD). One module neglects the magnetic field effects, while the other includes them via selected magneto-optical terms. To facilitate resonance scattering in 3D we approximated it by applying the atomic coherent scattering function in the observer's frame. This approximation dramatically reduces computational costs but keeps the magnetic sensitivity in the wings. With these modules, we numerically solved the 3D RT problem in the h&k wings of a two-term model atom of Mg+ using a model atmosphere from the enhanced network simulation by the radiation-MHD code Bifrost (Carlsson et al. 2016). Synthetic images as well as slit spectra in all Stokes parameters for different viewing angles were generated, analyzed, and compared against observations.
In this talk, I will justify the coherent scattering approximation, explain the computational demands, and show synthetic spectrograms as well as profiles. We will see how the following effects relate our synthetic data to observations: local symmetry breaking on granulation, global symmetry breaking as center-to-limb variations, PRD and the upper-term interference that define the wing shapes, and the magneto-optical effects that influence them all. Additionally, I will mention the role of the instrumental resolutions of the spectro-polarimeter.

Session 5

SPOTS – SpectroPolarimetric Observations of T Tauri Stars: preliminary results

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Proto-planetary disk (PPD) jets and winds are a key ingredient in the evolution of pre-main-sequence stars. They play a fundamental role in the extraction of angular momentum and in the disk dispersal, which set the physical conditions for the formation of planets. The standard analysis to probe such outflows is based on high-resolution spectroscopy of optical/infrared emission forbidden lines and Balmer/Paschen lines which usually present composite profiles associated with different jet/wind components. However, the physical origin of some of these components is still poorly constrained due to the lack of geometrical information on sub-au scales.

In our SPOTS (Spectropolarimetric Observations of T Tauri Stars) project we propose to unveil winds and jets at sub-au scale using the extra-dimension of information provided by linear spectropolarimetry thanks to the unprecedented combination of sensitivity and high-resolution provided by the recent facilities such as that of PEPSI@LBT.

In this poster we will present the preliminary results of the first observational run of SPOTS with PEPSI: we successfully detected strong linear polarimetric signals across the Balmer lines in two bright CTTs (RY Tau and GM Aur) with a spectral resolution never achieved before. For the first time, we also detected significant polarization signals across the Sodium D-lines at 589 and 589.6 nm while we did not detect any signals across the [OI] line at 630 nm, in contrast to the previous low-resolution observations.

Session 1

Spectro-polarimetric capability of SUNRISE III SCIP

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For the third flight of the international balloon project SUNRISE, the team led by NAOJ provides the near-infrared spectro-polarimeter (SCIP) through international collaboration with the Spanish and German teams. By combining the 1-meter aperture telescope, SCIP will simultaneously obtain spectro-polarimetric data of many spectral lines including Ca II 854.2 nm and 849.8 nm, K I D1/D2 lines, and Fe I 846.8 nm with a resolution higher than that of the HINODE Solar Optical Telescope. The observation will allow us to observe the three-dimensional magnetic field structure and its time evolution from the photosphere to the chromosphere and clarify the transport and dissipation processes of magnetic energies. We present here the capability of SCIP along with calibration results obtained from ground tests.

Session 2

Spectropolarimetry of solar prominences in He I 10830 Å with the Domeless Soler Telescope at Hida observatory

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The magnetic field is an important quantity for understanding the properties of solar prominences (or filaments); their structures are determined by magnetic fields, and thermal conduction and Alfven waves in prominences are controlled by magnetic fields. Polarimetry allows us to measure magnetic fields directly.

A new spectropolarimeter has been developed on DST (Domeless Solar Telescope) at Hida observatory. We observed several prominences in He I 10830 Å with spectral sampling about 0.03 Å. Our observations were made in the slit-scan mode, with the slit parallel to the limb. We integrated 80-100 images of 0.05-second exposure and obtained full Stokes profiles at each slit position. N/S of the polarization signal is 3×10^{-4} with respect to disk continuum, while in prominences N/S is about 1×10^{-3} with respect to peak intensity.

We performed Stokes inversions by using the inversion code HAZEL and constructed 2D maps of magnetic field vectors. As a result, the magnetic field in prominences is mostly between 10 and 20 G, but one of the prominences, which is the active-region prominence, has larger magnetic fields, up to 50 G. In this presentation, we introduce Stokes profiles of a few prominences and inversion results.