# Invited and Contributed Talks

| Tuesday, June 25 |
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| **HR observations — loop structure —hot plasma — small-scale transients** |

**Morning**

## From small-scale magnetic braids to the diffuse corona: New insights with Solar Orbiter observations (INVITED)

**Lakshmi Pradeep Chitta**

The solar corona, million Kelvin hot outer atmosphere of the Sun, is governed by magnetic fields. Plasma arches or loops supported by magnetic fields form the building blocks of the solar corona. With its unprecedented view of the corona, the Extreme Ultraviolet Imager (EUI) onboard the Solar Orbiter mission is shedding new light on the elusive magnetic processes that govern coronal loops. EUI captures untangling of small-scale coronal magnetic braids, and subsequent heating of plasma in some active region coronal loops. These observations suggest that magnetic reconnection in coronal loops might be operating on short timescales of a few 10 s and on spatial scales of a few 100 km. At the same time, EUI data emphasise another interesting, but often over-looked, aspect of the corona: the so-called diffuse corona where plasma evolves rather coherently on supergranular (~30 Mm) scales, and on timescales of hours, much longer than the typical coronal cooling timescales. In this talk I will discuss these two seemingly contrasting aspects of coronal loops and implications for coronal heating.

## Characteristics and energy flux distributions of decayless transverse oscillations in different coronal regions

**Daye Lim, Tom Van Doorsselaere, and David Berghmans**

Lim et al. (2023) have recently proposed that the slope (δ) of the power law distribution between the energy flux and oscillation frequency could determine whether high-frequency transverse oscillations give a dominant contribution to the heating ($\delta<1$). Using the meta-analysis of decayless transverse oscillations, it has been found that high-frequency oscillations could play a key role in heating the solar corona. We aim to investigate how (whether) the distributions of the energy flux contained in transverse oscillations and their slopes are influenced by different coronal regions. An analysis of transverse oscillations from 41 quiet Sun (QS) loops and 22 active region (AR) loops observed by SolO/EUI HRIEUV is performed. The energy flux and energy are estimated using analysed oscillation parameters and loop properties, such as periods, displacement amplitudes, loop lengths, and minor radii of the loops. It is found that about 71% of QS loops and 86 % of AR loops show decayless oscillations. We find that the amplitude does not change depending on different regions, but the difference in the period is more pronounced. Although the power law slope ($\delta=-1.79$) in AR is steeper than that ($\delta=-1.59$) in QS, both of them are less than the critical slope of 1. High-frequency transverse oscillations could play a more significant role than low-frequency oscillations in heating the QS and AR respectively.

### High resolution diagnostics of small coronal heating events in an active region core

**Paola Testa, Helle Bakke, Luc Rouppe van der Voort, Bart De Pontieu**

High resolution spectral observations of the lower solar atmosphere (chromosphere and transition region) during coronal heating events, in combination with predictions from models of impulsively heated loops, provide powerful diagnostics of the properties of the heating in active region cores. Here we analyze the first coordinated observations of such events with the Interface Region Imaging Spectrograph (IRIS) and the CHROMospheric Imaging Spectrometer (CHROMIS), at the Swedish 1-m Solar Telescope (SST), which provided extremely high spatial resolution and revealed chromospheric brightenings with spatial dimensions down to ~150 km.

We use machine learning methods (k-means clustering) and find significant coherence in the spatial and temporal properties of the chromospheric spectra, suggesting, in turn, coherence in the spatial and temporal distribution of the coronal heating. The comparison of IRIS and CHROMIS spectra with simulations suggest that both non-thermal electrons with low energy (low-energy cutoff ~ 5 keV) and direct heating in the corona transported by thermal conduction contribute to the heating of the low atmosphere in these observed events. This is consistent with growing evidence that non-thermal electrons are not uncommon in small heating events (nano- to micro-flares), and that their properties can be constrained by chromospheric and transition region spectral observations.

### Spatial and temporal evolution of elemental abundances in cooling flare loops

**Andy To, David Brooks, Shinsuke Imada, Ryan French, Lidia van Driel-Gesztelyi, Deborah Baker, David Long, William Ashfield**

We present a detailed analysis of the spatial and temporal evolution of coronal abundances in the cooling post-flare loops of the X8.2 event on 2017 September 10 using Hinode/EUV Imaging Spectrometer (EIS) observations. By employing Ca/Ar and Fe/S composition diagnostics, we derive first ionization potential (FIP) bias values over 12 EIS raster scans spanning 3.5 hours, capturing the cooling loops from the event's onset through the decay phase. We find persistent high FIP bias values (>2-6) at the loop tops, with peak phase values exceeding 4, while loop footpoints exhibit photospheric FIP bias (~1). We propose a scenario where high FIP bias plasma downflows from the reconnecting current sheet are confined to loop tops, and chromospheric evaporation fills the loop footpoints with low FIP bias plasma. As the loops cool, mixing between these two sources produces the observed FIP bias gradient along the loops. The localized high FIP bias at loop tops is likely diluted by bright footpoint emission in Sun-as-a-star measurements, potentially explaining discrepancies with spatially resolved observations. Moreover, the prolonged confinement of high FIP bias plasma at loop tops provides valuable insights into the formation of EUV knots in cooling post-flare loops.

### The Magnetic Origin of Solar Campfires: Solar Orbiter and SDO Observations

**Navdeep K. Panesar, Viggo H. Hansteen, Sanjiv K. Tiwari, David Berghmans, Mark Cheung, Daniel Müller, Frederic A**

Here we investigate the magnetic origin of different types of campfires, in quiet-Sun, using LOS magnetograms from SDO/HMI together with EUV images from Solar Orbiter/EUI and SDO/AIA. We find that (i) campfires are rooted at the edges of photospheric magnetic network lanes; (ii) most of the campfires reside above neutral lines and 77% of them appear at sites of magnetic flux cancelation between the opposite polarity flux patches; some of the smallest campfires come from the sites where magnetic flux elements were barely discernible in HMI; (iii) in the large majority of instances (79%), campfires are preceded by a cool-plasma structure, analogous to minifilaments in coronal jets; and (iv) although many campfires have "complex" structure, most campfires resemble small-scale jets, dots, or loops. Thus, "campfire" is a general term that includes different types of small-scale solar dynamic features. They contain sufficient magnetic energy (~$10^{26}$–$10^{27}$erg) to heat the solar atmosphere locally to 0.5–2.5MK. Our observations suggest that (a) the presence of magnetic flux ropes may be ubiquitous in the solar atmosphere and not limited to coronal jets and larger-scale eruptions that make CMEs, and (b) magnetic flux cancelation, most likely driven by magnetic reconnection in the lower atmosphere, is the fundamental process for the formation and triggering of most campfires. Finally, we compare jet-like campfires with those found in a Bifrost MHD simulation.

