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Book of Abstracts

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Current and Future Capabilities / 55

Modeling the Solar Atmosphere: Current challenges and future directions

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Realism of models has two components: sophistication of implemented physics and realism of the overall setup. Current 3D radiation MHD simulations of the coupled solar atmosphere are presenting a compromise on a middle ground. Domains are at best large enough to capture the extent of small active regions, but the commonly adapted use of periodic boundary conditions leads in many setups to an unrealistic magnetic field connectivity. Relevant physics in terms of radiation transport, including non-equilibrium treatment and ion-neutral effects are implement in a few commonly used simulation codes, but in many of larger domain models the resolution is just barely enough to start resolving processes of interest. More detailed physics better describing reconnection and energy dissipation can be only studied in dedicated simulations that focus on either small domains or reduce the dimensionality of the domain. In this talk I will touch on these challenges and present a few future directions: (1) We need simulations in local domains that are better informed by the global magnetic field structure of the corona. (2) We need higher resolution and reduction of numerical diffusivity and adoption of sub-grid models that better capture underlying physics. (3) We need a better quantification of model errors. Any combination of these improvements will come with a high cost and will require utilization of the latest computing platforms, including the use of GPUs. Data analysis is developing into a major bottle neck and will require a change in how we conduct and share large numerical simulations.

Current and Future Capabilities / 90

Current numerical approaches and how to expand them

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Task-based computing is offering a break-through in our capabilities to model astrophysical phenomena, and in particular in the context of solar modeling there are several routes along which we can take advantage of this general methodology. In the context of global modeling of the solar interior, we can utilize the ability to tune resolution as a function of depth, and by engaging very low diffusion low-Mach number Riemann solvers we can model the solar interior over time-scales sufficient to cover solar cycles. Given such global models, with large extents in space-time, we can then use static and adaptive mesh refinement to zoom-in on smaller (active) regions of space-time. With initial and boundary conditions from the larger scale models, and with BIFROST-compatible physics added, we can realistically model active region phenomena, first with (non-ideal) magnetohydrodynamics, and ultimately with particle-in-cell modeling of charged particle dynamics and particle acceleration in even smaller regions of space-time. An important technical development is needed to fully utilize these opportunities; a large fraction of the near-future supercomputing capacity is based on GPU-offloading, and we need to continue to develop and integrate accelerated solvers for magnetohydrodynamics and charged particle dynamics, while also staying on top of advances in hardware, firmware, and programming language standards related to offloading and hierarchical memory architecture.

Current and Future Capabilities / 78

Future high-resolution observation capabilities of the chromosphere and corona from Earth

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Instrumentation for solar observations always represents a trade-off between spatial resolution, spectral resolution, field-of-view, time-coherence, calibration, and available money. The current state-of-the art for optical and near-infrared wavelengths consists of Fabry-Perot interferometers, and various types of imaging spectrographs.

In this talk I will discuss some aspects of these considerations, and review current and upcoming instrumentation at DKIST, SST, and other observatories.

Current and Future Capabilities / 79

Future high-resolution observations of the low solar atmosphere from space

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In this talk I will provide a brief overview of the upcoming solar missions focused on the Sun's corona: MUSE and Solar-C/EUVST, scheduled for launch in 2027 and 2028, respectively. The Multi-slit Solar Explorer (MUSE) is a NASA MIDEX mission, composed of a multi-slit EUV spectrograph (in three spectral bands around 171Å, 284Å, and 108Å) and an EUV context imager (in two passbands around 195Å and 304Å). MUSE will provide spectral and imaging diagnostics of the solar corona at high spatial (~0.5 arcseconds), and temporal resolution (0.5 seconds). By obtaining spectra in 4 bright EUV lines covering a wide range of transition region and coronal temperatures along 37 slits simultaneously, MUSE will 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 spatial scales. Solar-C is a JAXA-led international mission with the EUV High-throughput Spectroscopic Telescope (EUVST) as its main payload. EUVST is a high-resolution (0.4 arcsecond), high-cadence (0.5s) single-slit spectrograph that includes multiple spectral passbands in the EUV and FUV, providing temperature coverage from the chromosphere to the flaring corona without any significant gaps. EUVST includes slit-jaw imaging in the photosphere, low chromosphere and upper chromosphere. I will describe the strong synergy between these missions and provide some examples of how the constraints on the properties of the solar atmosphere from these instruments can discriminate between predictions from various current numerical models for coronal heating, solar flares, and coronal mass ejections.

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What do we know about the photospheric and chromospheric magnetic field?

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Solar magnetic fields are essential ingredients for the energetics and dynamics of the lower solar atmosphere. After emergence, they continually interact with convective flows and with each other. The resulting field line braiding is believed to trigger magnetic reconnection in the chromosphere and above, generating a wide variety of features and contributing to atmospheric heating, both locally and globally. However, the exact conditions leading to magnetic reconnection are not yet well understood. Also, the origin of the field and the process of flux emergence are poorly known, particularly on the smallest scales.

Determining the topology and energy injected by the fields in the lower solar atmosphere is key to understanding these processes. Significant advances have been achieved through multi-line spectropolarimetric observations at ever increasing spatial resolution. Specific examples will be discussed here. However, the efforts have been hampered by insufficient polarimetric sensitivity, which makes it difficult to follow the evolution of the fields or even detect the weaker ones, particularly in the chromosphere. Thus, a direct confirmation of the scenarios suggested by numerical simulations is not possible in general. The lack of tools to infer the vector magnetic field from spectropolarimetric measurements has impeded progress, too. These limitations will soon be overcome, giving access to the elusive chromospheric fields. The interpretation of the new observations will require simulations of the entire solar atmosphere covering larger fields of view. Together, they will clarify the origin of solar magnetic fields, their structure, and their role in the heating of the solar atmosphere.

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Driving of atmospheric heating from the convection zone

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In this talk I will look at the scales at which photospheric motions generate waves and changes in the magnetic field topology. I will then discuss how these scales change throughout the solar atmosphere.

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Advances on multi-fluid modeling of the solar atmosphere

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Recent observational studies on abundances reveal the need to expand models by considering different fluids and/or species to be constrained with these observations and interpret them. Similarly, radiative MHD models fail to reproduce observations of the coldest parts of the chromosphere and some properties of the Mg II profiles. Mg II is formed where interactions between multiple ionized and neutral species prevent an accurate MHD representation. In addition, those regions are where MHD seems to break down, and microphysics may need to be considered, such as a meter-scale electrostatic plasma instability, the Thermal Farley-Buneman Instability (TFBI), which develops in these regions and efficiently converts kinetic energy into electron heating. In this presentation, I will summarize some of the advances in multi-fluid modeling, especially focusing on the multi-fluid Ebysus code and the need to validate and constrain those with existing and future observations.

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Towards multi-fluid simulations of the solar chromosphere

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Solar chromosphere has been at the focus of solar physics studies for decades, but its heating mechanisms are still unknown. Chromospheric plasma is strongly stratified, weakly ionized and not completely collision coupled. In this talk I will overview our recent results of the modeling of solar chromosphere, comparing a more standard single-fluid approach and a more novel multi-fluid approach. I will describe the challenges posted by the multi-fluid modeling, that still need to be overcome, and will talk about possible observables for the multi-fluid effects.

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Ebysus, a multi-fluid multi-species code: application to upper chromospheric magnetic reconnection with Helium-Hydrogen mixture

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Our understanding of magnetic reconnection (MR) under chromospheric conditions remains limited. Recent observations have demonstrated the important role of ion-neutral interactions in the dynamics of the chromosphere. Furthermore, the comparison between spectral profiles and synthetic observations of reconnections suggest that single-fluid MHD approaches appear to be inconsistent with observations. Indeed, collisions and multi-thermal aspects of the plasma, hydrogen and helium ionization effects play a major role in the energy balance of the chromosphere.

This work investigates multi-fluid/multi-species (MFMS) effects on MR in upper chromospheric conditions. We compare an MFMS approach based on a helium-hydrogen mixture with a two-fluid MHD model based on hydrogen only. We study the evolution of the MR and compare the two approaches including the decoupling of the particles, the evolution of the heating mechanisms, and the composition.

The simulations have been performed in the same numerical code Ebysus (Wargnier et al. 2022) which can solve any MFMS model for any species and/or ionized/excited level as desired. A numerical strategy based on a partitioned implicit-explicit orthogonal Runge-Kutta method has been considered. This algorithm allows an optimization of the timestep while estimating the error of the various terms involved in these models and guaranteeing reasonable computational costs.

Our results show that the presence of helium species leads to more efficient heating mechanisms than the two-fluid case. The different dynamics between helium and hydrogen species could lead to chemical fractionation and enrichment of helium. This could be of significance for recent observations of helium enrichment in switchbacks or CMEs.

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Role of chromospheric partial ionization on the dynamics of kink unstable flux ropes

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Recent observations performed by space missions (SDO, Hinode) prove the existence of mini-filament eruptions within the solar chromosphere that could be connected to the formation of chromospheric jets and spicules. The growth of the helical kink instability within these structures is responsible of the onset of magnetic reconnection and lead to explosive events occurring ubiquitously in the lower solar atmosphere. Numerical studies of low-lying loops neglect critical physics in the form of partial ionization, which can lead to enhanced reconnection rates and a more efficient heating and particle acceleration. Here we perform high resolution multi-fluid simulations of kink unstable flux ropes to elucidate the role of partial ionization in modifying the kink process. The complex charge-neutral coupling in our model includes ionization, recombination and radiative losses. Partial ionization leads to a faster onset of the non-linear phase of the kink instability, whose reconnection rate could be consistent with those estimated by observations of the smaller chromospheric filaments. The magnetic energy lost with reconnection is distributed differently between fully ionized plasmas and partially ionized plasma cases, with a larger increase of internal energy and temperature associated to partial ionization and additional heating terms, such as the frictional heating, resulting from multi-fluid dynamics. Partial ionization effects lead to a faster kink instability and the release of larger quantities of thermal energy, which is reflected by a more explosive chromospheric flux rope dynamics.

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Setting observational constraints on the chromospheric heating problem

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The chromospheric heating terms cannot be inferred directly from observational datasets. Furthermore, even estimating the thermodynamical state of the plasma usually involves complex NLTE inversion calculations. Therefore, it has been very difficult to quantify in which proportion different heating mechanisms could be operating at different locations of the chromosphere.

One of the most crucial constraints that we can set a any given location are the chromospheric radiative losses, as they represent the energy that (at least) must be replenish in the chromosphere at any given time.

In this talk I will tackle how the spatio-temporal estimates of the radiative losses and other proxies can be used to discriminate what heating mechanisms could potentially be at work from very high spatial-resolution observations of the solar chromosphere.

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First Results of the MURaM Chromospheric Extension

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The MURaM radiation-magnetohydrodynamics code has long been applied to simulate near-surface magnetoconvection, ranging from quiet sun conditions to complex active regions. The code includes the physics required to treat the convection zone, and the solar atmosphere from the photosphere to the corona. Until now, these simulations have been limited to a local-thermodynamic equilibrium treatment of the chromosphere, limiting it's realism. We have extended the MURaM code to include NLTE effects following the prescriptions used in the Bifrost code. In this work, we summarize the improvements made to the code. We study an initial model of the chromosphere, representing an enhanced network region. Comparing synthetic Mg II h&k spectra to IRIS observations we discuss the implications of the new model towards understanding the physics necessary to model the chromosphere.

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Constraining the acoustic wave flux in the solar chromosphere with observations and simulations

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This study presents a comparison of the high frequency wave power found in 3D numerical MHD models of the solar atmosphere (Bifrost and MURaM) with real observations of chromospheric lines. We also discuss the systematics originating from using different models to calculate the acoustic wave flux in the solar chromosphere. In particular, we synthesize from the MHD models spectral lines sampling the lower chromosphere (Mn I 280.1 nm, Na D1), middle chromosphere (Ca II 854.2 nm) and the upper chromosphere (Mg II h&k) with the RH15D code. We compare the synthetic observations with data from the IRIS observatory and the IBIS instrument at the DST. We also study the emerging lack of high frequency phase differences between the observed velocity diagnostics and how is this phenomenon affected by the rapidly changing line formation height. Based on these results, we investigate the systematics of inferring acoustic wave flux in the solar chromosphere. We find that the main uncertainty in determining the wave flux in the chromosphere is due to the changing height of formation and the associated changes in the plasma density. This effect leads to uncertainties of the inferred flux on the order of magnitude. Furthermore, the dynamic time-dependent chromospheric models also show significantly lower attenuation of the detected wave signals, compared with the previously used 1D semi-empirical models. The main takeaway from this study is that we need numerical chromospheric models that resemble closely the solar wave properties, to be able to infer the acoustic wave flux accurately.

