Book of abstracts

10$^{\text{th}}$ Coronal Loops Workshop

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Session I

Introduction

Coronal Loops: Past, Present, and Future

Harry Warren * [1]

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In this talk we discuss the evolution of observations and models of active region loops over the past 20 years. We discuss the interpretation of TRACE and SXT-era observations as evidence for impulsive heating and the challenges to this paradigm presented by data from EIS, XRT, and AIA. Finally, we discuss the promise of new data from the Solar_C-EUVST instrument.

*Speaker

New views of the magnetically closed corona with Solar Orbiter (invited)

Frédéric Auchère * [1]

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Solar Orbiter was successfully launched in February 2020 and completed its cruise phase in December 2021. During this period, the remote sensing instruments were mostly operated during limited periods of time for 'checkout' engineering activities and synoptic observations. Nonetheless, several of these periods provided enough opportunities already to obtain new insights on coronal physics. The first perihelion passage of the nominal mission phase occurred in March 2022 at a distance of 0.32 AU from the Sun. Observations were performed for the first time with the whole payload operating in full science mode. The fraction of data received to the ground at the time of writing already contains spectacular new views of coronal structures. We will present the main characteristics of the six remote sensing instruments and review early results from the cruise phase and first close encounter.

*Speaker

Session II

Advances in the modelling and observation of the photosphere-corona interaction

How are coronal loops rooted in the photosphere? (invited)

Cosima Breu * [1]

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The heating of the upper atmosphere is one of the major open problems in solar and stellar astrophysics. The question of how coronal loops are rooted in the photosphere and how energy is exchanged between different layers of the atmosphere is the subject of active discussions. A high resolution 3D MHD model of an isolated coronal loop driven by self-consistent convective motions at the footpoints is employed to study the magnetic coupling between the photosphere and corona. The model produces vortex motions that have been found to be abundant also in different layers of the atmosphere. Some of these vortices reach coronal heights and channel a strong Poynting flux into the upper atmosphere. In this talk, I will discuss the role of vortices and small-scale coherent motions within a magnetic concentration in energizing the corona.

*Speaker

Simulating convection-driven magnetic reconnection in 3D with Bifrost

Rebecca Robinson * [1], Mats Carlsson [1], Guillaume Aulanier [1]

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Simulating magnetic reconnection in the solar atmosphere is not a novel pursuit, but 3D simulations of realistic reconnection events that are entirely driven by convection have not been possible until recently. In this study, we demonstrate a Bifrost simulation of the quiet sun that includes a magnetic reconnection event that is self-consistently driven by convection. While the driving mechanism behind the reconnection is rooted in the convection zone, the reconnection region is located in the simulated corona between multiple loop systems and an overlying horizontal field, representing a complicated and interesting magnetic topology. This reconnection leads to coronal plasma temperatures on the order of a million Kelvin. We present this event as a case study for quiet sun heating and posit that this case is representative of reconnection events that may be ubiquitous in the real quiet sun.

*Speaker

Asymmetric twisting of coronal loops

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The bright solar corona entirely consists of closed magnetic loops rooted in the photosphere. Photospheric motions are important drivers of magnetic stressing which eventually leads to energy release into heat. These motions are chaotic and obviously different from one footpoint to the other, and in fact there is strong evidence that loops are finely stranded. One may also expect strong transient variations along the field lines, but at glance coronal loops ever appear more or less uniformly bright from one footpoint to the other. We investigate this issue by time-dependent 2.5D MHD modeling of a coronal loop including its rooting and beta-variation in the photosphere. We assume that the magnetic flux tube tube is stressed by footpoint rotation but also that the rotation has a different pattern from one footpoint to the other. In this way we force strong asymmetries, because we expect independent evolution along different magnetic strands. We show here preliminary results, which seem to indicate an important role of the time scales involved.

*Speaker

Cut-off of transverse waves through the solar transition region

Gabriel Pelouze * [1,2], Tom Van Doorsselaere [2], Konstantinos Karampelas [3,2], Julia M. Riedl [2], Tim Duckenfield [2]

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Transverse oscillations are observed both in coronal loops (as standing waves) and in open magnetic tubes (as propagating waves), with periods ranging from 1 to 10 minutes. These kink waves are interpreted as the result of a continuous photospheric driver at the footpoints of the loops or open magnetic tubes. Numerical simulations suggest that their dissipation in the corona could heat coronal loops through the Kelvin-Helmholtz instability. However, analytical works predict that these waves are subject to a cut-off in the transition region. As a result of this cut-off, only short-period waves (below 3 minutes) could reach the corona, in apparent contradiction with observations. In order to understand whether the dissipation of kink waves can indeed efficiently heat coronal loops, it is essential to understand how this cut-off affects their propagation into the corona.

Using 3D magnetohydrodynamic simulations, we modelled the propagation of kink waves in a magnetic flux tube. The simulation domain starts in the chromosphere, and extends into the corona through the transition region. By driving kink waves at different frequencies, we showed that they are indeed cut-off in the transition region. We then compared our simulations to several, inconsistent, analytical formulas for the cut-off frequency. This allowed us to identify the formula that yields the best predictions. Furthermore, we show that waves with periods longer than the cut-off can still reach the corona by tunnelling through the transition region. This would explain why such waves are observed in the corona.

*Speaker

Plasma properties in the Quiet-sun of the Transition Region

Yamini Rao * [1], Giulio Del Zanna [1], Roger Dufresne [1], Helen Mason [1]

[1] DAMTP, Cambridge University – United Kingdom

The center-to-limb variation of non-thermal velocities in the quiet Sun (QS) has been observed in our previous study using high-resolution spectral observations from the Interface Region Imaging Spectrograph (Rae et al., 2022). In our present work, we use diagnostic lines from O IV and S IV to estimate the electron densities and temperature. We also measure the path lengths for some of the QS observations used in our previous study, as well as an active region. We compare our QS results with those from the HRTS observations calculated using O IV and C IV. We also use new atomic models (Dufresne et al., 2021a,b) for the quiet Sun, which include density effects, photo-ionisation, and charge transfer to estimate the filling factors and path lengths. Our study of how data from such models can affect the analysis will be useful for interpretation of observations from Solar Orbiter SPICE spectrometer.

*Speaker

Diffuse solar coronal features originating from highly structured spicular footpoints

Nikolina Milanovic * [1], Lakshmi Pradeep Chitta [1], Hardi Peter [1]

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Besides organized into clear loop-like structures, there is also a component of emission from solar coronal plasma that appears to be rather diffuse and featureless. Often, this diffuse component constitutes a majority of coronal plasma. The magnetic landscape at the footpoints of this featureless component in the lower atmosphere is not well understood. Here we will concentrate on the origin of the diffuse corona above the quiet Sun network.

For this we use quiet-Sun network rasters recorded by IRIS and cotemporal SDO (AIA and HMI) observations which allow us to connect the atmosphere from the photosphere through the transition region into the corona. In the Si IV emission line at 1394 A from IRIS we identify spicular features associated with patches of enhanced magnetic field at the surface. Some of these features appear to clearly underlie footpoints of cool loops roughly 20 Mm in length, crossing the network cell. Intriguingly, similar spicular structures (but those associated with like-polarity magnetic patches on opposite sides of a network cell) form a canopy-like feature in the corona where we identify the origin of diffuse coronal emission.

This mostly featureless coronal canopy stretches across some 20 Mm and exhibits a slow evolution, on timescales of a few hours, following the gradual changes of the surface magnetic field. This is clearly distinct from the more dynamic small cool loops that dominate the visual appearance of other coronal network features in regions with a more mixed magnetic polarity, e.g. in a coronal bright point.

Our observations indicate that spicular features with similar appearance in terms of transition region emission and magnetic structure at their footpoints can result in distinctly different coronal emission patterns, from coronal bright points and cool loops to even rather diffuse emission.

*Speaker

Measuring the Photospheric Driving of Magnetic Footpointswith Quantifiable Uncertainties (invited)

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Coronal heating remains an active research area in solar physics. One key aspect to understand it is to describe how the photospheric motions stress the coronal magnetic field, building up magnetic free energy that is ultimately released to heat the plasma. The details of these motions determine both the rate of energy buildup and the complexity of the field, which in turn determine the magnitude and properties of the heating.
We present a novel framework with quantifiable uncertainties for investigating the photospheric driving of the coronal field, using observations from SDO/HMI, and the MuRAM and STAGGER simulations. Using advanced flow tracking methods, we show how one can accurately infer both translational and rotational motions of magnetic elements, giving access to fundamental quantities such as the kinetic helicity and mutual magnetic helicity change rates. Our framework is two-fold: (i) We track the granulation signal to map the quiet-sun photospheric supergranular cells at unprecedented accuracy in the Euler reference frame, offering a detailed view of the underlying flow advecting the photospheric section of the loops. (ii) We accurately track the moving magnetic features, including emerging flux, to get their horizontal velocity vector, and - unlike other methods - without using any apodizing or smoothing window that would otherwise smear or cancel out the fine-scale dynamics of rotational and shear motions, thus preserving the separating power offered by the instrument.