## Stereoscopic analysis of coronal loop morphology and dynamics

**S. Mandal, H. Peter , J. A. Klimchuk , S. K. Solanki, L. P. Chitta, R. A. Cuadrado, U. Schühle, L. Teriaca, D. Berghmans +3 more**

Coronal loops are some of the most easily recognizable features within the solar corona. Despite years of research, some aspects of these arched structures are still not well understood, such as the loop's cross-section and its variation along its length. In a recent study, we conducted a stereoscopic analysis of the morphology and dynamics of a coronal loop using high resolution images from two different spacecraft - the High Resolution Imager (HRI) of the Extreme Ultraviolet Imager on board the Solar Orbiter, and the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory. Our findings suggest that the observed loop exhibits similar widths in both datasets, indicating that the cross-sectional shape of the loop is circular. Additionally, the loop maintained a uniform width along its entire length, which supports the idea that coronal loops do not show expansions. Moreover, this loop's highly unusual dynamics make this a fascinating case study. I will discuss the implications of these results on our understanding of loop formations, particularly from the perspective of the 'coronal veil' hypothesis.

## The evolution of the coronal loop structure due to the phase mixing of Alfvén waves

**Harry Callingham, Ineke De Moortel, Paolo Pagano**

Coronal loops are known to host Alfvén waves propagating in the corona from the lower layers of the solar atmosphere and because of their internal structure, phase-mixing is likely to occur. The structure of the coronal loop could be significantly affected by the thermodynamic feedback of the heating generated by phase-mixing. However, this phenomenon can be sensitive to the period of the propagating Alfvén waves due to how short period waves can be easily dissipated and the way long period waves may accumulate considerable energy in resonating coronal loops. Using the Lare 2D code, a coronal loop model of a field-aligned thermodynamic equilibrium and a cross-field background heating profile is created, with an additional forcing term added to drive Alfvén waves with coronal amplitudes between 5-30km/s. We show that high frequency waves can generate heating corresponding to a 10% increase of the initial coronal shell temperature, chromospheric upflows of up to 0.6km/s and a coronal shell mass increase of 15%. These changes are sufficient to alter and maintain a new coronal loop density structure, broadening the region where efficient phase-mixing occurs. In contrast, low frequency waves are unable to be effectively dissipated, resulting in minimal changes to the loop structure. We see little evidence of wave energy accumulation in the corona and are unable to conclude that the dissipation of low frequency Alfvén waves can be an effective heating mechanism in coronal loops.

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**Afternoon**

## How high resolution observations improve our understanding of the high frequency dynamics in corona (INVITED)

**Elena Petrova, Tom Van Doorsselaere, David Berghmans, Norbert Magyar, Susanna PARENTI, Gherardo Valori, Joseph Plowman**

The ability to detect certain phenomena on the Sun is prescribed by the capabilities of our instrumentation. Throughout history, launching satellites equipped with cutting-edge instruments has consistently expanded our understanding of solar physics.
Launch of the Solar Orbiter is not an exception and since its launch already there have been a lot of new discoveries specifically focused on small scales such as for example campfires or picojets.
In this talk, I will delve into two recent studies that we've done utilizing data from the High-Resolution Imager in the Extreme Ultraviolet telescope (HRIEUV) onboard Solar Orbiter and discuss how those works fit and contribute into our current understanding of the waves.
The first study focuses on the detection of high-frequency decayless kink oscillations in small loops in a quiet region of the Sun. Due to the unprecedented imaging cadence of the corona, we were able to detect oscillations with periods that are shorter than the previously observed range, hinting at a significant energy budget associated with these phenomena.
The second one is related to detection of torsional Alfvén waves in a fan-spine topology. In this work we combine the observations from several instruments onboard Solar Orbiter, namely mentioned already HRIEUV, PHI and SPICE. This is the first time we see signatures of propagating torsional motion in corona as observed by the three instruments onboard Solar Orbiter.

## QS brightenings detected by Solar Orbiter HRIEUV: temperature diagnostics using spectroscopic data and simulation

**Dolliou A., Parenti S., Klimchuk J.A., Bocchialini K**

One of the main theories for the solar coronal formation (Parker, 1988) suggests that the energy is dissipated into this region through a high number of impulsive, low energetic heating events, called “nanoflares”. On the 30 May 2020, during the first high temporal and spatial resolutions observations of the EUV imager EUI/HRIEUV on board Solar Orbiter, 1463 small (400 – 4000 km) and short lived (10-100 s) brightenings were detected in the Quiet Sun (QS). We investigate if they are the signatures of the nanoflares plasma heating.
As HRIEUV is sensitive to both coronal and transition region emissions, our first goal is to understand if their signature is from hot coronal plasma.
We achieve our goal by using co-temporal QS data from EUI/HRIEUV, SPICE and Hinode/EIS on March 2022, and April 2023. We first detect the events in HRIEUV, and identify them in SPICE or EIS. We performed temperature diagnostics and concluded that these events are dominated by plasma below 1 MK. As such, they hardly contribute directly to coronal heating.
In order to further understand these events, we simulated their observational signatures using the HYDRAD 1D hydrodynamics code. Our aim is to see if there is a clear difference in the emissions from the impulsive heating of a short cool loop and a short and hot one. We show that loops with apex temperature below 0.1 MK, and heated up to transition temperatures, match well with the observations.

### Quantifying bursty and steady heating of the 4–8 MK corona of a solar AR using minimum, maximum, and average brightness maps

**Sanjiv K. Tiwari, Lucy A. Wilkerson, Navdeep K. Panesar, Ronald L. Moore, Amy R. Winebarger**

We present a method of quantifying coronal heating's bursty and steady components, applying it to \FeXVIII\ (hot94) emission of an active region (AR) observed by SDO/AIA. The maximum, minimum, and average brightness values for each pixel, over a 24 hour period, yield a maximum-brightness map, a minimum-brightness map, and an average-brightness map of the AR. Running sets of such three maps come from repeating this process for each time step of running windows of 20, 16, 12, 8, 5, 3, 1 and 0.5 hours. From each running window's set of three maps, we obtain the AR's three corresponding luminosity light curves. We find that the time-averaged ratio of minimum-brightness-map luminosity to average-brightness-map luminosity increases as the time window decreases, and the time-averaged ratio of maximum-brightness-map luminosity to average-brightness-map luminosity decreases as the window decreases. For the 24-hour window, the minimum-brightness map's luminosity is 5% of the average-brightness map's luminosity, indicating that at most 5% of the AR's hot94 luminosity is from heating that is steady for 24 hours. This upper limit on the fraction of the hot94 luminosity from steady heating increases to 33% for the 30-minute running window. This suggests that the heating of the 4--8 MK plasma in this AR is mostly in bursts lasting less than 30 minutes. At most a third of the heating is steady for 30 minutes.

### Modeling a microflare observed by AIA and FOXSI: Single power-law distribution for transients & background

**Abhishek Rajhans, Vinay Kahyap, Vishal Upendran, Durgesh Tripathi, Subramanian Athiray**

The solar corona has temperatures > 1 MK. This has been attributed to both steady background heating and transients like impulsive flaring events. We explore the possibility of the steady heating being attributable to a large number of small impulsive events generated from a single power law distribution of flare energies. We compare our simulations of a multi-stranded loops system, with data obtained from Atmospheric Imaging Assembly (AIA) and Focusing Optics X-ray Solar Imager (FOXSI) for a sub A-class event from the active region active region NOAA 12230. We simulate different cases, determined by the slope of the power law distribution, along with the maximum and minimum energies that can be dissipated in an event. The results show that the observed light curve, including the background and impulsive events, can be best explained by power-law distributions with slopes ≤2, with the maximum and minimum energies differing by more than 7 orders of magnitudes.