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High-resolution observations of chromospheric dynamics

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The chromosphere is a very dynamic part of the solar atmosphere. With short time scales and small spatial scales at which fundamental physical processes are taking place, it is a challenge to get a clear observational view of the chromosphere. The CRISP and CHROMIS tunable filter instruments at the Swedish 1-m Solar Telescope (SST) on La Palma are capable of fast wavelength sampling while operating near the diffraction limit of the telescope. In this talk, I will present some of the best observations of the chromosphere that we have acquired with the SST. Over the past decade, we have been running a program of multiple annual campaigns in coordination with IRIS. This long term effort has resulted in a database that covers an extensive range of different types of targets and allows us to concentrate on data that were acquired under the best conditions. These datasets help us to find constraints on what are the main mechanisms that drive the dynamics of the chromosphere.

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Understanding chromospheric dynamics

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Recent magnetohydrodynamic models show that many of the chromospheric features and their dynamics can be reproduced to some degree. The models demonstrate that the overall appearance of synthetic chromosphere depends mostly on the field configuration and the treatment of the small-scale dynamics. In this talk, the properties of these models are presented, as well as their comparison to observations. These results are then linked with outstanding questions, both in modeling and observations.

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Differentiable programming for spectra modeling and inference

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Nowadays, solar spectra are routinely analyzed to understand the physical mechanisms that trigger different physical phenomena. These spectral lines are modeled using approaches of increasing complexity, ranging from a simple Gaussian model to complex non-LTE radiative transfer calculations. In practice, these data are also affected by telescope degradation, may include some instrumental artifacts, and some signals may be buried under noise. During these years, different approaches have been developed to solve specific problems, proving solutions under various assumptions. Since many of these models are differentiable (and those that are not differentiable can be emulated with neural networks), we could use deep learning frameworks as a general infrastructure to implement these models and infer the parameters of interest in a flexible way. We can combine and incorporate different models, nonlinear transformations, spatial degradation (telescope PSF), spatial coherence (spatial smoothing), artifacts (e.g., fringes, blends with other lines), and physical constraints (e.g., magnetic field vector divergence). By construction, we can run these codes on GPUs with no extra modification, speeding up all computations. In this talk, I will present different examples with IRIS and SST data with an eye toward future missions such as MUSE and EUVST, highlighting the strengths and limitations of this novel approach.

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Small-scale loops heated to transition region temperatures and their chromospheric signatures in the simulated solar atmosphere

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Recent observations revealed loop-like structures at very small scales visible in observables that sample transition region (TR) and coronal temperatures. Their formation remains unclear.

We study an example of a bipolar system in realistic magnetohydrodynamic simulations and forward synthesis of spectral lines to investigate how these features occur.

Computations are done using the MURaM code to generate model atmospheres. The synthetic Hα and Si IV spectra are calculated at two angles (μ=1, μ=0.66) using the Multi3D code. Magnetic field lines are traced in the model and the evolution of the underlying field topology is examined.

The synthetic Hα dopplergrams reveal loops that evolve dramatically within a few minutes. The synthetic Hα line profiles show observed asymmetries and doppler shifts in the line core. They, however, also show strong emission peaks in the line wings, even at the slated view. The synthetic Si IV emission features partly coincide with structures visible in Hα dopplergrams and partly follow separate magnetic field threads. Some are even visible in the emission measure maps for the lg(T/K)=[5.0, 5.5] temperature interval. The emission areas trace out the magnetic field lines rooted in opposite polarities in a bipolar region.

We find that our results largely reproduce the observed features and their characteristics. A bipolar system with footpoints undergoing rapid movement and shuffling can produce many small-scale recurrent events heated to high temperatures. The morphology and evolution of the resulting observable features can vary depending on the viewing angle.

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Interplay between modelling and observations of the upper solar atmosphere

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Numerical simulations based on 3D MHD models have been used create and sustain a hot upper atmosphere of the Sun for various solar features, e.g. quiet Sun, bright points, or active regions. These models provide self-consistent explanations for quite a range of observational features e.g. for Ellerman bombs or UV bursts. They allow to follow the changes of the magnetic field, e.g. while field lines are braided, and by this show where and when energy is dissipated and what the consequences are for (synthesised) line profiles from the transition region and corona. However, many questions remain open. For example, numerical models usually show very high contrast in synthesized emission, while on the real Sun the majority of the emission is originating from a diffuse background. Is this background seen in the observations just a mixture of small-scale unresolved features, or are there some processes at work that we so far do not capture by numerical models? Coronal imaging from Solar Orbiter at an unprecedented spatial resolution do show not only features smaller than before, but also show, e.g., diffuse patches almost the size of a supergranule or thick loops that are stable for surprisingly long times. For all these features MUSE will provide information on profiles of coronal emission lines at a spatial resolution roughly matching Solar Orbiter EUV imaging. This will provide new constraints and challenges for our understanding of the upper solar atmosphere.

Corona / 91

Recent advances in Coronal Heating due to High Resolution Imaging: Results from the High-Resolution Coronal Imager

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The High-Resolution Coronal Imager (Hi-C) instrument has been launched twice from White Sands Missile Range, each time capturing the highest resolution coronal images ever obtained, first in the 193 Angstrom passband and then in the 171 Angstrom passband. These two rocket flights, which collectively have yielded only 10 minutes of data, have generated over 80 refereed publications. In this talk, I will discuss how these observations have advanced our knowledge of coronal heating and paved the way for the next generation of high resolution instruments, like the Multi-Slit Explorer (MUSE).

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MUSE diagnostics of coronal heating from MHD modeling of magnetically stressed coronal loops

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Chaotic photospheric motions progressively shuffle and braid the magnetic field confining plasma in coronal loops. The stressed field can suddenly lose equilibrium and develop instabilities, candidate to release magnetic energy into heat. There is long experience in modeling impulsive energy releases in coronal loops, from a purely hydrodynamic approach (e..g.,Reale+2000,Testa&Reale2020), to a full-MHD approach (Guarrasi+2014,Reale+2016,DePontieu+2022). In the MHD model an initial stratified atmosphere, including the steep transition region between the chromosphere and the corona, is in equilibrium with a loop-like magnetic field, which is progressively twisted by photospheric motions and can reconnect and release energy through anomalous diffusivity. The time-dependent 3D-MHD equations are solved numerically with the accurate Godunov-based PLUTO MHD code, including gravity, plasma radiative losses, and thermal conduction.
In this configuration we are currently investigating MHD kink instabilities in twisted magnetic strands (e.g.,Hood+2009). The initial helical current sheet progressively fragments in a turbulent way into smaller scale sheets, whose dissipation is similar to a nanoflare storm. The unstable loop expands and can disrupt nearby stable loops (e.g.,Tam+2015), thus triggering an MHD avalanche (Hood+2016).
Another target is reconnection jets, also called nanojets, observed in coronal loops, and linked to nanoflares (Antolin+2019).
We study them modeling the reconnection of two tilted coronal loops.
For all this work in progress, the combination of magnetic configuration and full loop atmosphere allows us to isolate the critical processes, still maintaining a high level of realism to address specific signatures in imaging and spectroscopic observations foreseeable with the MUSE mission.

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Flux emergence and the state of the outer solar atmosphere

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The dynamical evolution of the solar magnetic field(s) is a key ingredient in understanding the ubiquitous observed activity in the Sun. A fundamental process, which is responsible for this dynamical evolution, is the emergence of magnetic flux from the solar interior to the outer solar atmosphere. The cost of running realistic numerical models is no longer prohibitive in studying the rising of magnetic flux through the last 10-20 Mm of the solar convection zone and into the outer atmosphere. We review observational constraints on the flux emergence process and current and future modelling efforts using high performance computational resources and techniques. We will especially concentrate on the comparison between model generated synthetic observables against observed spectral signatures. We will discuss how MUSE observations of flux emergence will improve our understanding of solar and stellar magnetic fields and their role in producing the coronal field, igniting flares, and energising chromospheres and coronae and we will discuss what developments in modelling are necessary to form a coherent picture of these complex phenomena.

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MUSE 'observations' of coronal heating simulations.

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The Sun's atmosphere is powered by the complex convective motions which continuously churn the solar surface and stress the atmospheric magnetic field. However, describing the specifics of the resulting energy cycle, including the processes which ultimately drive energy dissipation and atmospheric heating remains a significant challenge. With this in mind, the community is continuously developing sophisticated MHD simulations to examine the atmospheric energy and mass cycles in more detail.

In this talk, I will review recent results from coronal heating simulations which show how a variety of processes (e.g. reconnection, MHD waves, turbulence) can contribute to maintaining atmospheric conditions. As the location, frequency and magnitude of energy release differs between proposed models, so does the plasma response. This includes the evolution of coronal temperatures and densities, and the generation of field-aligned plasma flows. Since these differences are potentially observable (e.g. with sufficient resolution and cadence), they can provide distinguishing signatures which can constrain the prevalence of each of these heating mechanisms in the Sun's atmosphere. Using synthetic emission derived from numerical models, I will discuss how signatures of elementary heating events may manifest in current and future observational datasets. In particular, I will consider how well the true nature of simulated plasma is reflected in synthetic intensities and spectral diagnostics, and thus detail what inferences can be made from real observations. By focussing on the observational capabilities of the upcoming MUSE mission, I will discuss which features of atmospheric evolution and heating it will unveil for the first time.

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Toward resolving the nonthermal motions in the solar corona

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The MUSE instrument will provide information on intensity and flows in the corona with unprecedented spatial and temporal resolutions. High-resolution 3D MHD models of coronal loops are thus timely and crucial to investigate the connection between heating events and resulting spectral diagnostics.
We carried out high-resolution simulations of a straightened coronal loop that is self-consistently heated and sustained by magnetoconvection. From the model, we synthesized spectral profiles in temperature ranges of 2–3 MK that the MUSE instrument could observe.
The resulting nonthermal linewidths are compatible with the observed values. Due to the high spatial resolution, our simulations partially resolved the energy cascade to small scales within the loop interior. A significant part of the injected Poynting flux is associated with flows on short timescales and small spatial scales, such as vortices propagating from the photosphere to the corona. Our model allows us to disentangle the contribution of motions perpendicular to the axial field of the loop and evaporative upflows that occur in response to coronal heating events.
In this talk, I will discuss the response of the coronal emission line profiles to energy injection and release and whether signatures of propagating vortices could be observed with MUSE.

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Modeling Coronal Bright Points

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Coronal Bright Points (CBPs) are ubiquitous structures in the solar atmosphere composed of hot small-scale loops observed in EUV or X-Rays. They are key elements to understand the heating of the corona; nonetheless, basic questions regarding their energization, heating mechanisms, the chromosphere underneath, or the effects of
flux emergence in these structures remain open.

We have used the Bifrost code to carry out a numerical experiment in which a coronal-hole magnetic nullpoint configuration evolves perturbed by realistic granulation. To compare with observations, synthetic SDO/AIA, Solar Orbiter EUI-HRI, IRIS images have been computed, in addition to synthetic MUSE observables to show the potential diagnostics capabilities of the future mission.

The experiment shows the self-consistent creation of a CBP through the action of the stochastic granular motions alone, mediated by magnetic reconnection in the corona. The reconnection is intermittent and oscillatory, and it leads to coronal and transition-region temperature loops that are identifiable in our EUV/UV observables. During the CBP lifetime, convergence and cancellation at the surface of its underlying opposite polarities takes place. The chromosphere below the CBP shows a number of peculiar features concerning its density and the spicules in it. The final stage of the CBP is eruptive: magnetic flux emergence at the granular scale disrupts the CBP topology, leading to different ejections, such as UV bursts, surges, and EUV coronal jets.

Apart from explaining observed CBP features, our results pave the way for further studies combining simulations and coordinated observations in different atmospheric layers.

