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Opening talk

MHD waves in the solar corona: highlights of observations and modeling in the past two decades (Invited)

Leon Ofman (CUA and NASA-Goddard Space Flight Center, USA)

The progress in high-resolution space-based observations of the solar corona from the SOHO spacecraft to TRACE and present day SDO satellites provided the data for coronal seismology, a method that enabled probing the magnetic field and other physical properties of the solar corona in a new way. While the theoretical grounds for coronal seismology were laid decades ago, the application of these MHD wave theories to observations became possible much later thanks to the high-resolution, and high cadence observations of waves in coronal structures, such as in loops, plumes, and active regions. This new synergy between theory and observations, as exemplified by the pioneering work of Prof. Nakariakov and others, lead to the breakthroughs that allowed nearly routine application of coronal seismology using instruments such as SDO/AIA in a variety of coronal structures. In parallel, the advancement of numerical modeling of MHD waves in realistic coronal structure plays a crucial role in further development of coronal seismology with application to more realistic structures, extending the limitations of idealized theoretical constructs. I will review briefly the advancements in observations of coronal MHD waves since their discovery in EUV more than two decades ago, the theoretical evolution of coronal seismology, and progress in MHD modeling. I will discuss the potential future directions of coronal seismology, possible improvement, and application to various waves in coronal structures.

Decaying kink and sausage oscillations and waves in the corona

Sausage oscillations in coronal flux tubes with localized magnetic twist (Invited)

Igor Lopin (Institute of Applied Astronomy of RAS, Russia)

The sausage oscillations in coronal flux tubes consisting of homogeneous core and thin magnetically twisted annulus are examined. Dispersion equation is derived and studied numerically and analytically for a number of limiting cases. Two families of symmetric radial modes are found to exist in the model. The first one includes an infinite number of trapped modes with phase speed lying in the range between the Alfve'n speeds in the core and in the annulus ($V_{Ai}< V_{ph} <V_{A0}$). The second family consists of infinite number of sausage modes with phase speed exceeding the Alfve'n speed in the annulus V_{A0}, which are either trapped if $V_{ph} <V_{Ae}$ or leaky if $V_{ph} >V_{Ae}$. The application of the obtained results to coronal seismology is discussed.

Coronal seismology with propagating kink waves (Contributed)

Richard Morton (Northumbria University, UK)

Collaborators: M. Weberg, J. A. McLaughlin

The propagating kink mode is found to be present throughout the corona and appears to be continually excited. The Coronal Multi-channel Polarimeter (CoMP) instrument made the initial discovery back in 2007, and has been able to provide a number of insights into the properties of the kink waves. The widespread and reliable presence means that the propagating kink mode can make a fantastic tool for measuring the global plasma structure of the corona. The kink waves can also be observed with SDO, although they are extremely challenging to measure. In this talk, I will discuss how we have been able to measure these waves in SDO and, through mass measurement, perform statistical seismology on coronal structures. I demonstrate their potential with an estimate of the density profile with a coronal hole.

Mapping the global magnetic field in the solar corona through magnetoseismology (Invited)

Hui Tian (Peking University, China)
Collaborators: Z. Yang, C. Bethge, S. Tomczyk, R. Morton, G. Del Zanna, S. McIntosh, B. Binay Karak, S. Gibson, T. Samanta, J. He, Y. Chen, L. Wang, X. Bai

Magnetoseismology, a technique of magnetic field diagnostics based on observations of magnetohydrodynamic (MHD) waves, has been widely used to estimate the field strengths of oscillating structures in the solar corona. However, previously magnetoseismology was mostly applied to occasionally occurring oscillation events, providing an estimate of only the average field strength or one-dimensional distribution of field strength along an oscillating structure. This restriction could be eliminated if we apply magnetoseismology to the pervasive propagating transverse MHD waves discovered with the Coronal Multi-channel Polarimeter (CoMP). Using several CoMP observations of the Fe XIII 1074.7 nm and 1079.8 nm spectral lines, we obtained maps of the plasma density and wave phase speed in the corona, which allow us to map both the strength and direction of the coronal magnetic field in the plane of sky. We also examined distributions of the electron density and magnetic field strength, and compared their variations with height in the quiet Sun and active regions. Such measurements could provide critical information to advance our understanding of the Sun's magnetism and the magnetic coupling of the whole solar atmosphere.