### Characterizing the evolution of hot plasma in solar active regions via NuSTAR differential emission measure analysis

**Jessie Duncan, Reed B. Masek, Albert Y. Shih, Lindsay Glesener, Will Barnes, Katharine K. Reeves, Iain G. Hannah**

Solar active regions (ARs) contain plasma across a broad range of temperatures, with the thermal distribution often observed to peak in the few millions of kelvin. Hard x-ray observations are uniquely sensitive to extremely hot (>10 MK) material, and are therefore essential for diagnosing the very hottest components of ARs. At quiet times, constraining this ultra-hot material is a crucial diagnostic of the frequency of heat input leading to the elevated temperature of the corona. At flaring times, observing the evolution of the very hottest material allows a complete picture of how flare heating proceeds. Differential emission measure (DEM) analysis uses observations by instruments sensitive to thermal plasma to estimate the amount of material present as a function of temperature. DEMs with HXR constraints are so far fairly limited in the literature, but represent an exciting opportunity to investigate hot AR plasma. The Nuclear Spectroscopic Telescope ARray (NuSTAR) is a sensitive HXR observatory which makes periodic observations of the Sun. Combining NuSTAR's HXR coverage with other instruments, we perform time-resolved DEMs of ARs at both quiet and flaring times. We discuss initial results from these NuSTAR DEMs, in

conjunction with future prospects for gaining further insight about active region heating using HXR observation.

### IRIS and NuSTAR observation and modeling of small energetic events: constraining non-thermal particle acceleration in ARs

**Vanessa Polito, Marianne Peterson, Lindsay Glesener, Paola Testa, Sijie Yu, Katharine K. Reeves, Xudong Sun, Jessie Duncan**

Several studies have shown that spectroscopic observations of the lower atmosphere with the Interface Region Imaging Spectrograph (IRIS), when combined with modelling, can provide crucial constraints of non-thermal particle acceleration in small active region energetic events. In this talk we will present recent results combing rare simultaneous observations by IRIS and the Nuclear Spectroscopic Telescope Array (NuSTAR) X-ray instrument. The IRIS spectroscopic observations show peculiar spectral characteristics that are typical signatures of energy deposition by non-thermal electrons in the lower atmosphere. The presence of the non-thermal particles is also confirmed by the NuSTAR spectral observations. We show that, by combining IRIS and NuSTAR multi-wavelength observations from the corona to the lower atmosphere with hydrodynamic simulations using the RADYN code, we can provide strict constraints on the particle acceleration mechanisms. This work presents the first NuSTAR, IRIS and RADYN joint analysis of a non-thermal energetic event in an active region and a self-consistent picture of accelerated electrons in the corona and the chromospheric response to those electrons.

### The imprints of coronal loop heating on periodic solar wind density structures

**Nicholeen Viall**

Decades of density measurements made throughout the inner heliosphere show that the solar wind is often comprised of mesoscale structures, i.e. structures much larger than kinetic scales, but smaller than CMEs or SIRs. One type of mesoscale solar wind structure manifests as periodic trains of density enhancements, with scales of 0.2 mHz (~90 minutes) to 5 mHz (~ a few minutes). Studies of elemental composition during these periodic density structures demonstrates that they are created at the Sun as the solar wind is formed. We demonstrate that interchange reconnection of open fields and coronal loops along S-web arcs is likely involved, and that the history of the coronal heating those loops experienced is retained in the elemental composition variations. We also show that the interchange reconnection may be periodically driven by jetlets and/or transverse Alfvenic fluctuation. Furthermore, we show that there are likely two populations of periodic density structures: one associated with longer coronal loops in helmet streamers, and the other a more globally distributed phenomenon. Lastly, we describe a new mission concept, Solar Divers, which would measure coronal loops in situ and potentially solving the coronal heating problem.

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| **(0)1D vs 3D Models — AR heating** |

**Morning**

## MHD modelling of nanojets in coronal loops (INVITED)

**Paolo Pagano, Gabriele Cozzo, Fabio Reale, Costanza Argiroffi, Paola Testa, Juan Martinez-Sykora, Bart De Pontieu**

Reconnection events in coronal loops are singularly too small and fast to be detected (nanoflares), whereas their collective action could be sufficient to sustain the million degrees corona against thermal conduction and radiative losses. Recent studies have observed and modelled the dynamic counter part of nanoflares, i.e. the nanojets, which are a byproduct of the magnetic reconnection and this avenue seems a viable one to crack the nanoflares enigma.
It remains to understand if there is a simple relationship between the properties of the nanoflare and the nanojet, so to explain in which cases the latter, when observed, could give away the occurrence of the former. We will analyse the physics of either phenomena to illustrate the detailed mechanism and key aspects which future studies should pay attention to.
Moreover, in order to study the nanoflare population, we need to detect and isolate nanojets even when several take place one after the other.
In MHD simulations, a number of detection techniques can be developed in increasingly more complex scenarios from the simple tangling of magnetic field lines to kink instabilities and cascade reconnection.
These 3D MHD simulations are key to bridge the gap between idealised magnetic reconnection models and future spectroscopic observations (MUSE) providing key indications on what observations can be planned to export this approach from MHD simulations to observations.

## Coronal loops are not one-dimensional: Scaling laws with respect to modelling stellar loops

**Cosima Breu, Ineke De Moortel, Tanayveer Bhatia, Hardi Peter, Damien Przybylski, Sami Solanki**

Coronal loops come in different shapes and sizes. Loop length, magnetoconvection at the footpoints and numerical resolution influence loop properties such as temperature, density and velocities. These parameters in turn influence observable quantities such as emission intensity and the width of spectral lines. We model coronal loops as straightened magnetic flux tubes in a Cartesian box including a realistic convection zone at each end. This setup simplifies controlling loop parameters such as the loop length. Analytical scaling laws relate properties such as maximum temperature, loop length and pressure. These scaling laws, however, assume one-dimensional loops in equilibrium. We review coronal loop scaling laws for a variety of 3D MHD loop simulations with different parameters with respect to modelling stellar coronal loops.

## MUSE EUV Spectroscopy of a kink-unstable coronal loops system

**G. Cozzo, P. Pagano, F. Reale, J. Reid, A. W. Hood, C. Argiroffi, A. Petralia, P. Testa, B. de Pontieu**

Turbulent photospheric motions drive the footpoints of coronal loops, possibly leading to the growth of magnetic stress along the loop. Thin coronal loops strands can become kink-unstable and magnetic energy can be released through impulsive and widespread heating events. It has been recently established that the kink-instability in a single coronal loop strand can propagate to nearby flux tubes and determine an avalanche process to involve larger scale coronal loops. The initial helical current sheet progressively fragments in a turbulent way into smaller scale sheets. Their turbulent dissipation leads to a sequence of a-periodic heat pulses, similar to nanoflare storms.