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The current state of wave-based heating mechanisms

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In recent years, a renaissance has occurred for wave heating mechanisms,
because of the plethora of wave observations in the corona since 10-20 years. This renewed interest in wave heating modelling has brought models from the 1D and cartoon level to full 3D wave heating models. It has been realised that the waves naturally induce the formation of small scales through turbulence, leading to an attractive pathway to heating. Despite this interesting pathway and continued modelling efforts, heating was only achieved in quiescent loops, and not in active region loops. Moreover, coupling to the lower atmosphere remains largely unexplored.
In the current talk, I will give an update on the latest models and progress in this field. I will offer a critical survey, point out problems and pathways to potential solutions.

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Deciphering the Nanojet Phenomenon

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The solar corona is shaped and mysteriously heated to millions of degrees by the Sun's magnetic field. It has long been hypothesised that the heating results from a myriad of tiny magnetic energy outbursts called nanoflares, driven by the fundamental process of magnetic reconnection. This theory recently received significant support through the observational discovery of nanojets - very fast (>100 km/s) and bursty (<20 s) jet-like structures with energies in the nanoflare range, uniquely characterised by being transverse to the loop and, in most cases unidirectional from the reconnection point. We have interpreted the nanojet as the telltale sign of small-angle reconnection leading to nanoflares. It can occur isolated or clustered, with large ensembles showing signatures of an MHD avalanche-like progression, leading to the formation of hot coronal loops. We have since observed nanojets in various structures in which dynamic instabilities such as Kelvin-Helmholtz play a role. Using state-of-the-art numerical simulations, we demonstrate that the nanojet is a consequence of the slingshot effect from the magnetically tensed, braided or curved magnetic field lines reconnecting at small angles. We further show that Alfvén waves can play a binding effect as reconnection triggers. This talk will discuss the open questions related to nanojets and their potential role in coronal heating. We show how next-generation instrumentation, such as MUSE and state-of-the-art simulations, can help elucidate this fascinating phenomenon.

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Decay-less oscillations of turbulent loops

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High-resolution, high-cadence EUV observations over the past decade have led to the discovery of a decay-less regime of kink oscillations in coronal loops. The means of excitation and sustaining such oscillations over many wave periods against energy dissipation mechanisms such as phase mixing and turbulence is still an unknown. Therefore, identifying the true nature of these decay-less oscillations is not only essential for their role as diagnostic tools for coronal seismology, but also for understanding their contribution to heating of the solar atmosphere. To that end, we will be presenting results of 3D magnetohydrodynamic simulations for continuously driven transverse waves in models of straight flux tubes in coronal conditions. Different driving mechanisms will be considered, from monochromatic transverse drivers, to oscillations driven by vortex shedding. We will focus on the manifestation of KH instability-induced turbulence in the cross-section of our simulated coronal loops, and the observational signature of the out-of-phase motions in synthetic data targeting instruments like SDO/AIA, Hinode/EIS and future missions such as MUSE. Parallels will be driven between our numerical models and those of impulsively oscillating loops, multi-stranded loops and loops driven by more complex drivers. Finally, the energy content of the driven oscillations of our turbulent loops will be discussed, showing how the underlying energy fluxes from low amplitude decay-less kink oscillations can potentially be of the order of the radiative losses for the Quiet Sun.

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Coronal heating diagnostics from high spatial and temporal resolution spectroscopic observations

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I will discuss how high resolution current and future observations of the solar atmosphere (e.g., with IRIS, SDO, Hinode, MUSE and EUVST), help us advance our understanding of the role of different physical processes – including, e.g., braiding, Alfven waves, accelerated particles resulting from magnetic reconnection – in heating the solar corona.. In particular I will focus on the synergy between high resolution spectroscopic observations and state-of-the-art models, and will discuss how future transition region and coronal observations from MUSE, EUVST, and other observatories, are expected to test and constrain coronal heating models.

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Solar coronal heating from small-scale magnetic braids

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Relaxation of braided coronal magnetic fields through reconnection is thought to be a source of energy to heat plasma in active region coronal loops. However, observations of active region coronal heating associated with untangling of magnetic braids remain sparse. One reason for this paucity could be the lack of coronal observations with sufficiently high spatial and temporal resolution to capture this process in action. Using new high spatial resolution (250–270 km on the Sun) and high cadence (3–10 s) observations from the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter we observed untangling of small-scale coronal braids in different active regions. The untangling is associated with impulsive heating of the gas in these braided loops. We assess that coronal magnetic braids overlying cooler chromospheric filamentary structures are perhaps more common. Furthermore, our observations show signatures of both spatially coherent and intermittent coronal heating during relaxation of magnetic braids. Our study reveals the operation of gentle and impulsive modes of magnetic reconnection in the solar corona. In this talk, we present these new EUI observations and discuss the implications for magnetic braiding associated coronal heating.

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Chromospheric and Coronal heating in active region plage by dissipation of currents

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It remains unclear which physical processes are responsible for the dramatic increase with height of the temperature in stellar atmospheres, known as the chromospheric ($\sim$10,000 K) and coronal (several million K) heating problems. Statistical studies of sun-like stars reveal that chromospheric and coronal emissions are correlated on a global scale, constraining, in principle, theoretical models of potential heating mechanisms. However, so far, spatially resolved observations of the Sun have surprisingly failed to show a similar correlation on small spatial scales, leaving models poorly constrained. Here we use unique coordinated high-resolution observations of the chromosphere (from the Interface Region Imaging Spectrograph or IRIS satellite) and the low corona (from the Hi-C 2.1 sounding rocket) and machine-learning based inversion techniques to show a strong correlation on spatial scales of a few hundred km between heating in the chromosphere and low corona for regions with strong magnetic field ("plage"). These results are compatible with recent advanced 3D radiative magnetohydrodynamic simulations in which the dissipation of current sheets formed due to the braiding of the magnetic field lines deep in the atmosphere is responsible for heating the plasma simultaneously to chromospheric and coronal temperatures. Our results provide deep insight into the nature of the heating mechanism in active solar regions.

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Signatures of drama in the not-so-Quiet Sun

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The majority of the Sun is covered by a system of relatively weak magnetic fields called the Quiet Sun (QS) which, despite being far weaker than active regions, plays an important role in energizing the solar atmosphere. With new generations of simulations and instrumentation, it is becoming feasible to understand the dynamics of the QS with more precision than before. Using Bifrost, we have analysed a simulated QS heating event that generates coronal temperatures up to 1.47 MK and is caused by the reconnection of a magnetic arcade and twisted flux rope with an overlying, nearly anti-parallel horizontal field in the corona. Understanding the magnetic topology and field evolution of this event have been the main goals of our fundamental studies, but we move forward now to synthetic observables in order to establish an observational context for this type of event. Synthetic observables of the simulated reconnection event reveal strong signals in SiIV, FeIX and FeXII; all of which are observable with IRIS and/or MUSE among other instruments such as SDO AIA, Hi-C, and the EUI onboard the Solar Orbiter. First results indicate strong emissions during the reconnection event as expected, with characteristics consistent with magnetic braiding and fast jets emanating from the reconnection site. We present this simulation as a case study for QS reconnection and introduce preliminary comparison studies between synthetic and actual observables, providing a baseline for future collaborations and studies on QS activity.

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Study Solar Eruptions from a Global Perspective: Current Status and Future Improvements on the Global MHD Models

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The solar coronal mass ejection (CME) is a global phenomenon that not only disrupts the solar atmosphere but also leads to hazardous space weather events when propagating through the heliosphere. The forecast capability of the CME impacts depends critically on our understanding about the plasma environment of the CME source region, and the physical processes involved when CME interacts with the ambient corona and solar wind. The upcoming MUSE mission with its large FOV and high temporal/spatial resolution will provide crucial measurements on these topics therefore shed new light on the evolution and propagation of CMEs and their effects on the surrounding corona. In this talk, I would like to highlight several aspects of CME impact in the form of global EUV waves, sympathetic eruptions, coronal dimmings, CME-driven shocks, and solar energetic particles (SEPs), as well as the current global modeling efforts and challenges. More importantly, I would like to discuss the unique measurements provided by MUSE, when combined with existing remote-sensing and in-situ observations (e.g., SDO, Solar Orbiter, Parker Solar Probe), will significantly improve the data-constrained CME modeling, which will eventually lead to a better space weather forecast capability.

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Recent and future observations connecting the solar wind to sources in the Sun's atmosphere

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The source regions of the solar wind, and their drivers and acceleration mechanisms, remain key topics of study in heliophysics with many open questions. One of the major challenges is to connect heliospheric measurements of the solar wind and solar energetic particles with possible source regions in the solar atmosphere, such as active region outflows and coronal holes, and there are now unprecedented opportunities with Parker Solar Probe (PSP) and Solar Orbiter (SO) in operation. There has been some recent success not only in connection science, but also in understanding the properties of these source regions using spectroscopic measurements from Hinode/EIS and IRIS, and high resolution imaging from Hi-C. I will give a brief overview of some of the recent developments, including results from PSP and SO/SPICE, and will outline some of the progress that can be expected from future high spatial and temporal resolution imaging spectroscopy from MUSE and Solar-C_EUVST. Finally, I discuss some advances in supporting numerical modeling that would aid in the interpretation of the observations.

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Predicted appearance of Magnetic Flux Rope and Sheared Magnetic Arcade Structures before a Coronal Mass Ejection via three-dimensional radiative Magnetohydrodynamic Modeling

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Magnetic Flux Ropes (MFRs) are free-energy-carrying, three-dimensional magnetized plasma structures characterized by twisted magnetic field lines and are widely considered the core structure of Coronal Mass Ejections (CMEs) propagating in the interplanetary space. The way MFRs form remains unclear as different theories predict that either MFRs form during the initiation of the CME or pre-exist the onset of the CME. The term "pre-existing structure" is synonymous with "filament channels." On the one hand, the theories predicting on-the-fly MFR formation require Sheared Magnetic Arcades (SMAs; low twist but stressed magnetic structures) for the filament channel/pre-existing magnetic structure of CMEs. On the other hand, a growing number of works using SDO/AIA observations (combined with non-linear force-free extrapolations; NLFFF) suggest that MFRs may be the form of filament channels, therefore pre-existing the CME eruption. However, due to the inability to routinely measure the 3D magnetic field in the solar atmosphere, we cannot unambiguously interpret optical and EUV imaging observations as projected on the plane of the sky. Therefore, a raging debate on the nature of the pre-eruptive structure continues. It is also possible that the filament channel/pre-eruptive structure evolves from SMA to MFR slowly, further complicating the distinction between these two types of structures in the solar observations. This work presents realistic simulated EUV observations synthesized on a time-evolving radiative MURaM MHD model along the slow evolution of an SMA converting to an MFR. We discuss the implications of our results in the context of filament channel formation and CME initiation theory.

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MPI-AMRVAC: open-source grid-adaptive simulations for solar physics and applications to prominences

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I will present recent additions to – and applications of – our open-source MPI-AMRVAC software (http://amrvac.org), designed to solve generic partial differential equations on any-dimensional, block grid-adaptive mesh hierarchies [2018, ApJS 234, 30 ; 2021, CaMWa 81, 316]. The MPI-AMRVAC 3.0 release is ready to go, and features various modules of direct interest to solar physicists, such as a novel plasma-neutral module to investigate solar chromospheric dynamics [2022, A&A 664, A55], or functionality for time-dependent data-driven applications [2021, ApJ 919, 39]. The ERC-funded project PROMINENT sets forth to study the 'coolest' part of the million-degree solar atmosphere: the prominence condensations formed by thermal instabilities. These represent state-of-the-art magnetohydrodynamic simulations, where the process of runaway condensations due to radiative losses is studied in unprecedented detail [2022, NatAstro 6, 942]. Our MPI-AMRVAC simulation toolkit shows that grid-adaptivity is essential to zoom in on details that may be resolved by future observing facilities. I will present an overview of ongoing and planned research activities to unravel the intricate multi-phase structure of the solar corona.