In both methods, the MHD simulations are offering validation, and quantifiable uncertainties for our methods. Our framework has been documented, and we recently made it available to the research community; we will give a brief overview on how to get started with it for your own research projects.

*Speaker

Undetected Minority-polarity Flux as the Missing Link in Coronal Heating

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During the last few decades, the most widely favored models for coronal heating have involved the in situ dissipation of energy, with footpoint shuffling giving rise to multiple current sheets (the "nanoflare" model) or to Alfvén waves that leak into the corona and undergo dissipative interactions (the wave heating scenario). As pointed out by Aschwanden et al., observations suggest instead that the energy deposition is concentrated at very low heights, with the coronal loops being filled with hot, dense material from below, which accounts for their overdensities and flat temperature profiles. While an obvious mechanism for footpoint heating would be reconnection with small-scale fields, this possibility seems to have been widely ignored because magnetograms show almost no minority-polarity flux inside active region (AR) plages. Here, we present further examples to support our earlier conclusions (1) that magnetograms greatly underrepresent the amount of minority-polarity flux inside plages and "unipolar" network, and (2) that small loops are a major constituent of Fe IX 17.1 nm moss. On the assumption that the emergence or churning rate of small-scale flux is the same inside plages as in the quiet Sun, we estimate the energy flux density associated with reconnection with the plage fields to be on the order of 10^7 erg cm^{-2} s^{-1}, sufficient to heat the AR corona.

*Speaker

A fast multi-dimensional magnetohydrodynamic formulation of the transition region adaptive conduction (TRAC) method

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The transition region adaptive conduction (TRAC) method permits fast and accurate numerical solutions of the field-aligned hydrodynamic equations, successfully removing the influence of numerical resolution on the coronal density response to impulsive heating. This is achieved by adjusting the parallel thermal conductivity, radiative loss, and heating rates to broaden the transition region (TR), below a global cutoff temperature, so that the steep gradients are spatially resolved even when using coarse numerical grids. Implementing the original 1D formulation of TRAC in multi-dimensional magnetohydrodynamic (MHD) models would require tracing a large number of magnetic field lines at every time step in order to prescribe a global cutoff temperature to each field line. We present a highly efficient formulation of the TRAC method for use in multi-dimensional MHD simulations, which does not rely on field line tracing. In the TR, adaptive local cutoff temperatures are used instead of global cutoff temperatures to broaden any unresolved parts of the atmosphere. These local cutoff temperatures are calculated using only local grid cell quantities, enabling the MHD extension of TRAC to efficiently account for the magnetic field evolution, without tracing field lines. Consistent with analytical predictions, we show that this approach successfully conserves the energy balance in the transition region and total amount of energy that is delivered to the chromosphere. Results from 2D MHD simulations of impulsive heating in unsheared and sheared arcades of coronal loops show, for the first time, that pressure differences, generated during the evaporation phase of impulsive heating events, can produce current layers that are significantly narrower than the transverse energy deposition.

*Speaker

Flows in Enthalpy Based Thermal Evolution of Loops

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Plasma-filled loop structures are common in the solar corona. Because detailed modeling of the dynamical evolution of these structures is computationally costly, an efficient method for computing approximate but quick physics-based solutions is to rely on space integrated 0D simulations. The enthalpy-based thermal evolution of loops EBTEL framework is a commonly used method to study the exchange of mass and energy between the corona and transition region. EBTEL solves for density, temperature, and pressure, averaged over the coronal part of the loop, the velocity at the coronal base, and the instantaneous differential emission measure distribution in the transition region. The single-fluid version of the code developed in 2012, EBTEL2, ignored the kinetic energy term throughout the evolution of the loop.

However, sometimes the solutions showed the presence of supersonic flows during the impulsive phase of heat input. It was thus necessary to account for this effect. We upgraded EBTEL2 to EBTEL3 by including the kinetic energy term in the energy conservation equation. We compared the solutions from EBTEL3 with those obtained using EBTEL2 as well as the state-of-the-art field-aligned hydrodynamics code HYDRAD. We found that the match in pressure between EBTEL3 and HYDRAD was better than that between EBTEL2 and HYDRAD. Additionally, the velocities predicted by EBTEL3 were in close agreement with those obtained with HYDRAD when the flows were subsonic. However, EBTEL3 solutions deviated substantially from HYDRAD's when the latter predicted supersonic flows. Using the mismatches in the solution, we proposed a criterion to determine the conditions under which EBTEL can be used to study flows in the system.

*Speaker

Session III

SunSpaceArt - Our Dynamic Sun

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The SunSpaceArt project is a team of scientists and artists who work together to deliver workshops in UK schools. Their aim is to spark imagination and develop creativity. The project is led by Dr Helen Mason, University of Cambridge, and funded by the STFC (Science and Technology Facilities Council). The team have worked with thousands of children (7-12 years old) and hundreds of teachers. The children have produced wonderful artwork about the Sun, Solar System and space science. We have focussed on schools in regions where an enhancement in science attainment is needed. Students with special educational needs and disabilities (SEND) have responded particularly well to our activities. The feedback has been outstanding *'Today I loved this lesson because the art and science inspired me'* (child). '*The SunSpaceArt activities provide an opportunity for all children to shine and take pride in their work and achievements.*' (teacher).
When 'in person' workshops were no longer possible (March 2020), we delivered material online (SunSpaceArt.org and YouTube) and held virtual workshops for children and training for teachers. In February 2021, we even ran a 12 hour long STEAM (STEM + Arts) Festival involving science, astronomy and space talks, craft activities, art, poetry and music. This celebration was aimed at children in the daytime and adults in the evening. It was a great success, reaching thousands of people, bringing a bit of sunshine to a rather dark and difficult winter. These online activities have enabled us to reach much further afield. In 2021, the SunSpaceArt team was the proud recipient of the Arthur C. Clarke Award in Space Achievement for Education and Outreach.
We wish to share our outreach work with the solar physics community, in particular the Loops community, to stimulate debate and to encourage others to share their own work with the public, students and children. The solar images and movies, and 3D models are truly inspirational. With new and exciting ground based solar observatories, recent NASA and ESA space projects such as Parker Solar Probe and Solar Orbiter, and future plans, there is a great opportunity to engage the public in our field of research.

*Speaker

Session IV

Wave diagnostics

On the assessment of the damping mechanism for transverse coronal loop oscillations

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This contribution aims to reflect on progress made in our understanding about the damping of transverse loop oscillations since their observational discovery more than two decades ago. Thoughts are focused on the strategies that were followed to assess the ability of different proposed mechanisms to explain the observations. Discussed examples include: direct discrimination based on a comparison between observed and theoretically predicted damping time-scales; the use of theoretically predicted scaling-laws relating oscillation properties; the comparison between forward-modelled and observed data-distributions; and the probabilistic assessment of evidence for a model in view of observed data. I plan to critically discuss these developments and the obtained results in the expectation of achieving further future progress.

*Speaker

Decayless kink oscillations detected with AIA and EUI

Valery Nakariakov * [1]

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Decayless kink oscillations are ubiquitous periodic transverse displacements of coronal plasma loops, detected in the high-resolution EUV imaging data. This regime of kink oscillations appears without any association with impulsive energy releases in the solar atmosphere, and may last for longer than several tens of oscillation cycles. Decayless kink oscillations have been demonstrated to be fast magnetoacoustic eigenmodes of host coronal loops, of the m=1 symmetry. Typical oscillation periods are about several minutes, and depend on the loop length, similarly to large-amplitude decaying kink oscillations. Typical apparent displacement amplitudes are lower than 1 Mm, i.e., often smaller than the pixel sizes of AIA and EUI. Nevertheless, decayless oscillations are confidently detected in coronal loops. We present analysis of long-term evolution of decayless oscillations, including the instantaneous periods and amplitudes, and their correlation with instantaneous parameters of the loop, such as the EUV brightness. In addition, we show that 66-163 s decayless oscillations of 0.08-0.17 Mm amplitude are detected simultaneously with AIA and EUI-HRI at 171 A and 174 A, respectively. In addition, transverse oscillations of a shorter period (around 30 s) and lower amplitude (around 0.075 Mm) are detected in multiple threads in the analysed loop bundle with EUI, which are naturally not visible by AIA due to insufficient time resolution.

*Speaker

Decay-less loop oscillations generated by steady-flow drivers

Konstantinos Karampelas * [1,2], Tom Van Doorsselaere [2]

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Over the past decade, high-resolution and high-cadence EUV observations have led to the discovery of decay-less kink oscillations in coronal loops. These are low amplitude oscillations, which show no apparent decay in their amplitudes over a many wave periods. Identifying the true nature and means of excitation for these oscillations is essential for their role as diagnostic tools of coronal seismology. One of the concepts explored in our studies is that of these undamped standing waves being self-oscillations, excited via the interaction of steady flows with coronal loops. We will be presenting the results of 3D magnetohydrodynamic simulations for two different models of straight flux tubes, which expand upon older analytical studies. The first model consists of a steady plasma flow around the loop footpoint, reminiscent of supergranulation flows, which excites an undamped oscillation, similarly to a bow on a violin string. The second model consists of a steady flow across the loop cross-section, reminiscent of upflows associated with coronal mass ejections. This generates Alfvenic vortex shedding that drives the resulting loop oscillation. The power spectral density graphs for both models identify the frequency of their fundamental standing kink mode as the dominant one and its independence from the flow strength. Traces of the second harmonic are found for the first model, having a frequency ratio to the fundamental mode matching the observations, while realistic oscillation amplitudes were identified in the second model. The results from both models act as a proof-of-concept for self-oscillations in coronal loops, showing for the first time in 3D simulations that these mechanisms can excite the observed decay-less transverse loop oscillations.