These magnetic processes are highly dynamic and non linear, and can be modelled with time-dependent 3D MHD simulations on high performance computing systems. Predictions to compare with solar observations require advances on two fronts. Modelling must include all important physical ingredients and a complete plasma atmosphere to derive realistic observables. The observations must resolve into sufficiently small temporal and spatial scales in the relevant spectral bands. Cozzo et al. (2023) describe a detailed 3D MHD model of a kink-unstable coronal loops system which allows for the derivation of observables in the EUV band. The EUV spectrometer on the forth-coming MUSE mission is tailored for probing plasma structure and dynamics at sub-arcsecond resolution with sampling rates of a few seconds.

### Numerical experiments on the role of MHD waves in triggering nanojets

**Ramada Sukarmadji, Patrick Antolin, Paolo Pagano, James McLaughlin**

Nanojets are nanoflare-sized bursts transverse to the guidefield produced by small-angle component reconnection events, which have been observed in many coronal loop-like structures (Antolin et al. 2021; Sukarmadji et al. 2022; Sukarmadji et al. 2024). However, we have a limited number of nanojet observations due to their small-scales (<1500 km in length) and short timescales (<25 s in duration), presenting a challenge to understand how nanojets are generated. We present numerical simulation results of nanojets based on the model in Antolin et al. (2021); which is of a two straight and adjacent flux tubes that are driven to form a small misalignment. MHD waves are introduced through the footpoint driving, and we conducted a parameter investigation of the effects of footpoint driving on the reconnection by varying the driving amplitudes. Our results show that driving the footpoints with amplitudes of 10km/s and larger produces a singular nanojet-like formation event characterised by the fast bi-directional flows, with an energy release of 10^{24} erg similar to Antolin et al (2021). Smaller driving amplitudes produce smaller scale and bursty reconnection events, or continuous energy release on the order of 10^{23} erg, without clear nanojet-like features. In all cases, the simulations suggest that magnetic reconnection can be triggered by propagating MHD waves in a braided field which locally increase the current.

### Loss of current sheet equilibrium: the nanoflare trigger?

**James A. Klimchuk, N. Dylan Kee, James E. Leake**

Understanding why current sheets do not reconnect until substantial stress has built up in a magnetic field is fundamental to explaining a wide range of explosive phenomena occurring on the Sun and throughout the universe. Nanoflares are a prime example. If the conditions for reconnection onset were too mild or too severe, the corona would be cooler or hotter than observed. Our examination of the force balance of realistic current sheets (having both finite length and finite width) has led us to suggest that current sheets undergoing slow shearing by photospheric driving may reach a critical shear whereupon they lose equilibrium, spontaneously collapse, and reconnect (Klimchuk et al. 2023). We here present 3D MHD simulations that verify this scenario.

### Flux-rope mediated turbulent reconnection

**Alexander Russell**

Turbulence is often observed in solar flares and other coronal energy releases, through the proxies of nonthermal broadening and polarization. Understanding the interplay between reconnection and turbulence is currently one of the most important challenges in solar and space plasma physics, for example, turbulence is widely believed to play a major role in magnetic reconnection. In the last few years, exciting advances in this area have been enabled by 3D direct numerical simulations that capture the generation of turbulence inside the reconnection layer. Interestingly, these simulations exhibit features associated with the Lazarian-Vishniac model of 3D turbulent reconnection (turbulence and field line dispersion) and features associated with 2D plasmoid mediated reconnection (flux ropes and an MHD reconnection rate of 0.01). This talk presents a new model of turbulent reconnection that reconciles aspects of turbulent and plasmoid-mediated reconnection, differing from the Lazarian-Vishniac theory by emphasizing the roles of locally coherent magnetic structures and magnetic helicity. This new conceptual model successfully describes the main features of self-generated turbulent reconnection simulations including the magnetic field structure and reconnection rate. Finally, we discuss future work, including the possibility that another reconnection regime may exist for very large shear angles.

### Diagnosing loop-expansion in active regions using emission measure

**Sherry Chhabra, Jeffrey Reep, Kalman Knizhnik, James Klimchuk**

Variable cross-sectional area has a large impact on the heating and cooling of loops. And although intensities of light curves at multiple wavelengths are drastically different for different degrees of area expansion, we have also shown that for an individual loop, the Emission Measure (EM) slopes do not exhibit any unique signatures that can be constrained by our current observations. Whether or not this behavior persists in ARs with thousands of loops of varied lengths and expansion factors has not been investigated. We use EBTEL2.0 to run a series of simulations for a collection of loops, where the range of loop lengths and expansion factors are guided by a 3-D MHD ARMS simulation. The EMs are then calculated by, 1. Integrating over the series of simulations, and 2. by creating EM loci curves from the modeled line intensities. We present our final results of the investigation of EM peak and slopes and how it varies based on different heating rates and nanoflare frequencies.

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**Afternoon**

### How does the heating frequency on elemental strands change as a function of active region age?

**Will Barnes, Stephen Bradshaw, Nicholeen Viall, Emily Mason**

The evolution of active regions over their lifetime, from initial emergence to the eventual complete dispersal of magnetic flux, has been well studied. However, how this evolution is connected to the detailed heating processes within an active region has been largely unexplored. In particular, it is not well known how the heating frequency on individual elemental strands within an active region is connected to the large-scale evolution of the active region. To address this question, we study two active regions, NOAA 11190 and 11339, over two rotations using observations from SDO/AIA and Hinode/EIS. We compute both the emission measure distribution and the time lag in order to diagnose the underlying heating frequency and its spatial distribution over the whole active region. Additionally, we make comparisons to forward-modeled observables from synthetic images composed of ensembles of field-aligned hydrodynamic models for several different heating frequencies. We also assess the ability of soft x-ray measurements from future observatories to diagnose these heating properties. In doing so, we are able to quantitatively assess how the spatial distribution of heating frequency over these active regions changes as they evolve and how this is connected to bulk properties of the active region such as the total unsigned magnetic flux.

### Self-consistent heating of the magnetically closed corona: generation of nanoflares and response of the plasma

**C. D. Johnston, L. K. S. Daldorff, J. A. Klimchuk, S. Sow Mondal & J. E. Leake**

The energy that heats the magnetically closed solar corona originates in the complex motions of the massive photosphere. Turbulent photospheric convection slowly displaces the footpoints of coronal field lines, causing them to become twisted and tangled. Magnetic stresses gradually build until reaching a breaking point when the field reconnects and releases a sudden burst of energy. We simulate this basic picture of nanoflares using high-fidelity 3D MHD simulations that start with a fully stratified atmosphere. These simulations include the effects of field-aligned thermal conduction and optically thin radiation and use the state-of-the-art Transition Region Adaptive Conduction (TRAC) method to capture the response of the plasma to the nanoflare heating. A detailed analysis of a particular nanoflare demonstrates that our simulations capture the explosive energy release from narrow current sheets via magnetic reconnection, where magnetic energy is converted into kinetic and then thermal energy through viscous dissipation of the shocks. Distributions of nanoflare energy and frequency are also discussed, and diagnostics that show the evaporative response of the plasma to this heating are presented. LOS integrations are computed to obtain synthetic images of intensity in different AIA channels. The collective behavior of nanoflares responsible for forming coronal loops in these synthetic images is discussed together with their measured densities, lifetimes, and length scales.