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

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A major coronal heating theory based on magnetic reconnection relies on the existence of braided magnetic field structures in the corona, where numerical simulations of stress-induced reconnection in braided loop-like structures have shown to 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 overshoots from their new rest position; thereby leading to transverse waves. This provides an efficient mechanism for transverse MHD wave generation in the corona, and also constitutes substantial direct evidence of reconnection from braiding. However, this wave-generation mechanism has never been directly observed. For the signature of small-angle reconnection, this has been identified through the recent discovery of nanojets. Nanojets are small, short-lived and fast jet-like bursts in the nanoflare range 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 results from braiding-induced reconnection identified by the presence of nanojets. This discovery provides major support to existing theories that transverse MHD waves can be a signature of reconnection and the coronal reconnection scenario identified by nanojets. Additionally, we will also review the latest observations from the IRIS nanojet observing programme, which suggests that this phenomenon is more common than expected and that the reconnection process has an energy flux on the same order as the necessary AR energy balance requirements.

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Data-constrained magnetohydrodynamics simulations of the solar atmosphere using the Bifrost code

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Data-constrained magnetohydrodynamics (MHD) simulations initialised with magnetic field extrapolations based on photospheric magnetograms have been quite successful in capturing many aspects of energetic events in the solar corona, like flare reconnections and coronal mass ejections. On the other hand, radiative-MHD codes like Bifrost initialised with analytical inputs have provided very realistic simulations of the solar atmosphere by including the physics of non-equilibrium states and radiative transfer. This work aims at setting up data-constrained simulations with the Bifrost code to study energetic events in the solar corona. As a first step, we perform MHD simulations using the Bifrost code, with the bottom boundary set at the photosphere. This allows us to take high-resolution photospheric magnetograms from the Swedish Solar Telescope (SST) directly as input for the lower boundary. To fine-tune the code parameters, we perform two sets of simulations initialised with: (a) analytical non-force-free-field (NFFF) input having a sheared-arcade geometry, which is known to produce magnetic flux rope through reconnections in other MHD simulations, (b) magnetic field obtained from NFFF extrapolations based on a photospheric magnetogram observed from SST having a dipolar geometry. We show that in the analytical case we can reproduce the flux rope formation, while the NFFF-initiated case shows a self-consistent evolution which is comparable to the SST chromospheric observations. We thus conclude that NFFF-initiated MHD simulations based on photospheric magnetograms can be very helpful in understanding coronal dynamics and needs to be developed further.

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SOLAR-C Mission and Numerical Modeling of Flaring Plasma

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Understanding the solar atmosphere, which connects to the heliosphere via radiation, the solar wind and coronal mass ejections, and energetic particles is pivotal for establishing the conditions for life and habitability in the solar system. SOLAR-C (EUVST) (EUV High-Throughput Spectroscopic Telescope) is designed to comprehensively understand the energy and mass transfer from the solar surface to the solar corona and interplanetary space, and to investigate the elementary processes that take place universally in cosmic plasmas. In order to interpret the observation results obtained by Solar-C and to understand the physics process in more detail, comparison with advanced numerical simulations is considered very important. The SOLAR-C team plans to work systematically to facilitate comparisons with numerical simulations.
Numerical simulation efforts have some issues such as radiative transfer. In this talk we will discuss the modeling results of non-equilibrium ionization during solar flares and discuss the importance of non-equilibrium ionization in the interpretation of SOLAR-C observations. In particular, when estimating physical quantities in the magnetic reconnection region, we have assumed the ionization equilibrium so far. Since SOLAR-C can observe various emission lines at the same time, it is expected that analysis can be performed without assuming ionization equilibrium. We believe that these models are useful not only for interpreting solar observations, but also for interpreting other astronomical remote sensing observations.

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3D reconnection in solar flares and the hot flare emission

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The 3D extensions to the Standard model of solar flares have been succcessfull in explaining various observed phenomena. Among them, there are (1) hot cores (sigmoids), (2) apparent slipping motion of flare looops, (3) saddle-shaped flare arcades, as well as (4) reconnection of the drifting flux rope with the surrounding corona or itself during the eruption. We review the properties of the 3D reconnection geometries and focus on predicted future observables in the hot flare plasma and its dynamics, especially those that the present instrumentation is insufficient to capture.

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Modeling flare heating with turbulent thermal conduction

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During solar flares, the impulsive release of magnetic energy drives plasma heating, fast flows, and intense brightening across the spectrum. Current models of solar flares are able to accurately reproduce many key observables, including the speed of chromospheric evaporation flows, plasma densities and atomic line intensities. However, after the cessation of impulsive heating, the models predict time scales for slowing flows and cooling to quiescence that are an order of magnitude faster than observed. Such a discrepancy indicates missing ingredients in the models. As shown in recent work, turbulence suppresses thermal conduction and is a likely candidate for explaining long duration cooling times. Even more, turbulent velocities produce broadened atomic line profiles, which have been observed in numerous flares. Here we report on our recent work modeling the response of the solar atmosphere to flare heating including turbulent thermal conduction suppression and its effects on atomic line profiles. Comparing model predictions with observations of a C-class flare, we find a moderate amount of turbulence best reproduces observed velocities and line widths.

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Modelling of pre-eruptive magnetic structure: the need to get the electric currents right!

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To understand the trigger of solar flares and eruptions it is necessary to obtain an accurate description of the 3D pre-eruptive coronal magnetic configuration. The latter is not directly observable and one must rely either on static modelling/extrapolation from 2D photospheric measurements, and/or on relatively idealized time-evolution of a magnetic model from numerical simulations. The limitations of both approaches has not permitted to produce magnetic models sufficiently reliable to solve the eruption trigger issue.

Meanwhile, flares are characterized by brightenings in the Ultraviolet and X-ray domains. The distribution of these brightenings is not random, and are, according to the standard model for flares, tightly related to the magnetic field structure. Such a link has received strong confirmations by studies of the magnetic topology, which positively correlated the spatial distribution of UV and X-ray emission with magnetic structures.

Based on a detailed study of a confined circular flare, we will show how the flare emissions can provide a critical information in order to properly model the magnetic configuration and how it can help to have an insight on the trigger mechanism of flare. We will address how critical the measure of vertical electric currents is for the proper modelling of the magnetic field. We will finally discuss the hope that new high-resolution instruments as well as new observation strategies, and in particular stereoscopic magnetic field measurement with SolO/PHI, will provide key information such as fine flare dynamics and next-generation current distribution maps, for advance model of the eruptive magnetic system.

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Interrogating Solar Flare Models with IRIS Observations and Looking to the Future

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Solar flares are transient yet dramatic events in the atmospheres of the Sun, during which vast amounts of magnetic energy is liberated. This energy is subsequently transported through the solar atmosphere or into the heliosphere, and together with coronal mass ejections flares comprise a fundamental component of space weather. Thus, understanding the physical processes at play in flares is vital. That understanding often requires the use of forward modeling in order to predict the hydrodynamic and radiative response of the solar atmosphere. Those predictions must then be critiqued by observations to show
us where our models are missing ingredients. While flares are of course 3D phenomenon, simulating the flaring atmosphere including an accurate chromosphere with the required spatial scales in 3D is largely beyond current computational capabilities, and certainly performing parameter studies of energy transport mechanisms is not yet tractable in 3D. Therefore, field-aligned 1D loop models that can resolve the relevant scales have a crucial role to play in advancing our knowledge of flares. In recent years flare loop models have revealed many interesting features of flares. For this review I highlight some important results that illustrate the utility of attacking the problem of solar flares with a combination of high quality observations, and state-oft-the-art flare models, demonstrating: (1) how models help to interpret flare observations, (2) how those observations show us where we are missing physics from our models, and (3) how the ever increasing quality of solar observations drives model improvements.

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Modelling and observations: what is (still) needed to understand the role of magnetic fields in flares and eruptions?

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Solar flares are amongst the most energetic events in our solar system. Accompanied by intense UV and X-ray emissions, energetic particles and coronal mass ejections can be injected into the interplanetary medium during flares. As these various aspects can have a large impact on solar system bodies and a detrimental effect on human activities, there is a strong interest to gain a deeper knowledge of these events.

Over the past decades, ground and space solar observatories and the variety of observations available (from imaging to plasma and particle diagnostics and magnetic field measurements), aided by numerical modelling and theory, have helped us refine a standard model for eruptive flares. At the core of such a model lies the dynamical evolution of magnetic fields that shape and power them. In particular, understanding how flux ropes become unstable, where and how reconnection takes place (especially in complex 3D structures), has shed some light in the understanding of flare processes at large.

Because of the intrinsically transient nature of solar flares and the energy range covered by such events, some questions are still pending: where and how is the energy deposited, how the non local magnetic field topology actual shapes eruptions, how to join the various aspects of flares, from particles to CMEs? This talk will aim at looking at how previous works on flare models are still challenged by new observations, and what are the steps that are needed to continue working towards a (more) complete understanding of solar flares.

Flares and Eruptions / 15

Understanding the Physics of solar coronal jets and surges: Unified approach with high resolution observations and numerical modelling

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Solar coronal jets are observed as collimated plasma flows with high velocity along magnetic field lines in a wide wavelength range, from X-rays to EUV. Occasionally these hot jets are closely related to cool surges, which are chromospheric ejections that emerge in the form of unwrinkled threads. Though these phenomena have been studied over the past few decades with different instruments and models, their physical origin is still actively debated. To have a deeper understanding of the origin and driving of solar coronal jets, we analyze several jet and surge events with very high-resolution observations from the Swedish 1-m Solar Telescope (SST) and the Interface Region Imaging Spectrograph (IRIS). Deeper physical understanding is developed with the aid of radiative MHD models using the Bifrost code. The different data sets constrain the numerical models as they provide details on different aspects of the origin and propagation of jets at different heights from the photosphere to the corona. It is anticipated that the unprecedented capabilities of MUSE will provide new insights in the physics of solar coronal jets.

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The gaps in our understanding of flare energy release: prospects with MUSE and other observatories

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The overall paradigm of flare energy release is well-known. An energy-bearing coronal magnetic field relaxes via magnetic reconnection to a lower energy state, and the energy released is converted and dissipated in the radiation flash that is a solar flare. But what does that energy conversion and energy dissipation involve? There are strong and long-standing pointers to an important role for heating by non-thermal particles, but also observational hints that waves and turbulence have important roles. Furthermore, how is the energy release into the closed field of the lower corona - resulting in the flare - connected to the energy release into the wider corona that can result in a CME? Diagnosing waves and turbulence requires spectroscopic information, flares require high cadence particularly in their earliest phases, and probing the link to the early evolution of CMEs requires observation over a large field of view. MUSE can provide all of these in the EUV and, particularly when employed together with other facilities such as Solar-C and new ground-based observatories, is certain to fill many of the gaps in our understanding.

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Diagnosing Magnetic Reconnection and Energy Release from High-resolution Observations of Flare Ribbons

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Magnetic reconnection governing energy release in solar flares takes place in the corona; the lower atmosphere responds rapidly to energy transfer from the corona, generating prominent radiation and dynamic signatures that help us infer properties of energy release and transfer. Fine-scale structures embedded in the generally curvilinear-shaped flare ribbons indicate the global organization of patchy reconnection events, each of them manifesting a packet of energy release. Recent observations have revealed some intriguing evolution timescales of the radiation and dynamic signatures on flare ribbons, and efforts have been made to quantify the amount of energy released over these timescales in the packets of spatial scales up to the instruments' resolving capability. It has not been clear what determines these timescales, what is the magnetic structure of these packets, and what physical mechanisms convert free magnetic energy to particle or plasma energies during or after magnetic reconnection. Crucial connections between the coronal and chromospheric signatures can be clarified in future observations and advanced numerical models.

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Insights into Solar Flare Reconnection and Energetics from Novel Forms of High-resolution Observation and Modeling

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According to our current understanding, solar flares are driven by magnetic energy stored in the solar corona being rapidly released through a process involving magnetic reconnection. This scenario was originally proposed on the basis of classic observations including radio and hard X-ray emission from non-thermal electrons accompanying rising emission from hot thermal plasma. Over the past decade complementary observations have offered novel ways to constrain, quantify, and model, flare reconnection and the energy conversion it initiates. High-resolution studies of chromospheric flare ribbons, including their downward velocity (condensation), allow inference of the structure and evolution of coronal reconnection. Multi-band EUV imaging of the high-density, high-temperature plasma sheet formed around the current sheet shows the degree of heating and plasma compression which must accompany reconnection. Similar imaging shows flux tubes retracting through the sheets (SADs), pointing to the location and patchy nature of that reconnection. These myriad, novel observational constraints can be accommodated by a theoretical model in which magnetic energy is released as flux tubes retract through the current sheet following their creation by localized reconnection episodes. The measured, global rate of reconnection reflects their rate of production rather than the local electric field within one episode. Global flare properties, comparable to observation, can be reproduced by convolving the response to a single retraction with that production rate.