*Speaker

On the decayless transverse oscillations in active region coronal loops: Observations from Solar Orbiter/ EUI

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Small amplitude transverse oscillations are common in active region coronal loops. These oscillations are decayless in that they show little to no sign of damping even after multiple wave periods. They also seem to have no apparent connection with any transient events such as flares. Interestingly, these properties are in stark contrast with the well-known high amplitude, rapidly damped, flare-driven kink waves. Although it has been a decade since the first detection of these decayless oscillations, the driver of these waves still remains to be fully understood. To this aim, we analyze high-resolution EUV data of an active region loop system taken through the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter. By following the system over multiple days, we found that these active region loops exhibit decayless oscillations only sporadically. To understand the overall picture along with the footpoint dynamics, we analyze UV and EUV data from Atmospheric Imaging Assembly (AIA) as well as LOS magnetic field information from HMI, both on board Solar Dynamics Observatory (SDO). Our analysis presents a puzzling case: although the ambient conditions remain unchanged throughout the observation period, the decayless oscillations sporadically appear and disappear. We will discuss these observational results and put them into the context of numerical modeling of such decayless kink oscillations.

*Speaker

Session V

Plasma diagnostics

Evolution of coronal abundances in an active region

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We study the temporal and spatial variations of coronal abundances, and the underlying chromospheric and transition region properties, in an active region. We use spectral observations of the active region, over several days, taken with Hinode/EIS and IRIS. For the analysis of the EIS spectral data we apply a novel inversion method to derive the temperature, density, and abundances simultaneously. We discuss possible implications of our findings.

*Speaker

Simulating the FIP effect in coronal loops using a multi-species kinetic-fluid model

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We investigate abundance variations of heavy ions in coronal loops. We develop and exploit a multi-species model of the solar atmosphere (called IRAP's Solar Atmospheric Model: ISAM) that solves for the transport of neutrals and charged particles from the chromosphere to the corona following a high-order (16-moment) approach. We investigate the effect of different mechanisms that could produce the First Ionization Potential (FIP) effect. We compare the effects of frictional and thermal diffusion as well as wave-particle interactions through the ponderomotive force. A particular attention is given to the modeling of the partially ionized upper chromosphere where most of the FIP fractionation likely occurs, by including a comprehensive treatment of collisions, non-equilibrium ionization/recombination processes and an improved radiative cooling. It is highly suspected that the processes that control the extraction of heavy ions from the chromosphere are closely connected to the mechanisms that heat up the solar atmosphere through wave-particle interactions for instance. That is tested in ISAM by the adoption of different heating prescriptions, that are either based on ad-hoc phenomenological laws or on the dissipation of Alfvén waves following both WKB and (pseudo) non-WKB approaches. A coupling with a more sophisticated non-WKB turbulence model called Shell-ATM is also attempted to better capture non-linear effects and wave-particle interactions. We show preliminary results on the composition distribution along a typical coronal loop and compare with typical FIP biases. This work was funded by the European Research Council through the project SLOW_SOURCE - DLV-819189.

*Speaker

Coronal abundance diagnostics with EIS and SPICE

Natalia Zambrana Prado [1], Slimane Mzerguat [2], Eric Buchlin * [2], Miho Janvier [2]

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[2] Institut d'astrophysique spatiale, CNRS, Université Paris-Saclay – France

Linking solar activity at the Sun and in the corona to the heliosphere is one of Solar Orbiter's main goals. Its SPICE (SPectral Imaging of the Coronal Environment) EUV spectrometer will provide relative abundance measurements which will be key in this quest. Indeed, different structures on the Sun have different abundances as a consequence of the FIP (First Ionization Potential) effect, and these abundance biases are "frozen" from the lower corona. As result, remote-sensing abundance diagnostics in the corona compared to in-situ measurements can help constrain the source of the solar wind plasma.

We present the Linear Combination Ratio (LCR) method that we have developed (Zambrana Prado and Buchlin 2019) to obtain the relative abundance bias from EUV line radiances. This method was designed to provide a simple diagnostics of this bias, while being mostly insensitive the DEM, thus requiring to observe only a low number of spectral lines compatible with the Solar Orbiter telemetry allocations.

Applying the method to Hinode/EIS data, we could reproduce an active region composition map obtained following DEM analysis. We also present the current status of applying the method to SPICE data, and the challenges remaining until we can routinely produce SPICE abundance maps.

*Speaker

Electron densities from Fe XIII EUV and IR lines

Jaroslav Dudik * [1], Giulio Del Zanna [2], Helen Mason [3,2], Elena Dzifcakova [4], Jan Rybak [5], Juraj Lorincik [7,6], Steven Tomczyk [8], Michael Galloy [9]

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We analyze the coordinated Hinode/EIS and COMP observations of the off-limb solar corona obtained during IHOP 316. Both the allowed EUV lines as well as the forbidden IR lines of Fe XIII allow for measurements of electron density. We analyze several coronal loops, and find excellent agreement in the densities obtained, to within 10%, once the photoexcitation is taken into account and the background subtraction is performed. In addition, the electron densities obtained from Fe XII EUV lines are also in agreement with those from Fe XIII. Therefore, the Fe XIII IR lines represent a viable density diagnostics using ground-based instrumentation.

*Speaker

Non-equilibrium processes and opacity in solar active region cores

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We present evidence, based on Hinode EIS and IRIS observations, that non-equilibrium processes are ubiquitous in the cores of active regions. In the quiet Sun, the Fe XII ratios of the allowed lines observed by EIS vs. the forbidden IRIS line is consistent with plasma being in equilibrium, but in all active region observations it is not. A likely explanation is the presence of non-Maxwellian electron distribution, although time-dependent ionization effects cannot be completely ruled out.
These results are in agreement with previous findings based on EIS observations.
We also show that some opacity effects in the strong coronal lines are ubiquitous in the cores of active regions. Clear evidence is obtained from the Fe XII lines observed by Hinode EIS.

*Speaker

Physical properties of active region upflows

Pascal Démoulin * [1,2], Deborah Baker [3], Miho Janvier [4], Lidia Van Driel-Gesztelyi [3], Cristina Mandrini [5]

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Large scale high-speed upflows have been detected by the EUV Imaging Spectrometer (EIS) on board the Hinode satellite. These upflows are typically observed in pairs at the following and leading borders of active regions (ARs). These long-lived upflows are located in regions of low electron density, low radiance, and over strong magnetic flux concentrations of a single polarity. The line-profile blueshifts range from a few to 50 km/s and they are faster in hotter coronal emission lines. Significant blue wing asymmetries, with velocities in excess of 70-100 km/s, are observed in the upflow regions. These properties contrast with the ones of the typically red shifted and dense coronal loops present in AR cores. The AR loops have a long-term expansion driven by the AR magnetic field emergence, then by spreading (due to convective motions). We conclude that AR upflows are originating from reconnection along quasi-separatrix layers between overpressure AR loops and neighboring underpressure loops. In particular, this explains why upflows occur in pairs and are long lived (months).

*Speaker

Single and Multiple Vantage Point 3D Coronal Reconstruction with the CROBAR Method

Joseph Plowman * [1], Amir Caspi , Don Hassler , Marcus Hughes , Dan Seaton , Matthew West

[1] Southwest Research Institute [Boulder] – United States

We present new results from a novel method for recovering a 3D picture of the Corona which we have begun to call CROBAR (Coronal Reconstruction Onto B-Aligned Regions). These regions extend the concept of coronal loops to fill every point in a coronal volume, following the structure and connectedness of the magnetic field as they do. The method then simultaneously fits the emission profiles of every B-aligned region to an observed emission measure image. It can obtain usable results even from a single perspective (e.g., Earths with SDO), and can also easily incorporated results from multiple perspectives. CROBAR can estimate both the coronal field and the plasma properties throughout the volume. We demonstrate these capabilities using both real data and MHD simulation output, and we also use this to investigate which perspectives and observables are best for determining coronal plasma structure.