### Investigating the temporal evolution of nanoflare contribution to solar active region heating

**Biswajit Mondal, Amy Winebarger, P.S. Athiray**

Nanoflares are thought to be prime candidates to heat the solar non-flaring active regions. However, their direct individual detection with current instrumentation remains challenging. Understanding the frequency and magnitude of nanoflares is crucial for understanding their role in coronal heating. In this study, we employ field-aligned hydrodynamic model to simulate the evolution of an active region (AR) under nanoflare heating scenarios. By comparing the stimulated

emission with EUV and X-ray observations, we determine the frequency of heating events and investigate how it evolves with the AR evolution. Additionally, we analyze the impact of observational parameters, such as instrument spatial resolution and energy band, on estimating nanoflare properties. Our findings contribute to advancing our understanding of the role of nanoflares in coronal heating and refining observational parameters for detecting these events.

### Nanoflare frequency and reconnection onset in driven active region magnetic fields

**S. Sow Mondal, C. D. Johnston, L. K. S. Daldorff, J. A. Klimchuk, J. E. Leake, & N. D. Kee**

The primary source of energy that sustains the high temperature of the magnetically closed corona has its origin in complex photospheric motions. Twisted and braided magnetic field lines release the stored magnetic energy through small but impulsive events known as "nanoflares". Contrary to what this basic image might suggest, heating is far more complicated than it seems. The frequency of the nanoflares and the onset of reconnection are two critical factors that affect the solar spectral irradiance. Using sophisticated 3D MHD simulations of a stratified solar atmosphere – from photosphere to corona – we realistically model the nanoflare energy release and plasma response for a given photospheric driving. We here describe our findings on the development of current sheets that are self-consistently generated in our simulation. Reconnection onset conditions along with the occurrence frequency and energy distribution of the nanoflares responsible for maintaining the hot solar corona are also presented.

### Deciphering solar coronal heating: Energizing small-scale loops through surface convection

**Daniel Nóbrega-Siverio, Fernando Moreno-Insertis, Klaus Galsgaard, Kilian Krikova, Luc Rouppe van der Voort, Reetika Joshi, Maria Madjarska**

The solar atmosphere is filled with clusters of hot small-scale loops commonly known as Coronal Bright Points (CBPs). These ubiquitous structures stand out in the Sun by their strong X-ray and/or extreme-ultraviolet (EUV) emission for hours to days, which makes them a crucial piece when solving the solar coronal heating puzzle. Here we present a novel 3D numerical model using the Bifrost code that explains the sustained CBP heating for several hours. We find that stochastic photospheric convective motions alone significantly stress the CBP magnetic field topology, leading to important Joule and viscous heating concentrated around the CBP's inner spine at a few megameters above the solar surface. We validate our model by comparing simultaneous CBP observations from SDO and SST with observable diagnostics calculated from the numerical results for EUV wavelengths as well as for the Halpha line using the Multi3D synthesis code. In addition, using k-means, we are able to discern clusters of loops with different behavior and study their properties.

### Range of scales in active regions and their influence on energy release

**Lars K.S. Daldorff, Craig D. Johnston, Shanwlee S. Mondal, James A. Klimchuk, James E. Leake and Dylan, N. Kee**

Magnetically closed loops in solar active regions have four distinct outer layers that are associated with the stratification of the atmosphere. Moving outwards from the photosphere, through the chromosphere, across the transition region and into the corona, each of these layers has a range of different temporal and spatial scales. Furthermore, the physical processes that govern the evolution of coronal loops also have a range of fundamental time scales that are determined by the relevant speeds e.g. sound speed (convection), Alfven speed (magnetohydrodynamics), and conductive and radiative cooling speeds (thermodynamics). Using high-fidelity 3D MHD photosphere-to-corona simulations of active region nanoflares, we investigate the influence of these different temporal and spatial scales on the energy release. Diagnostics that correlate the driving in the photosphere with the evolution of each of the individual layers and the outer atmosphere as a whole are also presented.

### Energy release and reconnection driven by random foot point motions acting on a variety of magnetic topologies

**Thomas Howson, Ineke De Moortel, Eric Priest, Cosima Breu,**

The convective motions at the Sun's surface drive energy into the solar atmosphere by advecting the foot points of magnetic field lines. This energy can then be released by the stressed magnetic field, driving impulsive events such as solar flares and heating the corona. The characteristic rate at which energy is injected and ultimately released, dictates observable properties of the atmosphere, such as coronal densities and temperatures. Importantly, the injection rate is not just sensitive to the photospheric motions but also to the evolution of the atmosphere itself. In this talk, I will discuss the results of a series of 3D MHD simulations of random foot point motions stressing the coronal magnetic field. These motions drive current formation, magnetic reconnection and ultimately, plasma heating. By examining each of these processes in detail, I will discuss the effects of different magnetic field topologies on the rate of energy injection and dissipation. Additionally, by considering magnetic reconnection rates in various field structures, I will constrain the errors in the estimations we derive from large scale simulations.

### Investigation of heating of active region coronal loops in non-eruptive solar active regions

**Aparna Venkataramanasastry, Sanjiv K Tiwari , Navdeep Panesar , Ronald Moore , Bart De Pontieu , Thomas Wiegelmann, Brian Welsch**

Based on the results from Tiwari et al. 2017, we investigate the importance of magneto-convection in heating active region (AR) coronal loops. They found via SDO/AIA observations and NLFFF extrapolations that loops connecting sunspot umbrae are invisible in EUV images and those with one loop footpoint in sunspot umbra or penumbra and the other footpoint in opposite-polarity sunspot penumbra or plage regions, are seen as bright and hot loops. They conclude that a combination of the magnetic field strength of the regions the loops are rooted in and the convective freedom of the regions play an important role in determining the amount of heating in these loops. Here, we aim to understand the statistical significance of the above findings. We select a sample of three kinds of ARs- those having a pair of sunspots, those with a sunspot in the leading polarity and a plage in the trailing polarity, and those that have no sunspot in any polarity. Using AIA images, we select ARs that have not produced flares stronger than a B-class in a duration of 48hours. We select the instances where bright loops are present and the nearest SDO/HMI SHARP vector-magnetograms in time to perform NLFFF extrapolations. We also perform differential emission measure calculations at these times using AIA images to verify the temperature characteristics. Using several ARs we plan to derive a realistic scaling law that includes "invisible" loops connecting sunspot umbrae inferred from the extrapolations.

## Waves — coronal cooling

### Morning

### Can we rely on EUV emission to identify coronal waveguides? (INVITED)

Petra Kohutova

Traditional models of coronal oscillations rely on modelling the coronal structures that support them as compact cylindrical waveguides. An alternative model of the structure of the corona has recently been proposed, referred to as the coronal veil model. We extend the implications of the coronal veil model of the solar corona to models of coronal oscillations. Using convection-zone-to-corona simulations, we analysed the structure of the self-consistently formed simulated corona, focusing on the spatial variability of the EUV emissivity and the variability of the Alfvén speed. We traced coronal features associated with large magnitudes of the Alfvén speed gradient, which are the most likely to trap MHD waves and act as coronal waveguides, and looked for the correspondence with emitting regions which appear as strand-like loops in the EUV emission integrated along the line-of-sight. We find that the structures bounded by large Alfvén speed gradients have complex cross-sections and low filling factors, suggesting only a small fraction of the waveguides is observable in the individual EUV lines. We finally discuss possible implications for coronal seismology.