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Deciphering the evolution of pre-eruptive CMEs

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Coronal mass ejections (CMEs) are the largest scale eruptions of plasmas in the solar corona. Many observations show that pre-eruptive CMEs always appear as bright structures in EUV high-temperature bands and rise slowly when approaching the onset of their eruption. However, the mechanisms behind these phenomena are still puzzling. In this work, we aim to explore these by combining observations and numerical simulations. Based on the observation of an eruptive event, we find that a moderate magnetic reconnection, evidenced by the weak thermal-dominated hard X-ray emission, occurs at the center of an X-shaped plasma sheet before the eruption. This reconnection forms the hot M-shaped threads and cusp-shaped loops, the former of which merges with the pre-eruptive CME and contributes to its heating and slow rise. More details of the heating and the slow rise phenomena are revealed by performing a thermal 3D MHD simulation of a pre-eruptive CME by MPI-AMRVAC. It is shown that the Ohmic heating, which is related to a weak magnetic reconnection, mainly contributes to the heating in the hyperbolic flux tube (HFT) and quasi-separatrix layers wrapping around the pre-eruptive CME. The slow rise of the pre-eruptive CME is also mainly driven by the reconnection in the HFT. All of the above results give us a better understanding of how the pre-eruptive CME gradually transitions from the quasi-static state to the eruption.

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3D MHD of Flares & Eruptions

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We discuss the current state of MHD modeling of solar flares and eruptions. We focus on models that yield synthetic observables accessible to current and future generations of remote sensing capabilities, such as MUSE, EUVST and ground-based observatories. A critical assessment of the successes and limitations of current models with be presented, as well as suggestions for paths going forward.

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Understanding the formation of flare-productive active regions using realistic flux emergence simulations

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Solar active regions are thought to be formed by the emergence of magnetic flux from the deep convection zone and, therefore, it is important to use a large computational domain covering the entire convection zone to understand the physics behind. However, the high acoustic speed makes it difficult to conduct magnetohydrodynamic simulations in such a deep domain. The R2D2 code overcomes this difficulty by implementing the reduced sound of speed technique, which allows us to conduct the simulations of active region formation in a much more realistic way. In this presentation, we will discuss how the large-scale convections in the deep layers affect the flux emergence process and contribute to the formation of complex-shaped active regions, which are prone to produce massive solar flares and coronal mass ejections.

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MHD turbulence formation in solar flares: 3D simulation and synthetic observations

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Unresolved mass motions are frequently detected in flares from extreme ultraviolet (EUV) observations, which are often regarded as turbulence. Non-thermal broadening of EUV emission lines caused by turbulence can be found at the entire flare region including flare loop top, legs, footpoints and the region above the looptop. Peaks in non-thermal velocity values tend to show up above the high density flare loops, reaching 100-200 km s^−1, while footpoints have lower non-thermal velocities of a few tens km s^−1. However, how this turbulence forms during the flare is still largely a mystery. Using a three-dimensional (3D) magnetohydrodynamic (MHD) simulation, we demonstrate how turbulent motions widely distribute throughout a flaring region, and can originate from a single source. The turbulence forms as a result of an intricate non-linear interaction between the reconnection outflows and the magnetic arcades below the reconnection site, in which the shear-flow driven Kelvin-Helmholtz Instability (KHI) plays a key role for generating turbulent vortices. The turbulence is produced above high density flare loops, and then propagates to chromospheric footpoints along the magnetic field as Alfvénic perturbations. The simulated strength and spatial distribution of the volume-filling turbulent motions show excellent agreement with observational results as revealed by synthetic views in EUV and by fitted Hinode-EIS spectra.

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Some long-standing puzzles regarding the dynamics of the solar chromosphere

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This presentation reviews several unresolved, puzzling observational findings concerning the dynamics of the solar chromosphere dating as far back as the 80s and 90s. Among these are the very high apparent phase speeds in the chromosphere (vanishing phase differences of high-frequency waves between chromospheric lines with supposedly vastly different formation heights such as Ca IR, Ca K, H α, He 10830), surprisingly low RMS values in He 10830 and UV lines formed in the chromosphere, and the lack of clear shock wave signatures in those lines. Can the new 3D radiation hydrodynamic simulations and/or the new high-resolution observations shed new light on these long-standing questions?

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The MHD modelling of streamer waves and its consistency with the observations

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The present work investigates solar coronal dynamics, in particular streamer waves. Recent observations combined with advanced numerical tools allow to gain insight into the nature of the coronal streamers and their oscillations. The numerical model for the streamer waves was constructed with the MPI-AMRVAC code in the framework of 2.5D ideal magnetohydrodynamics. We performed a parameter study to identify the sensitivity of the streamer dynamics to the background solar wind speed, spatial characteristics and strength of the excited perturbation and the input parameters for the model such as temperature and magnetic field. This allowed to investigate the theoretical concepts of the streamer waves physics and properties (such as wave mode identification) and to complement the statistical analysis of these events in order to perform streamer seismology. Following the numerical study, in the present work we investigate the consistency of the synthetic and the observational data. To this end, we have developed a tool to compute white light images of simulation snapshots. These are of special interest for the high-resolution white-light images from the METIS (SolO) and WISPR (PSP) instruments, which allow more detailed comparison. The present work aims to investigate the quality of numerical reproduction of the streamer waves phenomena and the prospects of advancing the numerical model based on observations.

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Hot Prograde Flows in Active Regions

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The EVE Sun-as-a-star Doppler information has produced a surprising result: hot active-region loops sustain steady flows on the order of 100 km/s. The flows only occur at the higher temperatures (lines of Mg XII and Fe XIV, for example), making the observation very differential and redundant. Both of the EVE spectrographs (MEGS-A and MEGS-B) show the effect. The flows are invariably in the prograde sense (E limb blue, W limb red), independent of latitude or solar cycle.
EVE detects the flows directly by the bulk Doppler shift of lines from isolated limb regions, and also systematically via cross-correlation of AIA image centroids with EVE Doppler shifts.

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Acoustic-gravity wave propagation characteristics in 3D radiation hydrodynamic simulations of the solar atmosphere

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There has been tremendous progress in the degree of realism of three-dimensional radiation magneto-hydrodynamic simulations of the solar atmosphere in the past decades. Four of the most frequently used numerical codes are Bifrost, CO5BOLD, MANCHA3D, and MURaM. Here we test and compare the wave propagation characteristics in model runs from these codes by measuring the dispersion relation of acoustic-gravity waves at various heights. An earlier study (https://doi.org/10.1098/rsta.2020.0170) used model runs with vastly differing setups (box size, cell size, cadence, duration, radiative transfer, average magnetic field strength). Here we compare model runs with an identical setup. There is much better agreement between the different models now than in the previous study, although there are still considerable differences in certain aspects. The cause of the high-frequency phase ridges in the convection zone is now understood. They result from standing waves in a cavity between the lower boundary and the bottom of the photosphere.

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Characteristics of accelerated particles in the solar atmosphere

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Solar flares evolve on multiple scales and cannot be explained or simulated without considering the effects of accelerated particles. The particles reach non–thermal velocities due to the release of magnetic energy through magnetic reconnection, and they are observed through hard X-ray emission and ultraviolet radiation produced in flare ribbons. However, the key processes behind the acceleration is heavily debated and the observed signatures point towards an energy distribution which varies significantly from flare to flare. We are embedding trace particles in realistic solar reconnection environments to study the characteristics of particle acceleration and investigate how large scale conditions affect the energy distribution. MHD simulations provide the solar environments and the trace particle motion is simplified by using the gyrocentre approximation.

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Prominence diagnostics from IRIS Mg II, MSDP Hα and ALMA observations using NLTE radiative transfer modelling

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Multiwavelength co-temporal observations of solar prominences are still rare, even if many space and ground-based observatories and techniques are available. In April 19, 2018 a quiescent prominence with fine structures was observed with IRIS, ALMA (band 3) and in Hα line with Wroclaw MSDP (Multichannel Subtractive Double Pass) spectrograph. Both UV and Hα data contains spectra which makes the available dataset extremely valuable. IRIS and MSDP provided 2D spectral maps, which together with ALMA T_b maps and NLTE (i.e., departures from Local Thermodynamic Equilibrium) techniques gives an unprecedented opportunity for a novel diagnostic, not available so far.

In this work we present analysis of the prominence spectral characteristics in Mg II h & k and Hα lines, looking for the statistical dependence between different parameters (metrics) in these line profiles. These combined data are also used for determination of plasma parameters in the prominence fine structures. Detailed diagnostics is based on extensive NLTE numerical simulations of the radiative transfer inside fine prominence structures. For model determination we use both the large grid of 1D-slab prominence models in NLTE computed with Multilevel Accelerated Lambda Iteration (MALI) techniques and 2D NLTE multithread models that take into account the prominence-corona transition region (PCTR) with the temperature increasing and pressure decreasing from the cool prominence core toward the surrounding coronal environment. Moreover, IRIS and MSDP spectral maps are compared with the brightness temperature mosaics from ALMA, providing an additional constraint on the plasma kinetic temperature.

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Solar jets: SDO and IRIS observations in the perspective of new MHD simulations

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Solar jets are observed as collimated plasma beams over a large range of temperatures and wavelengths. They have been observed in Hα and optical lines for more than 50 years and called surges. The term "jet" comes from X-ray observations after the launch of the Yohkoh satellite in 1991. They are the means of transporting energy through the heliosphere and participate to the corona heating and the acceleration of solar wind. Several characteristics have been derived about their velocities, their rates of occurrence, and their relationship with CMEs. However, the initiation mechanism of jets, e.g. emerging flux, flux cancellation, or twist, is still debated.
In the last decade coordinated observations of the Interface Region Imaging Spectrograph (IRIS) with the instruments on board the Solar Dynamic Observatory (SDO) allow to make a step forward for understanding the trigger of jets and the relationship between hot jets and cool surges. We observe at the same time the development of 2D and 3D MHD numerical simulations to interpret the results. We review a few jet studies based on IRIS spectra and SDO observations and show that with the same observations, different theoretical interpretations are possible based on different approaches, e.g. cartoons, non-linear force-free field extrapolation, 3D MHD data driven simulations.

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The solar PolArization and Directivity X-Ray Experiment (PADRE)

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Solar flares are known to accelerate electrons to high energies efficiently. However, how the underlying acceleration mechanisms work remains poorly understood. The angular distribution of the accelerated electrons, the resultant hard X-ray emission, and its polarization and directional anisotropy are key to solving this mystery. The solar PolArization and Directivity X-Ray Experiment (PADRE) is a 12U Cubesat observatory developed to solve this mystery. PADRE will investigate the accelerated electron angular distribution in solar flares with two complementary approaches (1) by making spatially-integrated spectro-polarimetric X-ray measurements (~10-100 keV) and (2) by coordinating with Solar Orbiter/STIX to make the first two-point measurements of X-rays and determining their directivity. We present the PADRE observatory concept, its science objectives, design, and updates. We will discuss the observations its two instruments (SHARP and MeDDEA) will make.

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Studies on porting the Bifrost legacy code to GPUs

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With the imminent exascale era, many legacy codes face a variety of challenges to become portable to GPU machines, like LUMI. We would like to give an overview on the status of Bifrost physics capabilities supported on GPUs and possible applications. We will share our experiences so far in exploring portability with directives approaches while using different compilers and architectures.

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Signatures of nanoflare heating in a 3D Bifrost simulation

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The solar corona is continuously studied through observations and numerical modelling due to its extreme temperatures. One of the prime candidates in understanding these temperatures is nanoflares, which are small-scale events associated with magnetic reconnection in the solar atmosphere. Observations of small-scale events with nanoflare energies are rare because signatures from non-thermal electrons are typically below the detection threshold. We investigate signatures in synthetic observables that arise from non-thermal electrons accelerated by magnetic reconnection in a 3D Bifrost simulation. Our analysis includes the transition region (TR) Si IV lines and the upper chromospheric Mg II h and k lines, which can be observed by space-based telescopes (e.g., IRIS). We also include the Ca II H and K and Ca II 854.2 nm lines that form deeper in the atmosphere and are readily accessible by ground-based telescopes (e.g., SST, DKIST). Our goal is to explore the impact of nanoflare events on the synthetic spectra and investigate the diagnostic potential of TR and chromospheric emission from small-scale events.