*Speaker

Session VI

Heating mechanisms

A review of small scale current sheets and coronal heating (invited)

Thomas Howson * [1]

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Magnetic field lines embedded in the photosphere are subject to continuous stressing, twisting and braiding by the complex convective motions that are observed at the solar surface. The advection of field line foot points by these flows, causes an injection of energy into the solar atmosphere. This Poynting flux can drive large scale impulsive events such as solar flares and, on a smaller scale, can also power coronal heating. As the magnetic field is tangled, it becomes increasingly non-potential, with intricate, narrow current layers proliferating the atmospheric volume. These current sheets encourage the release of energy through magnetic reconnection and/or Ohmic heating, raising the temperature of the local plasma. In this review talk, I will discuss the state of our understanding on current sheet formation and the subsequent release of energy in the solar corona. I will focus on the results of 3D MHD simulations which consider the injection of energy by photospheric motions, the build-up of stress in the magnetic field, the resultant heating and then, the atmospheric response. We shall see how the constant feedback between the energy injection mechanism (photospheric driving) and the energy release process is fundamental in determining the heating rates, and therefore the state of the corona.

*Speaker

EUV MUSE diagnostics of heating release from MHD loop modeling

Fabio Reale * [1,2], Paolo Pagano , Antonino Petralia , Paola Testa

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Photospheric motions drive twisting and braiding of coronal magnetic field confining loop plasma. The magnetic field can be stressed up to eventually diffuse and convert magnetic energy into heat through current dissipation. Fully 3D MHD loop simulations allow us to derive EUV spectral tracers that can directly track the dissipating currents, therefore providing evidence for the structuring and timing of the energy release and constraints for forthcoming MUSE observations.

*Speaker

Observational and numerical characterization of a wave-like front propagating along a coronal fan

Valeria Sieyra * [1], S. Krishna Prasad [1], Guillermo Stenborg [2], Elena Khomenko [3], Tom Van Doorsselaere [4], Andrea Costa [5], Alejandro Esquivel [6]

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On 2011 July 6 EUV channels of AIA instrument onboard SDO detected a recurrent, arc-shaped intensity disturbance over an active region. The intensity disturbance fronts were observed to propagate along a coronal loop bundle rooted in a small area of the dark umbra of the sunspot. Neither signatures of flare activity nor of a coronal mass ejection event were observed in association with the phenomenon. The coronal intensity perturbations are usually associated with slow magnetoacoustic waves that are generated in the lower atmosphere and propagate towards the corona through the magnetic field. They have several applications in coronal seismology, such as the determination of plasma temperature, loop geometry, magnetic field, thermal conduction and polytropix index. Periodicity and kinematic analysis reveals a recurrent accelerated pattern of 2.4 minutes propagating along the loop with speeds lower than the local sound speed. We attribute the accelerated profile to the projection effect of the speed caused by the inclination of the magnetic field respect to the local vertical. To shed light on the physical nature of the event and to quantify the projection effect, we perform 2D numerical simulations based on a simple symmetrical potential magnetic field configuration embedded in a gravitationally stratified atmosphere in hydrostatic equilibrium. We generate slow waves using a 3 minutes driver located in the lower atmosphere. To emulate the behaviour of the waves in a loop, we forward model the intensity in EUV for a fluxtube extracted from the simulations, recreating the height–time maps obtained from observations. The speed values obtained from numerical simulations are similar to those estimated from observations and exhibit an accelerated pattern. The numerical analysis confirms that the accelerated profile seen on EUV channels is due to a projection effect and responds to the slow magnetoacoustic propagating wave scenario.

*Speaker

Loop heating by non-linear damping of transverse waves

Tom Van Doorsselaere * [1], Norbert Magyar [1], Marcel Goossens [1], Bo Li [2], Bogdan Hnat [3], Michael S Ruderman [4], Rajab Ismayilli [1], Valeria Sieyra [1]

[1] KULeuven – Belgium
[2] Shandong University – China
[3] University of Warwick – United Kingdom
[4] Department of Applied Mathematics [Sheffield] – United Kingdom

Numerical simulations have revealed a new type of turbulence of unidirectional waves in a plasma that is perpendicularly structured (Magyar et al. 2017), named uniturbulence. In this presentation, we show an analytical description of the non-linear evolution of kink waves in a cylindrical flux tube, which are prone to uniturbulence. We calculate explicit expressions for the wave damping, and the resulting heating. The computed damping and heating rate τ/P depends on the density contrast of the flux tube and the background plasma and is inversely proportional to the amplitude of the kink wave. The dependence on the density contrast shows that this heating plays a role especially in the lower solar corona and in particular in coronal loops. We compare the analytical results with numerical simulations and observations. In both cases we find a reasonably good match.
In a next step, we consider the analytical model for the wave heating rate and assume a power law wave spectrum that drives a coronal loop of a given length and magnetic field strength. This allows us to predict wave heating functions and scaling laws, that are suitable for fitting observations.

*Speaker

Magnetic Reconnection in 3D vs. 2D and Dependency on Magnetic Shear

Lars K. S. Daldorff * [1], James E. Leake [2], James A. Klimchuk [2]

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[2] NASA – United States

Magnetic reconnection plays a central role for heating the solar coronal plasma – including during fares – as well as other places in the heliosphere and beyond, where each event can be characterized by its geometry and magnetic configurations, forming structures that we can categorize to be more 2D or 3D. Although the difference between reconnection rates in 2D and 3D has been noted before, we perform a comprehensive study and offer a possible explanation. We report on a study of the reconnection rate using the resistive MHD code LaRe3D. We show that the rate depends strongly on the existence and interaction of different tearing layers (oblique tearing modes) within the current sheet. Such modes are only present with a finite guide field and a spatial dependence in this third direction. We find, as have others, that reconnection rates are artificially high in 2D simulations, and we offer an explanation.

*Speaker

(When) Can wave heating balance optically thin radiative losses in the corona?

Ineke De Moortel * [1,2], Tom Howson [1]

[1] University of St. Andrews – United Kingdom
[2] Rosseland Centre for Solar Physics, University of Oslo – Norway

Why the atmosphere of the Sun is orders of magnitudes hotter than its surface is a long standing question in Solar Physics. Over the years, many studies have looked at the potential role of MHD waves in sustaining these high temperatures. In this study, we use 3D MHD simulations to investigate (driven) kink waves in a coronal loop. Due to the radial density profile, resonant absorption (or mode coupling) and phase mixing take part in the boundaries of the flux tube and the large velocity shears are subject to the Kelvin Helmholtz instability (KHI). The combination of these effects leads to enhanced energy dissipation and wave heating. From a study of a variety of wave drivers and coronal loop profiles, we find that only wave heating associated with a resonant driver in a lower density loop is able to balance radiative losses. For denser loops and/or drivers with non-resonant frequencies, the coronal structure will cool as the energy losses are greater than the energy injection and dissipation rates.

*Speaker

Transverse MHD waves as signatures of braiding-induced magnetic reconnection in coronal loops

Ayu Ramada Sukarmadji * [1], Patrick Antolin [1]

[1] Northumbria University – United Kingdom

A major coronal heating theory based on magnetic reconnection relies on the existence of braided magnetic field structures in the corona. Numerical simulations of stress-induced reconnection in braided loop-like structures invariably lead to low-amplitude transverse MHD waves. In this small-angle reconnection scenario, the reconnected magnetic field lines are driven sideways by magnetic tension but overshoot from their new rest position, thereby leading to transverse waves. Besides providing an efficient mechanism for transverse MHD wave generation in the corona, this direct causality also constitutes substantial evidence of reconnection from braiding. However, this wave-generation mechanism has never been directly observed. Furthermore, imaging observations of coronal loops in the EUV often lack the expected small-angle misalignments in their internal structure, casting doubt on this coronal heating mechanism. Recently, the telltale signature of small-angle reconnection in a sheared coronal structure has been identified through nanojets, which are small, short-lived, and fast jet-like bursts in the nanoflare range that are transverse to the guide-field. As for the waves, magnetic tension has been invoked to explain their characteristic transverse directionality. We present for the first time IRIS and SDO observations of transverse MHD waves in a coronal loop that directly result from braiding-induced reconnection, where the reconnection is identified by the presence of nanojets at the loop apex. This discovery provides major support to (a) existing theories that transverse MHD waves can be a signature of reconnection, (b) the existence of braiding in coronal structures and (c) the coronal reconnection scenario identified by nanojets.

*Speaker

Session VII

Heating diagnostics

Coronal heating studies with the Multi-slit Solar Explorer (MUSE)

Bart De Pontieu * [1], Paola Testa [2], Juan Martinez Sykora [3], The Muse Team

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The Multi-slit Solar Explorer (MUSE) is a recently selected NASA MIDEX mission, composed of a multi-slit EUV spectrograph (in three narrow spectral bands centered around 171Å, 284Å, and 108Å) and an EUV context imager (in two narrow passbands around 195Å and 304Å). MUSE will provide unprecedented spectral and imaging diagnostics of the solar corona at high spatial ($\approx$ 0.5 arcseconds), and temporal resolution (down to $\approx$ 0.5 seconds) thanks to its innovative multi-slit design. By obtaining spectra in 4 bright EUV lines (Fe IX 171Å, Fe XV 284Å, Fe XIX-XXI 108Å) covering a wide range of transition region and coronal temperatures along 37 slits simultaneously, MUSE will for the first time be able to "freeze" (at a cadence as short as 10 seconds) with a spectroscopic raster the evolution of the dynamic coronal plasma over a wide range of scales: from the spatial scales on which energy is released ($\approx$ 0.5 arcsec) to the large-scale often active-region size ($\approx$ 170 arcsec $\times$ 170 arcsec) atmospheric response. We use advanced numerical modeling to showcase how MUSE will constrain the properties of the solar atmosphere on the spatio-temporal scales ($\approx$ 0.5 arcsec, $\approx$ 20 seconds) and large field-of-view on which various state-of-the-art models of the physical processes that drive coronal heating make distinguishing and testable predictions. We describe how the synergy between MUSE, the single-slit, high-resolution Solar-C EUVST spectrograph, and ground-based observatories (DKIST and others) can address how the solar atmosphere is energized, and the critical role MUSE plays because of the multi-scale nature of the physical processes involved.