### MHD wave heating in the complex solar atmosphere

**I. De Moortel, T.A. Howson, E.Enerhaug**

Since the middle of the last century, it has been known that the atmosphere of the Sun is orders of magnitudes hotter than its surface. Over the years, many studies have looked at the potential role of MHD waves in sustaining these high temperatures. Using 3D MHD simulations of transverse, Alfvenic waves, we look at the role of the complexity of the magnetic field and the power spectrum of the wave driver. We focus on the efficiency of the wave-based heating in our models, in particular whether heating provided by the waves can balance coronal losses. Using wave identifiers based on fundamental wave characteristics such as compressibility and direction of propagation we show that, for particular line(s)-of-sight and assumptions about the magnetic field, we can correctly identify properties of the Alfvén mode in synthetic observations of a transversely oscillating loop.

### A new analytic model for nonlinear wave damping in coronal loops by Kelvin-Helmholtz instability-induced turbulence

**Andrew Hillier, Iñigo Arregui, Matsumoto Takeshi**

Observations of magnetohydrodynamic kink waves in coronal loops have provided a useful tool for probing the magnetic field of the corona. Linear theory has provided many insights in the potential evolution of these oscillations, and results from these models are often applied to infer information about the solar corona from observed wave periods and damping times. However, simulations show that nonlinear kink waves can host the Kelvin-Helmholtz instability (KHi) which subsequently creates turbulence in the loop, dynamics which are beyond linear models. In this talk, we present our work looking at the evolution of KHi-induced turbulence on the surface of a flux tube where a non-linear fundamental kink-mode has been excited. We show that there exists two stages in the KHi turbulence dynamics. In the first stage, we show that the classic model of a KHi turbulent layer growing linearly proportional to time is applicable. We adapt this model to make accurate predictions for damping of the oscillation and turbulent heating as a consequence of the KHi dynamics. In the second stage, the now dominant turbulent motions are undergoing decay. We find that the classic model of energy decay proportional to t^-2 approximately holds and provides an accurate prediction of the heating in this phase. Our results show that we can develop simple models for the turbulent evolution of a non-linear kink wave, but the damping profiles produced are distinct from those of linear theory that are common

## Transverse oscillations of coronal loops anchored in chromospheric plasma

**Konstantinos Karampelas, Daye Lim, Tom Van Doorsselaere**

EUV observations of the solar atmosphere have established the omnipresence of waves and oscillations in structures like loops and prominences, with decaying and decayless transverse oscillations of loops having been extensively used as diagnostic tools in coronal seismology. In the recent years, numerical models have also started to incorporate the effects of the transition region and chromosphere into the dynamical evolution of such systems. Here we will be presenting our recent 3D MHD simulation results of transversely oscillating stratified loops anchored in chromospheric plasma. Our models study both impulsive oscillations and oscillations driven by broadband drivers with a red noise spectrum. Our broadband drivers excite decayless oscillations with spectra revealing the fundamental mode and its harmonics. Combining our 3D models with forward modelling and an 1D analysis, we identify a shift of the loop eigenfrequencies caused by the presence of the chromosphere and uncover the nature of the previously reported "half-harmonic" mode. Our models also exhibit a stronger excitation of higher harmonics, closely matching those of a purely coronal loop without a chromospheric part. Finally, and we will discuss the important implications that this has for coronal seismology and we will compare our results against recent observations.

## MHD wave damping in hot coronal loops as probe of coronal heating

**Dmitrii Y. Kolotkov, Inigo Arregui, Valery M. Nakariakov**

It has recently been understood that the perturbed balance between heating and cooling processes in the corona plays an important role in the dynamics and stability of magnetohydrodynamic waves, referred to as the effect of wave-induced thermal misbalance (TM). TM causes the wave to either lose or gain energy from the coronal plasma, which makes the corona an active medium for magnetohydrodynamic waves.

In this talk, we demonstrate the potential of a recently developed theory of wave-induced TM and observed frequency-dependent damping of slow magnetoacoustic waves for constraining the link between the coronal magnetic field and the heating function, which is not directly available in extreme ultraviolet or soft X-ray observations traditionally used for coronal heating studies. We suggest the existence of two apparently distinct populations of hot coronal loops based on the mechanism that better explains measured damping properties of slow magnetoacoustic waves, observed with SOHO/SUMER. Our results indicate Bayesian evidence in favour of the model with TM in the majority of the events considered, with a small population of loops for which thermal conduction alone is more plausible. Whether this result is due to differences in the physical properties of the loops/host active regions themselves or the way compressive waves can exchange energy with a heated plasma must be subject to further investigation, which may help to reveal the coronal heating mechanism.

## About the source of sustained kink oscillations in coronal loops

**N. Poirier, P. Kohutova, S. Danilovic, R. Joshi, L. R. van der Voort**

Kink oscillations in coronal loops have long been observed in TRACE, SDO/AIA, and more recently in SolO/EUI images. Although their properties are quite well-known now, their driver and excitation mechanism remain under active debate. In this contribution I give an overview over recent publications and discuss how the different proposed ideas/theories can be reconciled into one unified vision. Radiative 3-D MHD simulations using the Bifrost code (Kohutova et al. 2021, 2023) are exploited as a sandbox to test this unified vision, as well as actual observations. We especially look at high-resolution coronal and photospheric/chromospheric observations taken recently by SolO/EUI/HRI and the Swedish 1-m Solar Telescope respectively. This work has been funded by the Research council of Norway (grant 324523).

## Kink oscillations in curved coronal loops

Mingzhe Guo, Tom Van Doorsselaere, Bo Li, Marcel Goossens

This work aims to clarify the influence of loop curvature on horizontally and vertically polarized kink oscillations. We conduct 3D MHD simulations of axial fundamental kink oscillations in curved density-enhanced loops embedded in a potential magnetic field. Both horizontal and vertical polarizations are examined, and their oscillation frequencies are compared with WKB expectations. We discriminate two different density specifications. In the first, the density is axially uniform and varies continuously in the transverse direction toward a uniform ambient corona. Stratification is implemented in the second specification to address the effect of evanescent barriers. Examining the oscillating profiles of the initially perturbed uniform-density loops, we found that the frequencies for both polarizations deviate from the WKB expectation by 10%. In the stratified loop, however, the frequency of the horizontal polarization deviates to a larger extent. The WKB expectation for straight configurations can reasonably describe the eigenfrequency of kink oscillations only in loops without an asymmetrical cross-loop density profile perpendicular to the oscillating direction. We also illustrate the lateral leakage of kink modes through wave tunnelling. It is found to be less efficient than resonant absorption, meaning that the latter remains a robust damping mechanism for kink motions even when loop curvature is included.