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A light bridge crossing the atmosphere

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Light bridges, as seen in photospheric layers, are irregular, bright, and elongated structures that cross the umbra during the formation and decay of sunspots or pores. They play an important role in our understanding of the evolutionary stages of sunspots as they can indicate the break-up of sunspots in the decay or the formation phases of complex active regions. These structures have been extensively studied in the photosphere with full spectropolarimetric data. From these works we have good knowledge of light bridges topology and thermodynamic properties at lower atmospheric layers but its physics higher up in the solar atmosphere as well as the impact of these highly dynamic structures in the energetics above their hosting sunspots is scarce.

Currently, we are in a very good moment to make a deep study of light bridges. On the one hand, the development of (relatively-)new instrumentation as IRIS satellite or CRISP and CHROMIS instruments, both installed at the SST. On the other hand, the development of inversion codes as the STiC upgrade that includes the multi-instruments/multi-resolution effects allow us the most accurate inference when observing with several instruments at the same time.

In this talk, we present the characterization of a light bridge observed with the SST and IRIS instrumentation covering the photosphere, chromosphere, and transition region with full-spectropolarimetry and spectroscopy. This allows us to study the thermal and magnetic connectivity of this structure throughout these layers as well as its impact in the energetics of the sunspot higher layers.

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Artificial observations of the Sun – The scientific potential of optimizing future solar observatories

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The *Atacama Large Millimeter/submillimeter Array* (ALMA) offers new diagnostic capabilities that complement other commonly used diagnostics for exploring our Sun. In particular, ALMA's abilities as an essentially linear thermometer of the chromospheric gas at unprecedented spatial resolution at mm wavelengths and future polarization measurements have great scientific potential. In concert with current and future ground-based and space-borne observatories, ALMA will thus certainly significantly contribute to answering long-standing questions about the structure, dynamics and energy balance of the outer layers of the solar atmosphere. In this context, ALMA data are also important for constraining and further developing numerical models of the solar atmosphere, which in turn are often crucial for the interpretation of observations.
Given the highly intermittent and dynamic nature of the solar chromosphere, realistic forward modeling requires time-dependent three-dimensional radiative magnetohydrodynamics that account for non-equilibrium effects and, typically as a separate step, detailed radiative transport calculations leading to synthetic observables that can be compared to observations. Additionally accounting for instrumental and seeing effects further aids the interpretation of observations and allows for designing and optimizing observing and post-processing strategies. The resulting scientific gain is demonstrated here using the example of the Solar ALMA Simulator (SASim). Applications of this approach to potential mm and radio observations with future facilities such as FASR and AtLAST are highlighted and the transfer of possible findings to the optimization of observations at shorter wavelengths (e.g., with MUSE or IRIS) are outlined.

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Dynamic formation of multi-threaded prominences with fine structure

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Prominences are large-scale structures found in the solar corona, characterized by two orders of magnitude larger densities and lower temperatures than their surroundings. On a large scale they are relatively stable structures, closer-up they exhibit intricate and complex dynamics with small-scale structures [1]. Prominences form via thermal instability, an in-situ condensation process that is triggered by plasma evaporation from the chromosphere. Prominence plasma offers us information on the processes within coronal heating, in addition to thermal-nonequilibrium cycles and instabilities within the corona (from thermal to Kelvin-Helmholtz and Rayleigh-Taylor) all of it relating to mass and energy circulation throughout the Sun's atmosphere. In this work, we use an open-source MHD code, MPI-AMRVAC [2] (http://amrvac.org/) to simulate the localized stochastic heating. The parameter space related to the stochastic heating needed to trigger thermal instability is broad [3] and still largely unexplored, particularly in multidimensional setups. We describe how varying the amplitude and height of such heating heavily influences the topology of the resulting prominences, most crucially their average density and temperature properties [4]. This has a critical influence on the appearance of these simulated structures in observations; we will explore corresponding Hydrogen spectrum variations according to the non-LTE problem. Finally, we demonstrate how the shear flows present throughout this inhomogeneous domain generate signatures of the Kelvin-Helmholtz instability within realistic and dynamically formed prominence threads [4]. Our efforts, including the ongoing migration to additional dimensions and higher resolution, are continuing to bring each aforementioned aspect yet closer to direct confrontations with observations.

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Investigating Chromospheric Holes in the Millimeter Continuum

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Studies of the solar chromosphere are an important component of our understanding of heating and energy transfer in the solar atmosphere — however, the predominance of non-equilibrium and non-LTE physics there complicates numerical simulation of this region. In contrast, the millimeter continuum serves as a "linear thermometer" of the chromosphere, allowing it to serve as a crucial observational constraint on such models.

Recent high-resolution observations of the Sun at 1.3 mm and 3 mm from the Atacama Large Millimeter Array (ALMA) have shown the presence of extended, long-lived cold regions termed *chromospheric holes.* While an archival study of ALMA data shows that these regions appear predominantly in magnetically active regions of the chromosphere, the mechanism of their formation is currently unknown.

To study the formation and evolution of these chromospheric holes, we present new observations of the quiet and active Sun at 1.3 mm and 0.9 mm, which represent the first high-resolution observations of the sub-millimeter Sun with ALMA. Additionally, simultaneous observations of these regions in the 4.7 um molecular band of carbon monoxide are used to constrain the formation height of the holes seen at 1.3 mm. Lastly, we compare the observed chromospheric holes to similar features seen in numerical simulations of the chromosphere, and discuss how high-resolution ALMA observations can be used to constrain magneto-hydrodynamic modeling of the chromosphere.

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Towards Realistic Solar Flare Models

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Solar flares release magnetic energy in reconnection events heating the atmosphere in the process. Solar flares are inherently multi-scale; The entire flare may stretch Mm scales and evolve on timescales of hours, while the reconnection region is far smaller, on the order of particle mean free path, and may have timescales of just a few seconds. The small scales break the fluid description (MHD) which is commonly used to model the solar atmosphere. To accurately model reconnection events a kinetic approach such as PIC is needed. PIC solvers are far more computationally demanding than MHD and modeling an entire flare with a kinetic approach is not feasible.

There are undoubtedly feedback effects between small and large scales. These effects are poorly understood as the resolution from observations is far too poor and currently, no simulation has resolved both small and large scales. The high-resolution, high cadence spectrograph observations available with SST/IRIS (and the extraordinary observational capabilities of MUSE in the future) combined with multi-scale simulations may offer new insights into these effects. Here we present the first steps towards an integrated solution where PIC and MHD solvers run concurrently in different parts of the computational domain. The ultimate goal is to model a solar flare and the surrounding corona in a realistic 3D simulation.

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Comprehensive simulations of solar prominences with MURaM

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Solar prominences consist of cool and dense plasma that is suspended in the corona, surrounded by hotter and less dense coronal material. As predecessors of coronal mass ejections, solar prominences are important drivers of space weather, but their exact formation mechanism is still unknown. We use the radiative magnetohydrodynamic code MURaM to simulate the formation and dynamics of prominences in the solar atmosphere. MURaM includes the relevant physical processes to realistically simulate the solar photosphere, chromosphere and corona.

By fixing bottom boundary conditions for the magnetic field, we create a stable dipped magnetic field configuration in a 3D box of 80 x 30 x 10 Mm in size and let it evolve. In the course of the simulation, a dense plasma seed ejected from the chromosphere settles into a magnetic dip and is cooled by radiative losses. The resulting pressure drop drives a strong flow of plasma into the feature and builds up a cool, long-lasting structure in the solar corona. This prominence is very dynamic but stable due to the stability of the underlying magnetic field. Its structure and dynamics are comparable to certain observations of real prominences. In this talk, we present the formation mechanism in our simulation and show how different radiative treatments influence the properties of the simulated prominence.

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Observation of EUV dynamic fibrils with Solar Orbiter and IRIS

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Detection of dynamic fibrils (DFs) in coronal images had been a difficult task so far, primarily due to their small size and the lower spatial resolution of the current EUV imagers. In this talk, I will present the first unambiguous detection of DFs in coronal EUV data using high-resolution images from the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter. Using the EUI 174 Å data, we find many bright dot-like features (of size 0.3-0.5 Mm) that move up and down (often repeatedly) in the core of an active region and produce parabolic tracks in a space-time map, akin to the chromospheric observations of DFs. Properties such as their speeds, lifetime, deceleration and lengths are also reminiscent of the chromospheric DFs. All this evidence strongly suggests that these bright EUV dots are basically hot tips of the cooler chromospheric DFs. Additionally, we observe that DFs located close to a sunspot exhibit higher speeds and stronger deceleration as compared to DFs that emerge from moss-type regions. Interestingly, not all of these differences are similar in nature to that of their chromospheric counterparts and therefore, our results pose new questions regarding the complex interplay between the driving mechanism of DFs, their magnetic field topology and their coronal counterparts. I will further discuss their evolutionary scenarios in corona (1 MK plasma) and transition region (0.1 MK plasma) using co-observations with IRIS and put those results in the context of the recent MHD modeling of DFs.

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On the onset of small-scale transients

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Solar transients exhibit different length, time and energy scales. Especially, the high-resolution observation facilities are drawing attention to the small scale transients for their possible roles in heating the atmosphere. However the onset of these events is not clearly understood. Here, we have taken a combined approach of observation and numerical studies to understand the triggering process. We have used the data of AIA/SDO, XSM/Chandrayaan-2 and IRIS who captured these small events (intermittent hot/cool loop systems, micro/nano-flares). To explore the underlying magnetic topology/properties, we have extrapolated the photospheric magnetic field using HMI/SDO. For this purpose, we have utilized the non-force-free-field (NFFF) extrapolation model. In this model, the bottom boundary possesses a non-zero Lorentz force which decays over height to give a nearly force-free region as per the usual trend seen in solar corona. Energy estimates highlight the role of flux cancellation in powering such events. Again, from the extrapolation we found a series of small connectivities collocating the multi-thermal loop systems seen in the observation. These field lines can interact with each other and reconnect component wise at a higher height attributing to the heating of the loop systems or triggering the small scale flares.

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Augmenting Bifrost code capabilities with Dispatch framework

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For over a decade, the Bifrost code has established itself as a capable tool for simulating stellar atmospheres. Many scientific projects benefitted from Bifrost's detailed numerical models of the chromosphere and corona in the quiet Sun. Although it is a very optimized code, its time integration method, which uses global time stepping, makes it prohibitively expensive to run an experiment with very large FOV and boundaries set deep in the convective zone and high corona at the same time. Both conditions are necessary to model an active Sun with the details Bifrost is famous for.

To address this bottleneck, we embedded Bifrost in the Dispatch, a hybrid MPI/OpenMP high-performance simulation framework that uses local time steps for each small sub-domain and its parallelism depends only on nearest-neighbor MPI communications, which gives theoretically unlimited scaling.

This work compares legacy Bifrost simulations and newer models run with Dispatch/Bifrost. We will also expand on performance differences and the challenges we encounter during porting Bifrost to the Dispatch framework.

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Modeling Mg II h&k in an enhanced network region simulated with MURaM

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Current models of the solar atmosphere involve a comprehensive set of physics including the treatment of magnetic fields, heat conduction and radiative transfer (RT). Forward models that simulate the different layers of the solar atmosphere self consistently open the door to study the most complicated layers of the atmosphere that are subject to non local thermal equilibrium (NLTE) and non equilibrium (NE) processes such as the chromosphere. The resulting spectra of such models, that are obtained using RT codes, show significant discrepancies from the observations. In particular, chromospheric spectral lines such Mg II h&k have typically too narrow line widths and different peak asymmetry ratios in the models compared to observations of quiet sun regions. In this work, we use the recently developed radiative MHD code MURaM to simulate an enhanced network (EN) region. We discuss the resulting spectra that are obtained using 1D and 3D radiative transfer computations. From the 1D computations, we find that compared to previous models, the line widths as well as the peak separations of Mg II h&k in our MURaM simulations are on average larger. We discuss comparisons of spatial averages as well as in bins of regions that have similar magnetic flux. In addition we discuss 3D effects calculated using the RT code Multi3D.