*Speaker

Preliminary Results from the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS)

Amy Winebarger * [1], Sabrina Savage [1], Ken Kobayashi [1], P. S. Athiray [2], Dyana Beabout [1], Stephen Bradshaw [3], Patrick Champey [1], Peter Cheimets [4], Jonathan Cirtain [5], Edward Deluca [4], Giulio Del Zanna [6], Jaroslav Dudik [7], Leon Golub [4], Helen Mason [6], David Mckenzie [1], Brian Ramsey [1], Katharine Reeves [4], Paola Testa [4], Genevieve Vigil [1], Robert Walsh [8], Harry Warren [9]

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[5] BWXT – United States
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[8] University of Central Lancashire – United Kingdom
[9] Naval Research Laboratory – United States

The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is a sounding rocket mission that aims to observe the soft x-ray solar spectrum (0.6 – 2.5 nm) with both spatial and spectral resolution over a substantial field of view. This wavelength range has several high temperature and abundance diagnostics that can be used to assist in diagnosing the coronal heating mechanism. MaGIXS launched from White Sands Missile Range on July 30, 2021 and successfully observed the Sun through a 4' × 33' effective slot, producing "overlappograms", where the spatial and spectral information are overlapped and must be unfolded. In this presentation, I will report on the MaGIXS launch and data collection and provide preliminary analysis of MaGIXS data.

*Speaker

Thermal properties of the smallest EUV brightenings observed with SolO/HRI-EUV and SDO/AIA.

Antoine Dolliou * [1], Susanna Parenti [1], Frédéric Auchère [1], Karine Bocchialini [1], Gabriel Pelouze [1]

[1] Institut d'Astrophysique Spatiale, CNRS, Université Paris-Saclay – France

In the context of the solar corona heating, we will present our measurements of short time scale cooling of small UV brightenings derived from a multi-wavelength observation with SDO/AIA and SolO/EUI-HRI.
On May 2020, the high resolution UV imager EUI-HRI, onboard Solar Orbiter, made its first observation of the quiet solar corona at the highest resolution (200 km in the corona) and cadence (5 s) up to this day. This observation is of particular interest, because it falls within the context of small scale heating, potentially explaining the temperature of the solar corona in the order of MK (Parker, 1988). During this 5 minutes sequence, 1467 small brightenings of variable sizes (400 to 4000 km) and lifetimes (10 to 200 s) have been detected (Berghmans et al., 2021); their temperature has been estimated to peak between 1.2 and 1.4 MK.

In order to study the thermodynamics of these events, we measure their time lags between the multichannel light curves of SDO/AIA. These time lags can be a consequence of heating or cooling processes of plasma along the line of sight (Viall & Klimchuk 2011, 2012).

Cross-correlation between two AIA sequences pixel by pixel results in a map of time lags and their associated maximum correlation values. We use couples between 6 EUV channels of AIA to cover a large range of coronal and transition region temperatures, while taking into account the effects of coronal red noise and background variations. We compare the pixel-by pixel distributions of time lags and maximum correlation values between the events and the background in the quiet sun.

As a result, we measure the time lags of these brightenings to be mostly inferior to 12 s, which is the AIA cadence. Moreover, the **positive** asymmetry in the time lag distributions detected for the couples the AIA 193 – 171 and AIA 211 – 171 can be interpreted as a signature of short time scale **cooling**.
As of now, time lags have only been compared with models of nanoflares in large coronal loops (Viall & Klimchuk, 2013). In this context, short time lags are a consequence of nanoflares peaking at transition region temperatures, not coronal temperatures. That being said, this model is

*Speaker

adapted for small events in active regions, not in the quiet sun. This is why we are currently investigating time lags from models more consistent with our observations, such as reconnection of small scale loops or flares.

Narrowing down causality between coronal heating mechanisms and observations (invited)

Patrick Antolin * [1]

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Proving direct causality - necessary and sufficient cause - between a coronal heating mechanism X and an observational signature Y is challenging. It may even be always impossible in the strictly physical sense. First, we need to show that X came before Y, that chance has nothing to do with it, and that we would not have Y without X. However, the advent of high-resolution instrumentation in solar physics combined with advanced numerical modelling significantly narrow down the cause and effect relationship, thus enabling direct approaches to identify coronal heating agents. Over several decades two major coronal heating candidates have emerged, MHD waves and magnetic reconnection. But this is by no means a black and white dichotomy as each mechanism can be cause and effect of the other and can operate in unison. In addition, we may never resolve the relevant dissipation scales in imaging and spectroscopic observations where each agent has theoretically unique imprints. Despite this impossible task, telltale signatures of each mechanism can emerge at larger observable scales. Prime examples are specific out-of-phase relations between spectroscopic observables as a signature of transverse MHD waves dissipating via a combined resonant absorption - Kelvin-Helmholtz mechanism and nanojets as a signature of reconnection-driven nanoflares in braided coronal loops. This talk will review such recent observational and numerical work and discuss the exciting possibilities provided by new missions such as Solar Orbiter.

*Speaker

Doppler Shifts and their Centre to Limb Variation in Transition Region

Durgesh Tripathi * [1], Abhishek Rajhans [1], James Klimchuk [2]

[1] IUCAA – India
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It has been proposed that field aligned downflows in the solar transition region are an indication of cooling and draining plasma following impulsive coronal heating. Such flows would show centre to limb variation (CLV) of measured Doppler shifts that vanishes completely at the limb. In this work, we study the CLV of Doppler shifts in the Si IV lines using IRIS observations. Our results show that although there are hints of CLV in the data, there are sizeable Doppler shifts near the limb. Moreover, simulations of impulsively heated loops predict much smaller velocities than observed in the Si IV line. These results indicate that the downflows are not associated with impulsive coronal heating. We suggest that, instead, they are primarily due to Type-II spicules. We introduce the idea of a chromospheric wall (associated with classical Type-I spicules) that diminishes the CLV of the Doppler shifts and may produce non-zero Doppler shifts at the limb.

*Speaker

Role of small-scale impulsive events in heating the X-ray bright points of the quiet Sun

B Mondal * [1], J. A Klimchuk [2], S. V Vadawale [1], A Sarkar [1], N. P. S Mithun [1], A Bhardwaj [1], P. S. Athiray [5,4,3], G. Del Zanna [6], H. E Mason [6]

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Coronal nanoflares are thought to be one of the prime candidates that can keep the solar corona hot at its multi-million Kelvin temperature. Because of line-of-sight averaging and other effects, individual nanoflares are difficult to detect; though their presence can be inferred through various other techniques such as Differential Emission Measure (DEM) analysis. During the minimum of solar cycle 24, we estimate the disk-integrated DEM using X-ray and EUV observations from the Solar X-ray Monitor (XSM) onboard the Chandrayaan-2 orbiter and AIA onboard the Solar Dynamic Observatory. In the absence of conventional active regions, X-ray bright points (XBP) are the dominant contributor of the disk integrated X-rays. We estimate the DEM of these XBPs. They are found to be associated with bipolar magnetic fields and consist of small-scale loops. We simulate such XBP loops using the EBTEL hydrodynamic code. The lengths and magnetic field strengths of these loops are obtained through potential field extrapolation of the corresponding photospheric magnetogram. Each loop is assumed to be heated by nanoflares having a power-law energy distribution that depends on the loop properties. The composite distribution for all the loops has a power-law slope close to 2. The simulation output is then used to obtain the integrated DEM. It agrees remarkably well with the observed DEM at temperatures above 1 MK. Our results suggest that the nanoflares are primarily responsible for XBP heating.