| Thursday, June 27 |
|---|
| **Waves — coronal cooling** |

**Afternoon**

### Liquid sunshine: drizzle, showers, and torrential rain on the Sun (INVITED)

**Seray Şahin and Patrick Antolin**

The corona is the outer layer of the solar atmosphere and has a puzzling temperature hundreds of times higher than the underlying surface, which is a major unsolved astrophysics problem. The corona also contains a substantial quantity of cool material called coronal rain, hundreds of times colder and denser plasma grouped in showers, and is mainly observed in quiescent and flaring active regions (AR). The properties of rain are known to be deeply linked to the way the corona is heated, but its dynamics, origin, and morphology are yet poorly understood. In particular, the rain's spatial and temporal occurrence in an AR is unknown. Rain formation is driven by thermal instability (TI) in coronal loops that are in thermal non-equilibrium (TNE). In this presentation, I will be showing the first high-resolution imaging statistical study of coronal rain (and showers) in terms of its origin, dynamics, morphology, energetics, and its link to coronal heating and solar flare mechanisms. In this study, we find that the volume under TNE-TI conditions can be over half the AR volume, indicating a prevalence of strongly stratified and high-frequency coronal heating. Overall, plasma downflows in the form of rain showers corresponds to half of the observed solar flare energy, placing coronal rain as a major player in the mass and energy circulation in the quiescent and flaring solar corona.

### The effect of thermal nonequilibrium on the open-closed boundary

**S. K. Antiochos and P. J. MacNeice (NASA/GSFC)**

In recent years both numerical models and observations have indicated that thermal nonequilibrium (TNE) is a ubiquitous process in the large-scale corona. The physical origin of TNE is that if the heating in a coronal loop is spatially localized near the chromospheric footpoints on a scale that is small compared to the loop height, then no static or steady equilibrium is possible. Given this result, TNE would be expected to be more likely on the largest coronal loops, in particular, those at an open-closed boundary such as the edge of a helmet streamer. A key point is that for such loops the plasma beta is expected to become large near streamer tops, so the plasma pressure variations resulting from TNE are likely to have a strong effect on the magnetic field and vice versa. In typical studies of TNE the beta is assumed to be very low and the field is taken to be rigid. We present 2.5D MHD simulations of TNE in a streamer field configuration. We find that TNE does, in fact, drive magnetic field dynamics at the streamer apex, which corresponds to the base of the heliospheric current sheet. We discuss the role of TNE in determining the reconnection that occurs at the current sheet. Furthermore, we discuss the implications for observations of the corona and wind. This work was supported by the NASA LWS Program.

### Dynamical thermal instability in coronal loops

**Varsha Felsy, Ramon Oliver, Jaume Terradas**

The state of coronal loops essentially depends on the complex interplay between plasma flows, gravity, heating, radiative cooling and conduction. Numerical simulations show that, under the influence of a steady or quasi-steady footpoint heating, coronal loops can be in a state of thermal non-equilibrium (TNE), characterised by a localised thermal runaway that leads to the formation of cold and dense condensations (coronal rain). In this work we apply a thermal instability analysis and show that TNE numerical simulations are thermally unstable to the Balbus isochoric stability criterion. Our loop simulations are symmetric with respect to the apex. For this reason, condensations start to form at two symmetric positions along the loop and later merge at the apex. We also find that thermal instability (TI) triggers the evaporation of the chromospheric material required to feed the condensations. The so-called incomplete condensations appear when the TI locations are too near the loop feet and the evaporation flows are unable to provide enough energy to raise the condensations to the apex.

### Hot and cold: coronal heating and the ubiquity of multi-thermal plasma structures in the global solar corona

**Cooper Downs, Emily I. Mason, Jon A. Linker, Ronald M. Caplan, Peter Riley, Roberto Lionello**

The current wealth of multi-wavelength coronal observations has made it increasingly clear that the plasma state of the corona is inherently dynamic and multi-thermal. From small-scale jets, to active region loops, to large-scale coronal fans at streamer boundaries, we observe a constantly evolving mixture of hot (>1.5 MK) and cool plasma (<1.1 MK) in the corona, with cool plasma often outlining distinct loops or topological boundaries. Understanding the ubiquitous nature of these structures requires one to connect how they are heated to their inherent magnetic geometries. In this context, we study outputs from our recent data-assimilative, data-driven, continuously evolving thermodynamic MHD simulation of the global solar corona during the weeks leading up to the April 8th 2024 total solar eclipse. In this simulation, we document a near ubiquitous presence of multi-thermal plasma structures forming in different morphologies, from thermal-non-equilibrium in active region loops, to cool loops forming and perturbing null-point topologies (fan-spine and x-point), to large-scale coronal fans. Leveraging the inherently large parameter space for heating and flux-tube geometry that such a simulation provides, we examine the fundamental connection between the strength and stratification of coronal heating to the formation, dynamics, and maintenance of these multi-thermal structures.

### Hot meets cold: from eruptions to post-flare coronal rain

**Samrat Sen, Avijeet Prasad, Valeriia Liakh, Rony Keppens**

The formation of coronal rain in a post-eruptive flare is not fully understood. We perform a resistive-magnetohydrodynamic simulation to explore the evolution of sheared magnetic arcades to explore the formation, and eruption of magnetic flux ropes (MFRs), followed by the appearance of coronal rain in the post-flare loops. The system is in mechanical imbalance at the initial state, and evolves self-consistently in a non-adiabatic atmosphere under the influence of radiative losses, thermal conduction, and background heating. The system relaxes to a semi-equilibrium state from its initial mechanical imbalance condition after a short transient temporal evolution. After this period, a series of erupting MFRs is formed due to spontaneous magnetic reconnection, and current sheets are created underneath the erupting flux ropes. Gradual development of thermal imbalance is noticed at a loop top in the post-eruption phase, which leads to catastrophic cooling and formation of cool-condensations. The dynamical and thermodynamic properties of these cool-condensations are in good agreement with observations of post-flare coronal rain. The presented simulation supports the development and eruption of multiple MFRs, and the formation of coronal rain in post-flare loops, which is one of the key aspects to reveal the coronal heating mystery in the solar atmosphere.

### Collective and non-collective properties of non-linear torsional Alfvén waves

**S. A. Belov**

In coronal plasma loops, an observational detection of torsional Alfvén waves is complicated, because these waves are usually considered to be non-collective. This non-collectivity means that the wave consists of cylindrical surfaces evolving independently. However, in the non-linear regime, this non-collective behaviour can be modified. To shed light on this problem, the propagation of non-linear torsional Alfvén waves in straight magnetic flux tubes has been investigated numerically and analytically.

Numerical simulations using the MHD code Athena++ have shown the existence of a radially uniform density perturbation induced by the torsional Alfvén wave. The uniformity of this perturbation does not depend on the radial structure of the mother Alfvén wave. To support these results, an analytical study has been conducted. This study demonstrates that the radial and axial velocity plasma perturbations are induced by ponderomotive force. At the same time, a non-equal elasticity of a magnetic flux tube in the radial and axial directions drives the density perturbation. The last mechanism can be interpreted qualitatively as the interplay between the Alfvén wave perturbations, external medium, and the flux tube boundary conditions.
The existence of the collective and radially uniform density perturbations accompanying non-linear torsional Alfvén waves could be considered as an additional observational signature of Alfvén waves in the upper layers of the solar atmosphere.