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Prominence dynamics induced by a distant eruption

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Prominence oscillations are commonly known for their use in prominence seismology when the plasma and magnetic field properties are derived from the oscillatory properties such as periods, damping, and times. However, how the oscillations are induced in those dense and cold structures remains unclear. Observations from SDO/AIA, SMART showed the activations with the incoming waves, which could affect global prominence configurations. These waves were produced by eruptive events. In this study, we aim to obtain a full understanding of how the flux rope eruption generates disturbances and how the energy of those is trapped and induces prominence oscillations. We perform a 2.5D numerical experiment with MHD code MPI-AMRVAC using the magnetic field structure of two dipoles nested in gravitationally stratified corona. The converging and shearing footpoints motions serve for stable and eruptive flux rope formation. Since we include radiative cooling, background heating, and thermal conductivity, we form the prominence according to a levitation-condensation scenario: the denser plasma is levitated by the rising flux rope and condensed due to the thermal instability, which develops when background heating and thermal conduction cannot balance the radiative losses. We find that the eruption produces an energetic wave that reaches a distant prominence affecting its global configuration and triggering motions. Overall, the prominence dynamics are complex, showing a mixture of the oscillation of the different polarizations with respect to the magnetic field. We obtained the synthetic views, which show many details that may be important for future high-resolution observations.

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Properties of shock waves in the quiet Sun chromosphere

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Short-lived (100s or less), sub-arcsec to a couple of arcsec sized features of enhanced brightenings in the narrowband images at the $\mathrm{H_{2V}}$ and $\mathrm{K_{2V}}$ positions of the Ca II H&K lines in the quiet Sun are known as bright grains. These bright grains are interpreted as manifestations of acoustic shock waves in the chromosphere. Using simulations, earlier studies have shown that upward propagating acoustic waves from the lower atmosphere turn into shocks in the chromosphere due to a drop in the gas density by several orders of magnitude. Earlier observational studies to quantify temperature enhancements and line-of-sight (LOS) velocities had limitations like limited spatial resolution and less optimal assumptions like local thermodynamic equilibrium (LTE). In this study, using the highest known spatial and spectral resolution observations of grains acquired from the CHROMIS and CRISP instruments of the SST, we have inferred the time-varying stratified atmospheric properties using a non-LTE inversion code. The Ca II K profiles of bright grains show enhancement in the $\mathrm{K_{2V}}$ peak intensities with the absence of the $\mathrm{K_{2R}}$ features. We found average enhancements in temperature at lower chromospheric layers (at $\log \tau_{500} \simeq -4.2$) of about 1.1 kK with a maximum enhancement of $\simeq 4.5$ kK. These temperature enhancements are co-located with upflows, as strong as -6 km s^{-1}. The LOS velocities at upper chromospheric layers at $\log \tau_{500} < -4.2$ show consistent downflows greater than $+8$ km s^{-1}. This study provides observational evidence to support the interpretation that the bright grains are manifestations of upward propagating acoustic shocks against a background of downflowing atmospheres.

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Global MHD simulations of the solar convective zone using a volleyball mesh decomposition

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In this contribution I present our first results from global MHD simulations of the Solar convective region using DISPATCH framework. The simulation spans 0.655 - 0.995 of the solar radius, over the entire surface using Cartesian patches, arranged in a Volleyball decomposition.
I present the current status and future outlook.

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Hot Plasma Flows and Oscillations in the Flare Loop-top Region: Observations and Modeling

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In this study, we investigate motions in the hot plasma in the above-the-loop-top (ALT) region during the 2017 September 10 X8.2 flare event. We examine the region to the south of the main flare arcade, where there is data from the Interface Region Imaging Spectrograph (IRIS) and the Extreme ultraviolet Imaging Spectrometer (EIS) on Hinode. We find that there are initial blueshifts of 20−60 km/s observed in this region in the Fe XXI line in IRIS and the Fe XXIV line in EIS, and that the locations of these blueshifts move southward along the arcade over the course of about 10 minutes. The cadence of IRIS allows us to follow the evolution of these flows, and we find that at each location where there is an initial blueshift in the Fe XXI line, there are damped oscillations in the Doppler velocity with periods of ~400 s. We use MHD simulations to investigate the possible sources of these oscillations. The reconnection outflows in the simulations impinge on the loops below, creating a "magnetic tuning fork", i.e. horn-shaped magnetic field lines that oscillate due to the rebounding reconnection outflow, creating magnetoacoustic waves. Simulations show a rapid growth of MHD instabilities around the upper parts of the ALT region (the arms of the magnetic tuning fork). Despite the presence of turbulent flows, the ALT region shows a coherent oscillation driven by the backflow of the reconnection jet, as in the observations.

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Multiwavelength Analysis of the 2021 October 28 X1.0 Solar Flare

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Solar eruptive phenomena are often associated with a variety of radio bursts observed from metric to kilometric wavelengths. Type II and type III bursts are both generated via the plasma emission mechanism, when beams of relativistic electrons interact with ambient plasma producing radio emissions at the local plasma frequency or its first harmonic. Here, we analyze a unique multi-spacecraft observation of the 2021 October 28 event when Solar Orbiter, Parker Solar Probe, STEREO-A, and Wind detected a very intense complex radio burst associated with the X-flare. We complement space-based radio data with ground-based radio measurements. We correlated the locations and onset times of radio emissions with EUV images (SDO/AIA), and X-ray data (Solar Orbiter/STIX). We discuss how current radio observations from multiple spacecraft can be used to identify the solar origin of the electron events.

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Spinning spicule bunches and their connection to solar corona - An insight by means of 3D simulations and solar observations

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Spicules are one of the most intriguing phenomena of the lower solar atmosphere. In spite of decades of research, they remain mysterious. From our initial work on how solar p-modes may generate spicules (Nat. 2004), through showing the formation of a forest of them using radial MHD simulations (Nat. Phys. 2022), finally we are able to report a more unified theory of spicular physics, underpinned with solar observational confirmation. First, bringing together SDO and IRIS observations, numerical simulations of the Sun (from convective zone to low corona) and laboratory fluid dynamics experiments we unveil insights into the mechanism underlying the ubiquity of jets: the nonlinear focusing of quasi-periodic waves in anisotropic media of magnetized plasma as well as polymeric fluids under gravity is sufficient to generate a forest of spicules on the Sun.

Next, using Hinode BFI data together with 3D rMHD simulations, we successfully capture the observed rotation amongst clusters of spicules. We show how this occasional swirly spicular motion is linked to hot rotating plasma columns – that we label as coronal swirling conduits (CoSCo). The spicules themselves appear as folds of drapery made of dense and cool plasma, in the upper solar atmosphere. A particular class of tall CoSCos seen in our simulations can potentially form by feeding on spicules and channeling this energy to the upper reaches of the solar atmosphere.

Finally, we propose, how with DKIST data the next step may be made in this context.

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A Model for Gradual Phase Heating Driven by MHD Turbulence in Solar Flares

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Coronal flare emission is commonly observed to decay on timescales longer than one-dimensional flare loop models typically predict. This discrepancy is most apparent during the gradual phase, where emission from impulsively driven models decays over minutes, in contrast to the hour or more often observed. Magnetic reconnection is invoked as the energy source of a flare, but should deposit energy into a given loop within a matter of seconds. Models supplementing this impulsive energization with a prolonged, persistent *ad-hoc* heating have successfully reproduced long-duration emission, but without providing a clear physical justification. Here we propose a model for extended flare heating by the slow dissipation of turbulent Alfvén waves initiated during the retraction of newly-reconnected flux tubes through a current sheet. Using one-dimensional simulations, we track the production and evolution of MHD wave turbulence trapped by reflection from high-density gradients in the transition region. Turbulent energy dissipates through non-linear interaction between counter-propagating waves, modeled here using a phenomenological one-point closure model. AIA EUV light curves synthesized from the simulation reproduced emission decay on the order of tens of minutes. Moreover, turbulent broadening of synthetic high-temperature spectral lines decreased naturally in approximately 15-minutes, further corroborating separate spectroscopic observations. We find this simple model offers a possible mechanism for generating the extended heating demanded by observed coronal flare emissions self-consistently from reconnection-powered flare energy release.

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Thermally enhanced tearing in solar current sheets: Explosive reconnection with plasmoid-trapped condensations

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Thermal instability plays a major role in condensation phenomena in the solar corona, e.g. for coronal rain and prominence formation. In flare-relevant current sheets, tearing instability may trigger explosive reconnection and plasmoid formation. However, how both instabilities influence the disruption of current concentrations in the solar corona has received less attention to date. We incorporate the non-adiabatic effects of optically thin radiative energy loss and background heating, and use a resistive magnetohydrodynamic simulation of a 2D current layer to explore how the thermal and tearing modes reinforce each other. We find that the current sheet fragments through an explosive reconnection process, characterized by the formation of plasmoids which interact and trap condensing plasma. Our parametric survey explores different resistivities and plasma-beta to quantify the instability growth rate in the linear and nonlinear regimes. We notice that for dimensionless resistivity values within $10^{-4} - 5 \times 10^{-3}$, we get explosive behavior. We calculate the mean growth rates for the linear and different non-linear phases of the evolution. We note that the formation of plasmoids is noticed for the Lundquist number range between $4.6 \times 10^3 - 2.34 \times 10^5$. We quantify the temporal variation of the plasmoid numbers and the density filling factor of the plasmoids for different physical conditions. I will also discuss about the ongoing work of our more realistic 3D model of the thermally influenced tearing mode instability, where the localized cool condensations gather, realizing density and temperature contrasts similar to coronal rain or prominences.

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Wave properties in footpoints of coronal loops as a result of an inclined acoustic-gravity wave driver in 3D MHD simulations

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There is strong evidence that the energy required to heat the solar chromosphere and corona may be caused by the strong magnetic field interacting with convective motions from the photosphere. Acoustic-gravity waves, or "p-modes", are resonant modes of the solar interior driven by pressure gradients and are known to leak into the solar atmosphere. It is thought that these p-modes may be guided by magnetic flux bundles in the solar atmosphere and convert to MHD tube waves which can then transport energy to the upper atmospheric layers. Using 3D MHD numerical simulations, we model a straight, expanding coronal loop as a magnetic field enhancement in a gravitationally stratified solar atmosphere which includes a transition region and chromosphere. We implement a driver at one footpoint modeled by an acoustic-gravity wave which is slightly inclined with respect to the vertical axis. We aim to analyse how the, initially acoustic wave energy flux, may be converted into magnetic energy and, if so, in what form. To do this, we calculate the ratio of acoustic to magnetic flux and compare this against an analytical conversion factor. As a result of the cylindrical domain, eigenmodes of a magnetic cylinder are excited and we show that the kink mode may be guided by the loop, as a result of the inclined driver breaking the azimuthal symmetry of the system. We discuss the resulting wave dynamics, energetics and potential observable features, including the transverse velocities and density perturbations at the loop apex, due to the driver implemented.

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Investigating transition region explosive events in a quiet-Sun model

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Explosive events are characterized by non-Gaussian profiles of the emission lines formed in the transition region. Traditionally, the spectra from explosive events with enhanced wings have been explained by reconnection of oppositely directed magnetic field. We used a 3D radiation MHD model to investigate if this 2D picture also holds in a more realistic setup of a quiet Sun simulation. For this, we located profiles of Si IV synthesized from the model that show signatures of bi-directional flows. The events we identified by this are consistent with observed explosive events in that they are clustered around the edges of the network and are (mostly) not heated to coronal temperatures. We examined the magnetic field structure in and around some of these explosive events and find that the majority of these does not show oppositely directed magnetic field that is reconnecting. Instead, mostly the field lines reconnect at small angles, i.e., they undergo component reconnection. Even though these explosive events do not reach coronal temperatures, they share the same magnetic setup as we found before for transient coronal brightenings, sometime referred to as campfires. This could imply that the only major difference between an explosive event and a campfire is the amount of converted magnetic energy and the density in the reconnection region. Still, we will further explore the current simulation and new models with more flux emergence and cancellation to investigate if our current results also hold in a more general setup.