*Speaker

Inferring quiet Sun heating using machine learning

Vishal Upendran * [1], Durgesh Tripathi [1], Mithun N.P.S. [2], Santosh Vadawale [2], Aveek Sarkar [2]

[1] IUCAA – India
[2] PRL – India

The solar corona consists of a million-degree Kelvin plasma – including the ever-existing quiet Sun. Hence, the energetics and heating of this background must be studied to get to the roots of the coronal heating problem. In this work, we perform a study of the light curves from solar corona using machine learning (ML)-driven by the empirical forward model of Pauluhn and Solanki (2007) (PSM). First, we analyze $>$ 300,000 light curves, each spanning approximately 8 hours, from individual pixels from 171, 193, and 211 Å passbands of AIA. With our ML scheme, we infer the flaring frequency, flaring timescale, and power-law slope α (which are the free parameters of PSM) and their associated uncertainties. We find impulsive events to be a viable source of generating intensity. These events have a typical time scale of 10-20 minutes and occur at 2-3 events per minute. Furthermore, we find that the correlations between free parameters may be explained by the domination of conduction losses and the existence of an energy reservoir. We then apply this scheme on full disc integrated and flux-calibrated light curves from X-ray Solar Monitor onboard Chandrayaan-2. Such an inversion gives us a lower bound of the energy flux in QS resulting from luminosity. We find the X-ray results to consistently follow the trends on moving from cooler to hotter plasma emission as seen in AIA, though the smallest of events are noted to be of the order of 1e20 ergs. Furthermore, these events have a range of α, from 1.5 to 2.1, while the typical time scales are 6-12 minutes, and the flaring frequency is $\approx$25 events per minute. These findings give us a deeper understanding of the viability of impulsive events in heating the solar corona and the advantages offered by data-driven ML algorithms in accelerating science. Finally, these findings stress the importance of future high spatio-temporal observations to infer the presence of sub-resolution heating events in the corona.

*Speaker

The 'coronal veil' hypothesis: evidence, implications, and future studies (invited)

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[4] NASA Goddard Space Flight Center – United States
[5] National Center for Atmospheric Research (NCAR) – Bulder, USA, United States

We analyze 3D MHD simulation of the solar corona generated with MURaM code (Rempel 2017) that had previously been shown to reproduce many important aspects of solar observations (Cheung et al, 2018). The synthetic Extreme Ultraviolet (EUV) images constructed from this simulation are qualitatively realistic; in particular, they contain bundles of realistic coronal loops. We analyze individual loops in these bundles, and attempt to identify their volumetric counterparts. We find that in many cases, a loop cannot be linked to an individual thin strand in the volume. While many thin loops are present in the synthetic images, the bright structures in the volume are fewer and of complex shape. We demonstrate that this complexity can form impressions of thin bright loops, even in the absence of thin bright plasma strands. We also show that it can be difficult to discern from observations whether a particular loop corresponds to a strand in the volume, or a projection artifact, even when multiple viewing angles are available. While we base our analysis on a simulation, the main findings are independent from a particular simulation setup and illustrate the intrinsic complexity involved in interpreting observations resulting from line-of-sight integration in an optically thin plasma. This study may lead to substantial changes in how we interpret loop observations, as it challenges currently used techniques and models. How can we determine, with with solar observations, whether this is actually what is happening in the Sun? In the talk, I will go over potential pitfalls for observational validation of the veil hypothesis. I will also discuss possible ways forward.

*Speaker

Cross Sections of Coronal Loop Flux Tubes

James Klimchuk * [1], Craig Deforest [2]

[1] NASA Goddard Space Flight Center – United States
[2] Southwest Research Institute – United States

Coronal loops reveal crucial information about the nature of both coronal magnetic fields and coronal heating. The shape of the corresponding flux tube cross section and how it varies with position are especially important properties. They are a direct indication of the expansion of the field and of the cross-field spatial distribution of the heating. We have studied 20 loops using high spatial resolution observations from the first flight of the Hi-C rocket experiment, measuring the intensity and width as a function of position along the loop axis. We find that intensity and width tend to either be uncorrelated or to have a direct dependence, such that they increase or decrease together. This implies that the flux tube cross sections are approximately circular under the assumptions that the tubes have non-negligible twist and that the plasma emissivity is approximately uniform along the magnetic field. The shape need not be a perfect circle and the emissivity need not be uniform within the cross section, but sub-resolution patches of emission must be distributed quasi-uniformly within an envelope that has an aspect ratio of order unity. This raises questions about the suggestion that flux tubes expand with height, but primarily in the line-of-sight direction so that the corresponding (relatively noticeable) loops appear to have roughly uniform width, a long-standing puzzle. It also casts doubt on the idea that most loops correspond to simple warped sheets, although we leave open the possibility of more complex manifold structures.

*Speaker

Understanding the cross-field thermal structure of a coronal loop using slow magnetoacoustic waves

S. Krishna Prasad * [1], Tom Van Doorsselaere [1]

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One of the critical parameters in distinguishing the two dominant theories of coronal heating is the cross-field thermal structure of a coronal loop. While the traditional methods like the filter ratio or the DEM technique determine this to an extent, the line-of-sight integration of the emission still poses a problem and it is difficult to eliminate the possible contamination from other structures in the background/foreground. Here, we aim to use propagating slow waves to probe both the longitudinal and the transverse temperature structure within a coronal loop. In order to achieve this, we build a 3D MHD model of a multi-stranded loop and excite the slow waves by perturbing the plasma at the bottom. The multi-wavelength propagation characteristics of the waves are then studied using synthetic images generated via forward modelling techniques. A comparison is also made with observations reported in the past to draw some important inferences.

*Speaker

Accelerated particle beams in a 3D simulation of the quiet Sun

Lars Frogner * [1,2], Boris Vilhelm Gudiksen [2,1], Helle Bakke [1,2]

[1] Rosseland Centre for Solar Physics – Norway
[2] Institute of Theoretical Astrophysics [Oslo] – Norway

Accelerated particles are ubiquitous in the solar atmosphere. They are produced when stress built up in the magnetic field is released through magnetic reconnection. While much has been learned about the role of accelerated particles on the Sun by modelling isolated flare events in one dimension, less is understood about how acceleration and transport of energetic particles influence, and in turn are influenced by, the evolution of the atmosphere in a complex three-dimensional setting.

We have taken a step towards this goal by incorporating simple models of particle acceleration and transport into a realistic radiative magnetohydrodynamic simulation of the quiet solar atmosphere.

By identifying locations where conservation of magnetic topology is violated, we determined where electrons are likely to be accelerated. We then estimated the parameters of the resulting non-thermal electron distributions based on the local conditions and computed the energy deposited by the electrons along their field line-aligned trajectories due to Coulomb collisions with the ambient plasma.

Extended sites of reconnection occur throughout the corona, most of them located in the lower part. The resulting electron beams deposit their energy both along the coronal part of magnetic loops and near their footpoints in the transition region and chromosphere, as presented by Frogner et al. (2020).

References:

Frogner, L., Gudiksen, B. V., & Bakke, H. 2020, Astronomy & Astrophysics, 643, A27, publisher: EDP Sciences

*Speaker

Session VIII

Thermal non-equilibrium

Multi-scale manifestations of thermal non-equilibrium in coronal loops (invited)

Clara Froment * [1]

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Thermal non-equilibrium (TNE) is a highly non-linear process in which a quasi-steady and stratified heating can force a coronal structure to enter a periodic thermodynamic evolution. TNE can lead to the formation of cool and condensed material in the hot solar corona, in the form of coronal rain, that appear during the cooling phases of these thermal cycles. TNE is now also detected in the form of ubiquitous long-period (a few hours) EUV pulsations, mainly found in solar coronal loops.

I will give an overview of the latest developments, on both observations and modelling of long-period EUV pulsations in coronal loops and their relationship with coronal rain events. I will show in particular that they are two aspects of the same phenomenon and why understanding the characteristics of thermal non-equilibrium cycles is essential to understand the circulation of mass and energy in the corona.

*Speaker

The role of thermal instability in thermal non-equilibrium

Biel Castell [1], Ramon Oliver * [1], Jaume Terradas [1], Manuel Luna [1], Cooper Downs [2], Zoran Mikic [2]

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Field (1965) studied the stability of a homogeneous and static plasma in the absence of gravity and magnetic field. In this work he considered the linear regime, in which a small perturbation can grow exponentially and give rise to the formation of cold condensations. This is the thermal instability (TI) process. On the other hand, some numerical simulations of coronal loops subject to a steady heating concentrated near their feet show a behaviour reminiscent of TI: loops seem to achieve an equilibrium state, but they actually evolve slowly and after some time suffer a catastrophic cooling that ends with the formation of a cold condensation. The whole process is called thermal non-equilibrium (TNE). In this contribution we address whether the thermal runaway of TNE is caused by a TI. We compare the temperature growth time at the onset of TNE and compare it with that of TI. Our analysis of some numerical simulations show that the temperature and density at the loop apex are such that it should be thermally stable, whereas the whole loop is in a TNE state. The conclusion for these simulations is that TI plays no role in the TNE.

*Speaker

Prevalence of Thermal Non-Equilibrium over an Active Region

Seray Sahin * [1], Patrick Antolin [1]

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The solar corona is characterised by its puzzling multi-million-degree component. On the other hand, observations in the last decade have shown that the corona also contains a large amount of cool material called coronal rain, whose clumps are 10 –100 times cooler and denser than the surroundings and are often organised in larger events termed showers. Thermal instability (TI) within a coronal loop in a state of thermal non-equilibrium (TNE) is the leading mechanism behind the formation of coronal rain but no investigation on showers exists to date. In this study, we carry out a morphological and thermodynamic imaging and multi-wavelength study of coronal rain showers observed in an active region off-limb with IRIS and SDO, spanning chromospheric to transition region and coronal temperatures. Rain showers were found to be widespread across the active region over the 4.5-hour duration of observation time, with average length, width and duration of 27.37±11.95 Mm, 2.14±0.74 Mm, and 35.22±20.35 min, respectively. We further find a good correspondence between showers and the cooling coronal structures consistent with the TNE-TI scenario, thereby properly identifying coronal loops in the coronal veil, including the elusive expansion with height in the EUV. We estimate the total number of showers to be 155±40, leading to a TNE volume of $4.56 \pm (3.71) \times 10^{28}$ cm^3, i.e. on the same order of the active region volume. This suggests a prevalence of TNE over the active region indicating strongly stratified and high-frequency heating on average.