### Modelling of propagating Alfvénic waves in a gravitationally stratified open coronal loop

**Yuhang Gao; Tom Van Doorsselaere; Hui Tian; Mingzhe Guo; Zihao Yang**

In the open-field regions of the solar corona, such as coronal holes, many transverse waves propagate along field-aligned magnetic loops, generally interpreted as kink/Alfvénic waves. Previous studies have underscored their potential applications in coronal heating, solar wind acceleration, and seismological diagnosis of various physical properties. However, these propagating kink waves are rarely studied considering both vertical and horizontal density inhomogeneity with advanced 3D magnetohydrodynamic (MHD) simulations. In this study, we establish a 3D MHD model of a gravitationally stratified open coronal loop, incorporating a velocity driver at the bottom boundary to induce propagating kink waves. It is found that resonant absorption and density stratification both affect the wave amplitude. When diagnosing the relative density profile with velocity amplitude, resonant damping should be properly considered to avoid possible overestimation. In addition, unlike standing modes, propagating waves appear to suppress the full development of Kelvin-Helmholtz instability. Nevertheless, phase mixing within the loop boundary can still generate small-scale structures, partially dissipating wave energy and leading to localized temperature increases, especially at higher altitudes. Moreover, forward modelling is conducted to synthesise observational signatures, which emphasises the promising potential of future coronal imaging spectrometers (like MUSE) in studies of coronal MHD waves.

Friday, June 28

**Morning**

### The Solar-C EUVST mission and the study of coronal loops

**I. Ugarte-Urra**

The Solar-C mission, to be launched in 2028, is an international collaboration led by JAXA with the goal to understand the origins of solar activity by observing fundamental physical processes in the solar atmosphere. The main instrument on board is the Extreme UltraViolet High-Throughput Spectroscopic Telescope (EUVST), a next generation spectrograph and slit-jaw imaging system, that will provide seamless spectroscopic coverage of the chromosphere, transition region, corona, and flares at high spatial resolution (0.4" or 300km) with cadences as low as 0.5s in flares and 5s in coronal conditions. We present the scientific objectives of the mission, the instrument specifications, data products, and discuss how EUVST will be a critical resource for the study of coronal loops, as well as phenomenology and key physical processes often associated to them, such as nanoflares, waves, spicules, chromospheric evaporation and reconnection.

### Slitless imaging spectroscopy for active region loop heating : Hinode EIS observations

**P. S. Athiray, A. Winebarger, D. Brooks, S. Tiwari**

Understanding the frequency of heating events in solar active region (AR) is one of the most important problems in solar physics. The temperature in ARs can vary strongly with time and can contain sub-regions that evolve and develop separately. Tracking the spatial and temporal evolution of temperature and density simultaneously requires continuous observation of the entire AR via imaging and spectroscopy. Traditionally a slit is employed through which light enters the instrument and get dispersed to yield spectrally pure observations. Imaging is performed through a rastering process, which limits co-temporal observations and often can be slow to miss events that evolve in other areas of AR. Wide-field imaging spectroscopy offers simultaneous coverage of a large field of view as well as obtaining spectral information in the same direction, which results in spatial-spectral confusion. Such data are called spectroheliogram, which can be unfolded using the state-of-the-art inversion techniques. The EUV Imaging Spectrometer (EIS) onboard the Hinode satellite carried wide slots, which is a powerful data to study the evolution of AR, when properly unfolded. EIS slot data are underutilized due to complexity involved in the unfolding of spatial-spectral overlaps. Here, we present our study of coronal heating in an AR using long duration Hinode EIS slot observations.

### Giant post-flare loops in active regions with extremely strong coronal magnetic fields

**Costas E. Alissandrakis, Gregory D. Fleishman, Viktor V. Fedenev, Stephen M. White, and Aleksander T. Altyntsev**

We report the first detection of thermal free-free emission from post-flare loops at 34GHz in images from the Nobeyama Radioheliograph (NoRH). We studied 8 loops, 7 of which were from regions with extremely strong coronal magnetic field reported by Fedenev et al. (2023). Loop emission was detected in a wide range of wavelength bands, up to soft X-rays, confirming their multi temperature structure and was associated with noise storm emission in metric waves. The comparison of the 17GHz emission with that at 34GHz showed that the emission was optically thin at both frequencies. We describe the structure and evolution of the loops and compute their density, obtaining values for the top of the loops between 1 and 6×10^10 cm^–3, noticeably varying from one loop to another and in the course of the evolution of the same loop system; these values have only a weak dependence on the assumed temperature, 2 MK in our case, as the sources are in the optically thin regime. The estimated density values are above those reported from EUV observations, which go up to about 10^10 cm^–3. This difference could be due to the fact that different regions are sampled in the two domains and/or due to the more accurate diagnostics in the radio range, which do not suffer from inherent uncertainties arising from abundances and non-LTE excitation/ionization equilibria. We also estimated the magnetic field in the loop tops to be in the range of 10-50G.

### Determining coronal magnetic reconnection rates from SDO AIA observations of post-flare loops

**Anna Rankin, Robert Walsh**

There have been several attempts to calculate indirectly the magnetic reconnection rate in the corona by analysing observations of solar flares, many of which have focused on X-ray and EUV data collected during Solar Cycle 23. This current study builds upon the method outlined in Isobe et al. (2002, ApJ, 566, 528) by examining SDO/AIA EUV observations of solar limb post-flare loops to define a range of spatial characteristics for the target loop systems. In particular, an estimation of the footpoint velocity due to ongoing reconnection was undertaken by calculating the velocity at which successive loops brighten in the emission lines during the postflare phase. We take advantage of the exceptional AIA dataset, which covers the entirety of Solar Cycle 24 as well as capturing the whole solar disc at higher spatial and temporal resolutions across multiple EUV wavelengths. The resulting rich dataset includes numerous limb flare examples, enabling direct comparisons between individual limb flare configurations with subsequent magnetic reconnection rate estimations. Preliminary results from these investigations will be presented, as well as implications for future analysis of post-flare loops, including very high-resolution observations from the recent (April 2024) Hi-C Flare observing campaign.

### The thermodynamic consequences of null points in the corona

**Daniel Johnson, Alan W. Hood, Peter J. Cargill, Jack Reid, Craig D. Johnston, Ineke De Moortel**

Magnetic null points are regions of a magnetic field where the field strength vanishes. They play an important role in several heating mechanisms that may enhance local coronal temperatures (e.g. via magnetic reconnection, Ohmic heating or by guiding waves). The geometry of a magnetic field changes abruptly about a null point, which can inhibit cooling via conduction and, hence, also lead to enhanced temperatures. A proper treatment of thermal conduction at null points is also often overlooked. In this presentation, we discuss the treatment of thermal conduction at nulls and the consequences that null points impose on the local thermodynamic state of the corona. We contrast these results to equivalent straight field solutions, without nulls, and show that the solutions differ significantly. We present this analysis for several forms of heating and support our discussion with numerical and analytical results.