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A statistical study of flare ribbon spatial evolution with IRIS

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Due to the magnetic connectivity between the flaring current sheet and magnetic footpoints, flare ribbon behavior must reflect current sheet processes at flare onset. In recent years, attention has turned to the role of the tearing mode instability in breaking down the current sheet at flare onset. The instability allows energy release to accelerate via the reconnection of progressively smaller magnetic island structures, theorized to produce a rate of energy release close that observed in solar flares. In French et al 2021, IRIS 1.7 second cadence slit-jaw observations of a small B-class flare were analyzed to explore the timing and growth rates of spatial scales along flare ribbons. The initialization of exponential growth from a specific spatial scale to all spatial scales was indicative of the tearing-mode instability, and power laws in the spatial domain matched those predicted by simulation work of the tearing-mode induced plasma turbulence. The analysis, however, was just for one small, confined flare. In this work, we expand this methodology of French et al 2021 for a wider selection of eruptive and non-eruptive solar flares, ranging in size and complexity. We utilize high-cadence IRIS SJI observations of the ribbons, (with spectra when available), and compare the behavior of spatial scales along/across the ribbons with simulations of magnetic reconnection, to shed further light on the role of plasma instabilities during the onset of flares and eruptive events. Included in the flare list are observations from the new IRIS sub-second observing program.

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Formation of the IRIS OI and CI lines in a flare

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The OI 135.56 nm line and CI 135.58 nm line are weak lines that are covered by NASA's Interface Region Imaging Spectrograph (IRIS) mission which studies how the solar atmosphere is energized. The emission in the OI 135.56 nm line is dominated by a recombination cascade. This line provides powerful diagnostics of unresolved velocity fields in the chromosphere. In this work, we study the formation of the OI and CI lines in a 1D RADYN simulation of a flare. We use the radiative transfer code RH to get a non-LTE solution with hydrogen, carbon, and oxygen solved simultaneously. We find that the OI line is optically thin and the CI line is optically thick. Normally, the oxygen line is stronger than the carbon line but in flares, the ratio is opposite. Our results show that the intensity of the OI line peaks before the intensity of the CI line. We find that as the electron density increases in the flare, the collisional rates between other levels increase, causing a less increase in the radiative rates corresponding to the OI line. For carbon, as the electron density increases, there is more coupling between the source function and the Planck function, and the intensity of the CI line peaks.

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Multi-fluid generalization of the Braginskii model

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Confronting numerical simulations with observational studies
is necessarily based on an underlying theoretical description, which describes the dominant physical processes that are being numerically simulated and observationally analyzed. We consider several generalizations of the well-known fluid model of Braginskii (1965). We use the Landau collisional operator and the moment method of Grad. We focus on the 21-moment model that is analogous to the Braginskii model, and we also consider a 22-moment model. Both models are formulated for general multi-species plasmas with arbitrary masses and temperatures, where all the fluid moments are described by their evolution equations. The 21-moment model contains two "heat flux vectors" (3rd and 5th-order moments) and two "viscosity-tensors" (2nd and 4th-order moments). The Braginskii model is then obtained as a particular case of a one ion-electron plasma with similar temperatures, with de-coupled heat fluxes and viscosity-tensors expressed in a quasi-static approximation. We provide all the numerical values of the Braginskii model in a fully analytic form (together with the 4th and 5th-order moments). For multi-species plasmas, the model makes calculation of transport coefficients straightforward. Formulation in fluid moments (instead of Hermite moments) is also suitable for implementation into existing numerical codes. It is emphasized that it is the quasi-static approximation which makes some Braginskii coefficients divergent in a weakly-collisional regime.

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Comparison of activity indicators in a 3D model atmosphere

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The Sun, being the nearest star, can be used as a reference case for solar-like stars due to the availability of many spatiotemporally resolved solar spectra. Amongst several spectral lines, some of the strongest chromospheric diagnostics are the Ca II H & K lines which can be used to gauge the temperature stratification of the atmosphere as the line core and wings are formed in different regions of the solar atmosphere. Furthermore, the Hα line is a tracer for the magnetic structures and its line core provides an estimate of the mass density. The brightness temperatures from ALMA observations provide a new complementary view of the activity and the thermal structure of stellar atmospheres. Therefore, the synthetic Ca II and Hα spectra are compared to corresponding millimetre continuum maps to get insights into the stellar structure.

The 1.5D radiation transfer codes RH and Multi3D are used to obtain synthetic spectra for the Ca II lines and the Hα line from an enhanced network atmosphere model simulated with the state-of-the-art Bifrost code. The activity indices generated from these lines could further be used to compare the spectra of sun-like stars with the solar spectrum. These indices can shed light on the physical properties like temperature stratification, magnetic structures, and mass density distribution in stellar atmospheres. The overall aim of the presented study is to establish more robust solar/stellar activity indicators using ALMA observations in comparison with classical diagnostics.

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Formation Of The Lyman Continuum During Solar Flares

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The Lyman Continuum (LyC; <912Å) forms at the top of the chromosphere, making it a powerful tool for probing the chromospheric plasma during solar flares. SDO/EVE has observed many LyC disk-integrated flares, though this is a largely untapped dataset (aside from Machado et al 2018). Further, SolO/SPICE also provides partial coverage of the LyC (704-790Å), whilst the upcoming Solar-C/EUVST will observe 460-1220Å. It is important, therefore, to have solid theoretical predictions of the LyC formation properties during flares for comparison with current/future observations. To understand the effects of non-thermal energy deposition during flares, we analysed LyC spectra from a set of radiation hydrodynamic flare models (RADYN). The spectral response of the LyC, and the resulting temporal evolution of the NLTE departure coefficient of hydrogen, b_1, and the colour temperature, T_c, was investigated in response to a range of non-thermal electron distributions. The LyC intensity was found to increase by 3-5.5 orders of magnitude dependent on the injected energy flux. Generally, b_1 decreased from 10^{2-3} to 10^{-1-1} indicating a stronger coupling to local plasma conditions, while Tc increased from 8-9kK to 10-16kK. Both optically thick and thin components of LyC were found, in agreement with recent observations. The optically thick layer formed deeper in the chromosphere during a flare compared to quiescent conditions, whereas the optically thin layers form at higher altitudes due to chromospheric evaporation in low-temperature, high-density regions propagating upwards. Our analysis paves the way for an interpretation of existing and upcoming LyC observations.

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A study of chromospheric and coronal reconnection sites in the aftermath of flux emergence.

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Quasi-simultaneous Ellerman bombs and UV bursts have been shown to result from the reconnection of emerging flux with itself when part of the emerging field remains in photospheric heights while the flanks of the retained field rise to chromospheric and coronal heights (Hansteen et al A&A 626, A33, 2019; Ortiz et al A&A 633, A58, 2020). This conclusion was reached using 3D Bifrost numerical simulations and comparison to observations. However, emerging flux and the mutual cancellation of field strands in it do not always result in that type of transient events. In this lecture we discuss a number of instances of such a process of reconnection in emerging flux regions, highlighting the similarities and differences between them and the appearance, or otherwise, of such transient events. To that end, results from a 3D Bifrost numerical model are combined with a-posteriori synthesis of chromospheric, TR and coronal lines.

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Properties of ubiquitous magnetic reconnection events in the lower solar atmosphere

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Magnetic reconnection in the deep solar atmosphere can give rise to enhanced emission in the Balmer hydrogen lines, a phenomenon referred to as Ellerman bombs. Recent high quality Hβ observations indicate that Ellerman bombs are more common than previously thought and it was estimated that at any time about half a million Ellerman bombs are present in the quiet Sun. We performed an extensive statistical characterization of the quiet Sun Ellerman bombs (QSEBs) in these new Hβ observations from Swedish 1-m Solar Telescope. The lifetime varies between 9 s and 20.5 min. The maximum area ranges between 0.0016 and 0.2603 Mm^2. A subset (14%) of the QSEBs display enhancement of the Hβ line core. On average, the line core brightening appears 0.88 min after the onset of brightening in the wings, and the distance between these brightenings is 243 km. This gives rise to an apparent propagation speed ranging between 14.3 and +23.5 km/s, with an average that is upward propagating at +4.4 km/s. The average orientation is nearly parallel to the limbward direction. QSEBs are nearly uniformly distributed over the field of view but we find empty areas with the size of mesogranulation. QSEBs are located more frequent near the magnetic network where they are often bigger, longer lived and brighter. We conclude that QSEBs are ubiquitous in quiet Sun and appear everywhere except in areas of mesogranular size with weakest magnetic field (B_{LOS} <= 50 G). Our observations support the interpretation of reconnection along vertically extended current sheets.

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Radiative losses above a quiet-Sun region

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The heating of the outer layers of the solar atmosphere is still far from being completely understood. In this sense, in the last few years we have witnessed a huge step forward in our understanding from both a theoretical and an observational perspective. This has been possible due to the inclusion of new physics in the former and the deployment of new observing facilities that has opened unprecedented technical capabilities required for the study of these highly dynamic layers. As a major result, it has been found that understanding the heating problem involves a coupled system (the solar atmosphere), thus requiring its study as a whole system.

One important missing piece in this context is the capability to observationally constrain the various physical mechanisms that heat the outer layers in the numerical simulations. In this contribution we present the application of a newly-developed inversion algorithm that expands the capabilities of the NLTE inversion code STiC to better handle inversions combining multi-resolution observations. This is of utmost importance for the chromosphere and above as their intrinsic highly stratified nature makes it mandatory to combine observations from different observing facilities with disparate optical behaviours. In particular, we combine observations of a quiet-Sun area co-observed with the SST (CRISP and CHROMIS) and IRIS. By the inference of the various physical properties of the atmosphere we compute the radiative losses from different sources and discuss their potential physical origin.

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Rayleigh-Taylor instability-induced interactions between turbulence and magnetic reconnection in the Solar Prominences.

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The internal dynamics of solar prominences have been observed to be highly complex for many decades, many of which also indicate the possibility of turbulence. Prominences represent large-scale, dense condensations suspended against gravity at great heights within the solar atmosphere. Therefore, it is no surprise that the fundamental process of the Rayleigh-Taylor (RT) instability has been suggested as the potential mechanism for driving the dynamics and turbulence remarked upon within observations. Observations have also revealed the presence of bi-directional jets due to current sheets in the prominence body, thus highlighting the shift of topology of the magnetic fields induced due to the gravity-driven flows.

We begin with the 2.5D fully-resistive magnetohydrodynamic (MHD) high-resolution simulations with the open-source **MPI-AMRVAC** code and follow the far nonlinear evolution of an RT instability that starts at the prominence-corona interface. We use statistical analysis to investigate the evolution of turbulent regimes, which corresponds to the observational counterpart. Furthermore, the strength of the mean magnetic field directed into the 2D plane, and its alignment with the plane itself, creates a system with varying turbulent behavior. The intermittent heating and energy dissipation events are caused by magnetic reconnection, which we investigate in detail by the 2.5D fully-resistive MHD model. Based on the evolution of plasma beta (β) along the prominence's height, the stratified numerical model generates different dynamics of turbulent magnetic reconnection. As a result, we observe that the turbulent dynamics and prominence reconnection events are unique from those occurring elsewhere in the solar corona.

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Solar Flare Ribbon Fronts: Constraining flare energy deposition with IRIS spectroscopy

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Lower atmospheric lines show peculiar profiles at the leading edge of ribbons during flares. In particular, increased absorption of the BBSO/GST HeI 10830 A line (e.g. Xu2016), as well as broad and centrally reversed profiles in the MgII and CII spectra observed by the IRIS satellite (e.g. Panos2018) have been reported. In this work, we aim to understand the physical origin of the IRIS ribbon front line profiles, which seem to be common of many, if not all, flares. To achieve this, we quantify the spectral properties of the IRIS MgII ribbon front profiles during four large flares and perform a detailed comparison with a grid of radiative hydrodynamic models using the RADYN code. We also studied their transition region counterparts, finding that these ribbon front locations are regions where transition region emission and chromospheric evaporation are considerably weaker compared to other parts of the ribbons. Based on our comparison between the IRIS observations and modelling, our interpretation is that there are different heating regimes at play in the leading and trailing regions of the ribbons. More specifically, we suggest that bombardment of the chromosphere by more gradual and modest non-thermal electron energy fluxes can qualitatively explain the IRIS observations at the ribbon front, while stronger and more impulsive energy fluxes are required to drive chromospheric evaporation and more intense TR emission. Our results provide a possible physical origin for the peculiar behavior of the IRIS chromospheric lines in the ribbon leading edge and new constraints for the flare models.