*Speaker

Simulations of Thermal Non-Equilibrium Caused by Nanoflares

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We present the results of models of nanoflare heated coronal loops using the 1-D hydrodynamic ARGOS code. The nanoflares are modeled by discrete pulses of energy along the loop. We explore the occurrence of cold condensations due to the effective equivalent of thermal non-equilibrium (TNE) in loops with steady heating. We examine the dependence on nanoflare timing and intensity and also on location of nanoflares along the loop. In addition to exploring the parameter space for nanoflares with regular recurrence and constant locations in the loop, we also investigate the effects of randomized nanoflares in time and intensity and also location. We find that randomizing the timing and intensity of nanoflares tends to diminish the likelihood of TNE compared to regularly occurring nanoflares with the same average properties, but that TNE can sometimes occur in regimes where regular nanoflares would not produce TNE. Also, the condensations stay in the loop for a shorter amount of time when the nanoflares are random. We offer explanations for all of this behavior.

*Speaker

Plasmoid-Fed Prominence Formation (PF^2) during flux rope eruptions

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We report a new, plasmoid-fed scenario for the formation of an eruptive prominence, involving reconnection and condensation. We use grid-adaptive resistive two-and-a-half-dimensional magnetohydrodynamic simulations in a chromosphere-to-corona setup to resolve this plasmoid-fed scenario. We study a preexisting flux rope (FR) in the low corona that suddenly erupts due to catastrophe, which also drives a fast shock above the erupting FR. A current sheet (CS) forms underneath the erupting FR, with chromospheric matter squeezed into it. The plasmoid instability occurs and multiple magnetic islands appear in the CS once the Lundquist number reaches a critical value. The remnant chromospheric matter in the CS is then transferred to the FR by these newly formed magnetic islands. The dense and cool mass transported by the islands accumulates in the bottom of the FR, thereby forming a prominence during the eruption phase. More coronal plasma continuously condenses into the prominence due to the thermal instability as the FR rises. Due to the fine structure brought in by the plasmoid-fed process, the model naturally forms filament threads, aligned above the polarity inversion line. Synthetic views at our resolution of 15 km show many details that may be verified in future high-resolution observations.

*Speaker

Session IX

Posters

Multi-stranded simulations to model FOXSI and AIA observations: Single power-law distribution for transients & background

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Solar Coronal heating, which maintains the Corona at $\gtrsim$1 MK can be attributed to uniform steady background heating and transients like impulsive flaring events. Here we explore the possibility that the steady heating is attributable to a large swarm of small impulsive events with a single power-law distribution of flare energies. We perform a 0D hydrodynamic simulation of a multi-stranded system of loops, mimicking EUV data obtained from Atmospheric Imaging Assembly (AIA) and X-ray data Focusing Optics X-ray Solar Imager (FOXSI) for an isolated loop complex. The total energy budget is constrained by FOXSI luminosity. We parameterize the system with the slope of power-law distribution, minimum and maximum energy dissipated in single event, constrained by total energy from FOXSI and strand radius from Hi-C. Preliminary results indicate that the observed light curves can be best explained by a power-law with negative slope (α) in the range 1.6$\leq \alpha \leq$1.8 and maximum and minimum energies differing by more than 7-8 orders of magnitudes. We discuss the implications of these results and possible extensions.

*Speaker

Soft X-ray Spectral Diagnostics of Flaring Loops with Chandrayaan-2 XSM

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Determination of temperature structure and other physical parameters of flaring plasma can provide insights into the heating and particle acceleration mechanisms in solar flares. We present spectroscopic investigations of the evolution of plasma parameters during the course of a sample of solar flares using observations with the Solar X-ray Monitor (XSM) on Chandrayaan-2. XSM provides disk integrated soft X-ray spectrum of the Sun in 1 – 15 keV energy range with high resolution and time cadence. Using the broadband soft X-ray spectra consisting of the continuum and well-resolved line complexes of major elements like Mg, Si, and Fe, we investigate the consistency of isothermal and multi-thermal assumptions on the flaring plasma. We find that while the X-ray spectra of weaker flares are consistent with isothermal emission, for brighter events, the observed spectra significantly depart from an isothermal model during the impulsive phase. Detailed analysis shows that the spectra can only be explained with the presence of multiple temperature components. We then fit the impulsive phase spectra with parameterized Differential Emission Measure (DEM) models and find that a single broad temperature distribution or multi-peaked distribution fits the spectra well. Observations with SDO AIA are then used to investigate the spatial distribution of the multiple temperature components. We also present the evolution of elemental abundances during the flares obtained from the DEM analysis and discuss their implications. We will also discuss prospects of joint analysis of soft X-ray observations with XSM along with other multi-wavelength observations for disentangling thermal and non-thermal particle populations during solar flares.

*Speaker

Coronal heating in QS and Coronal holes

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The problems of solar coronal heating, solar wind formation, and acceleration are intimately tied to the underlying magnetic field topology. This dichotomy manifests as differences in Coronal Holes (CH) vis-a-vis nearby background Quiet Sun (QS) regions. While this differentiation is seen clearly in the corona, they apparently cease to exist lower in the atmosphere – however, they are clearly found when the underlying photospheric magnetic flux density ($|B|$) is considered. In this work, we study the chromospheric Mg II h&k, the C II 1334 Å, and the TR Si IV line in CHs and QS as a function of $|B|$. We find all lines to show an increase in intensities and velocities with $|B|$. The chromospheric lines show reduced intensity, excess blueshifts, and excess redshifts in CHs over QS for regions with similar $|B|$. CHs show excess blueshifts and reduced intensity and redshift in the TR line. Cross-correlation of chromospheric and TR velocities shows that flows in the same direction are tightly correlated in both regions, while the chromospheric downflows are also correlated with TR upflows. The TR downflows (upflows) are larger in QS (CHs) for similar chromospheric flows. The observed flows and intensities may be explained by invoking interchange (closed-loop) reconnection in CHs (QS) in a stratified atmosphere, thereby suggesting a unified scenario for the QS heating and solar wind formation.

*Speaker

Observational Signatures of Coronal Heating in MHD Simulations Without Radiation or a Lower Atmosphere

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It is extremely difficult to simulate the details of coronal heating and also make meaningful predictions of the emitted radiation. Thus, testing realistic models with observations is a major challenge. Observational signatures of coronal heating depend crucially on radiation, thermal conduction, and the exchange of mass and energy with the transition region and chromosphere below. Many magnetohydrodynamic simulation studies do not include these effects, opting instead to devote computational resources to the magnetic aspects of the problem. We have developed a simple method of accounting approximately for the missing effects. It is applied to the simulation output *post facto* and therefore may be a valuable tool for many studies. We have used it to predict the emission from a model corona that is driven by vortical boundary motions meant to represent photospheric convection. We find that individual magnetic strands experience short-term brightenings, both scattered throughout the computational volume and in localized clusters. The former may explain the diffuse component of the observed corona, while the latter may explain bright coronal loops. Several observed properties of loops are reproduced reasonably well: width, lifetime, and quasi-circular cross-section (aspect ratio not large). Our results lend support to the idea that loops are multi-stranded structures heated by "storms" of nanoflares.

*Speaker

Realistic solar flare models

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Despite decades of research, the coronal heating problem remains unsolved. One potential method of providing the required energy is via high-velocity particles produced in reconnection events such as in solar flares. Accurate descriptions of the reconnection region require a kinematic approach, such as PIC solvers, but solar flares are multi-scale events. PIC solvers are extremely computationally demanding, and we cannot realistically model the entire flare with this approach. Alternatively, the MHD approach is much cheaper but fails at accurately modeling the small scales of the reconnection region. We present the first steps of an integrated solution where MHD and PIC solvers are running concurrently in different parts of a computational domain. The ultimate goal will be to model a solar flare and its surrounding corona in a realistic 3D simulation.

*Speaker

Solar Orbiter EUI/HRIEUV observations of moss at high spatial and temporal resolution: are these nanoflares ribbons?

Susanna Parenti * [1], James A. Klimchuk [2], Frédéric Auchère [1], * Eui Team

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[2] NASA Goddard Space Flight Center

Moss regions, which are most visible in warm (≈ 1 MK) emissions such as those detected in the AIA/SDO 171 band (Fe IX-X), are identified as the transition region footpoints of hot (≈ 3MK) loops in the active region core. Past investigations at moderate spatial resolution revealed the moss to be dense with relatively small intensity variations, and to have a filling factor less than 1. These properties indicated two possibilities for the heating of the loops connected to the moss: (1) the loops are spatially resolved and heated in a quasi-steady fashion or by high frequency nanoflares; (2) the loops are spatially unresolved and heated by low or intermediate frequency nanoflares. Solar Orbiter, launched in February 2020, has recently reached its first perihelion at about 0.32 AU. The observations carried out with the high temporal (3s cadence) and spatial (less than 200 km) resolution EUI/HRIEUV (174 Å) telescope has revealed interesting now properties of the moss. It is highly dynamic on small spatial scales. In this work, we investigate the idea that small, elongated emission structures that move perpendicular to the main axis may by the counterparts of spreading flare ribbons, but are associated with much smaller nanoflares. We examine the implications for the frequency of nanoflare heating.

*Speaker

Characteristics of accelerated particles in the solar corona

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The evolution of a solar flare is multi-scaled and cannot be explained or simulated without considering the effects of accelerated particles. The particles reach nonthermal velocities due to the release of magnetic energy through magnetic reconnection, but the energy distribution among these particles is unknown, as well as the key processes behind the acceleration. We are embedding trace-particles in realistic coronal reconnection environments to study the characteristics of the accelerated particles and investigate how large scale conditions affect the energy distribution. The coronal environments are obtained through MHD simulations and the trace-particle motion is simplified using the gyrocentre approximation.

*Speaker

The effect of small scale reconnection on the solar transition region

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Emission from the solar chromosphere is an excellent diagnostic for small scale heating events in the solar corona. Assuming that small flares behave as larger flares, they should release a not insignificant amount of their energy in the form of accelerated particles. The effect of such bombardment of the transition region produces emission that is discernable from the standard thermal conduction scenario. The particles travel along the magnetic loop much faster than the thermal conduction front, so the initial emission at the loop foot point is therefore dominated by the thermalisation of the accelerated particles, followed by the thermal conduction front. Multiple events in the same flux bundle, so called nano flare storms on the other hand is very difficult to tell from thermal conduction, as the transition region is already heavily perturbed by the first volley. We present a number of cases where the effect of the particles are highlighted.

*Speaker

Contribution of uniturbulence to coronal heating in a coronal hole

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Coronal heating is a long-standing problem, still unresolved, and understanding it will allow us to comprehend the mechanism of energy transport from the photosphere to the corona. Several mechanisms that can contribute to this phenomenon have been suggested. One of them is the Alfvén wave turbulence which has been widely explored and used in coronal heating models in combination with MHD equations. However these models do not exhibit enough wave heating in the polar regions with an open magnetic field, suggesting that there is something missing in this derivation for open magnetic regions. A similar but less exploited mechanism is the uniturbulence (Magyar et al. 2017, 2019a). In this process the turbulence is not generated by counter propagating waves but due to transverse inhomogeneities in density. Thus the propagating Alfvénic waves can non-linearly self-deform, generating a cascade to smaller scales and consequently dissipating. This mechanism is quite attractive because the solar wind is an inhomogeneous medium. Nevertheless, as of yet, there are no models of coronal heating incorporating the effects of uniturbulence. The energy dissipation rate of kink waves for homogeneous media with a certain density contrast has been calculated by Van Dorsselaere et al. 2020. In this calculation they considered the Elsässer variables with a small density perturbation. In this work I will show a comparison of the dissipation rate and gradient of the wave pressure for the Alfvén wave turbulence and the kink uniturbulence for typical parameters of a coronal hole. These quantities resulted in similar values for the lower corona, suggesting that uniturbulence can contribute alongside the Alfvén wave turbulence to generate more heating and acceleration of the solar wind. With the aim of studying the evolution of the wave energy density discriminating both type of waves, I will present a new equation in terms of Alfvén and kink waves. As a next step we will couple this equation to MHD simulations in order to have a model that includes the coronal heating and the acceleration produced by the two types of waves.

*Speaker

Automated detection and subsequent analysis of coronal loop widths across Solar Cycle 24

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NASA SDO's Atmospheric Imaging Assembly been tracking the variation in activity of the solar atmosphere across the entirety of Solar Cycle 24. The underlying structure of the corona and how it evolves across the eleven year solar cycle has often been a matter of targeted, localised observations eg. detection and measurement of individual loop measurements within an active region at a single instant of time. For a more reliable, quantitative description of coronal activity, a longer term surveying of loop structures and their basic parameters is required.
This presentation outlines results from an automated examination of AIA data collected across multiple EUV wavelengths throughout the entire solar cycle 24. The widths and latitudinal occurrence of several hundred thousand coronal loop-like structures are determined and analysed. The results indicate the presence of a power law for coronal loop widths which exists across the solar cycle and shows consistent signs of variation throughout the cycle in all examined EUV wavelengths. These observed power laws can be argued to follow those predicted by self-organsied-criticality models, with gradients of ≈1.6-1.8 recorded in 171 and 193 Angstroms (A) at the period coinciding with solar maximum, and 2.6 - 3.4 in 211 A and 304 A populations. The relationships shown between periods of activity are consistent across wavelengths with some important caveats outlined.

The well-known North-South asymmetry evolution across solar cycles is noted in the coronal data, with the peak hemispheric predominance of loops matching the predominance of sunspot areas very closely. A loop width butterfly diagram demonstrates the same asymmetry as sunspot areas across cycle 24.

Future work will be outlined for examining data from SOHO's EIT instrument (which addresses solar cycle 23), and how Solar Orbiter's EUI observation could aid future analysis across solar cycle 25.

*Speaker

Self-consistent nanoflare heating in model active regions

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MHD avalanches involve small, narrowly localized instabilities spreading across neighbouring areas in a magnetic field.
Cumulatively, many small events release vast amounts of stored energy.
Straight cylindrical flux tubes are easily modelled, between two parallel planes, and can support such an avalanche: one unstable flux tube causes instability to proliferate, via magnetic reconnection, and then an ongoing chain of like events.
True coronal loops, however, are visibly curved, between footpoints on the same solar surface.
With 3D MHD simulations, we verify the viability of MHD avalanches in a more physical, curved geometry, in a coronal arcade.
MHD avalanches thus amplify instability across strong astrophysical magnetic fields and disturb wide regions of plasma.
Contrasting with the behaviour of straight cylindrical models, a modified ideal MHD kink mode occurs, more readily and preferentially upwards.
Instability spreads over a region far wider than the original flux tubes and their footpoints.
Consequently, sustained heating is produced in a series of 'nanoflares', collectively contributing substantially to coronal heating.
Overwhelmingly, viscous heating dominates, generated in shocks and jets produced by individual small events.
Reconnection is not the greatest contributor to heating, but rather facilitates those processes that are.
Localized and impulsive, heating shows no strong spatial preference, except a modest bias away from footpoints, towards the loop's apex.
Prospects for extending the model to include self-consistent treatment of energetic transport, in particular thermal conduction, and the implications of realistic physical plasma parameters are discussed.

[*]Speaker

Modeling the EUV spectral signature of nanoflare heating

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The nanoflare model of coronal heating is one of the most popular scenarios invoked to explain the apparent diverse behavior of coronal observations at different wavelengths. The model proposes that coronal loops are formed by elementary magnetic strands that are braided and tangled by the displacement of their footpoints by convective motions. The consequent magnetic discontinuities produced in adjacent strands favors current sheet formation and reconnection that leads to plasma heating and possibly also particle acceleration. Among other features, the model predicts plasma flows at different temperatures. These flows should have measurable effects on observed spectral lines: the complex combination of the emission from plasmas at different temperatures, densities and velocities in simultaneously evolving and spatially unresolved strands, is expected to produce characteristic Doppler-shifts and line broadenings. Our aim in this work is to explore these effects by constructing synthetic versions of known EUV spectral lines from the plasma evolution of multiple strands obtained using a Simple Cellular Automaton Model (SCAM) developed in previous works, in combination with the Enthalpy Based Thermal Evolution of Loops (EBTEL) model. Among other results, we found Doppler-shifts and non-thermal broadenings that agree with previous observations by other authors. We suggest that our findings might be useful to guide future modeling and observations, particularly in regard to future instruments like the recently proposed soft X-ray spectrometer designed to diagnose plasmas in the 5 to 10 MK temperature range.

*Speaker

Solar data, data products, and tools at MEDOC

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MEDOC (Multi-Experiment Data and Operation Centre), initially created as a European data and operation centre for the SoHO mission, has grown with data from other solar physics space missions, from STEREO to SDO. In addition to observational data, MEDOC also provides datasets derived from observations (maps, catalogues... including new products developed for the ESA Space Weather portal), tools for data analysis and interpretation, and numerical simulation results. MEDOC is also operating the SoHO/GOLF and Solar Orbiter/SPICE instruments and preparing the redistribution of data from the Solar Orbiter remote-sensing instruments. All data are publicly available from web interfaces and from programmatic interfaces (with clients for IDL and Python), allowing classical data analysis as well as automatic queries, data download, and processing to be made on large datasets.

*Speaker