Kink oscillations in coronal loops with elliptical cross-sections (Contributed)

Mingzhe Guo (Shandong University, Weihai)
Collaborators: B. Li, T. Van Doorsselaere

The cross sections of solar coronal loops are suggested to be rarely circular. We examine linear kink oscillations in straight, density-enhanced, magnetic cylinders with elliptical cross-sections by solving the three-dimensional MHD equations from an initial-value-problem perspective. Motivated by relevant eigenmode analyses, we distinguish between two independent polarizations, one along the major axis (the M-modes) and the other along the minor one (the m-modes). We find that, as happens for coronal loops with circular cross-sections, the apparent damping of the transverse displacement of the loop axis is accompanied by the accumulation of transverse Alfvenic motions and the consequent development of small-scales therein, suggesting the robustness of the concepts of resonant absorption and phase-mixing. In addition, two stages can in general be told apart in the temporal evolution of the loop displacement; a Gaussian time dependence precedes an exponential one. For the two examined density ratios between loops and their surroundings, the periods of the M-modes (m-modes) tend to increase (decrease) with the major-to-minor-half-axis ratio, and the damping times in the exponential stage for the M-modes tend to exceed their m-mode counterpart. This is true for the two transverse profiles we examine. However, the relative magnitudes of the damping times in the exponential stage for different polarizations depend on the specification of the transverse profile and/or the density contrast. The applications of our numerical findings are discussed in the context of coronal seismology.

Resonant absorption: compression and vorticity (Invited)

Marcel Goossens (KU Leuven Centre mathematical Plasma Astrophysics)
Collaborators: I. Arregui, R. Soler, T. Van Doorsselaere

This presentation investigates the changes in spatial properties when magnetohydrodynamic (MHD) waves undergo resonant damping in the Alfven continuum. The analysis is carried out for a 1D cylindrical pressure-less plasma with a straight magnetic field. Compression and vorticity are used to characterise the spatial evolution of the MHD wave. Compression is traditionally seen as a marker for magneto-sonic waves. It is non-zero everywhere. The most striking result is the huge spatial variation in the vorticity component parallel to the magnetic field. Parallel vorticity can be seen as a marker for Alfven waves. It vanishes in the uniform part of the equilibrium. However, when the MHD wave moves into the non-uniform part, parallel vorticity explodes to values that are orders of magnitude higher than those attained by the transverse components in planes normal to the straight magnetic field. In the non-uniform part of the equilibrium plasma, the MHD wave is controlled by parallel vorticity and resembles an Alfven wave, with the unfamiliar property that it has pressure variations.

Decayless kink oscillations of coronal loops

Transverse oscillations of coronal loops induced by circular-ribbon flares and the related jets (Invited)

Qingmin Zhang (Purple Mountain Observatory CAS, China)

Kink oscillations are prevalent in corona loops. In this talk, I will show the multiwavelength observations of kink oscillations of an EUV loop triggered by two homologous circular-ribbon flares on 2014 March 5. The oscillation triggered by the first C2.8 flare is decayless with a smaller amplitude, while the oscillation triggered by the M1.0 flare is decaying with a larger amplitude. Besides, I will report the kink oscillation of a long coronal loop induced by a flare-related jet. The magnetic field strength of the loop is estimated using two independent approaches: coronal seismology and NLFFF extrapolation. The results are in the same order of magnitude.

Excitation of decayless kink oscillations by random motion (Invited)

Michael Ruderman (University of Sheffield, UK; Space Research Institute IKI Russian Academy of Sciences, Russia)
Collaborators: N. S. Petrukhin

We study kink oscillations of a straight magnetic tube with a transitional region at its boundary. The tube is homogeneous in the axial direction. The plasma density monotonically decreases in the transitional region from its value inside the tube to that in the surrounding plasma. The plasma motion is described by the linear magnetohydrodynamic equations in the cold plasma approximation. We use the ideal equations inside the tube and in the surrounding plasma, but take viscosity into account in the transitional region. We also use the thin tube and thin transitional or boundary layer (TTTB) approximation. Kink oscillations are assumed to be driven by a driver at the tube footpoint. We derive the equation describing the displacement in the fundamental mode and overtones. We use this equation to study kink oscillations both in the case of random driving. We assume that the driver is described by a stationary random function. The displacements in the fundamental mode and overtones are also described by stationary random functions. We derive the relation between the power spectra of the fundamental mode and all overtones and the power spectrum of the driver. We suggest a new method of obtaining information on the internal structure of coronal magnetic loops based on the shape of graphs of the power spectrum of the fundamental mode.

Generating decay-less loop oscillations via self-oscillatory processes (Contributed)

Konstantinos Karampelas (Northumbria University, UK)
Collaborators: T. Van Doorsselaere

Identifying the means of excitation of decay-less oscillations in coronal loops is essential for their role as diagnostic tools in coronal seismology and their potential use as wave heating mechanisms of the solar corona. However, despite them being the focus of many observational and numerical, no definitive answer has yet been reached. In our studies, we explore the concept of these standing waves being self-oscillatory processes. We perform 3D magnetohydrodynamic simulations of straight flux tubes for two different models. The first model consists of a weak steady plasma flow around the loop footpoint, reminiscent of supergranulation flows. The second model consists of a stronger flow across the loop cross-section, reminiscent of upflows associated with coronal mass ejections, which generates Alfvenic vortex shedding. We show that both methods lead to the development of low-amplitude transverse standing waves, for the first time in full 3D simulations. By plotting the power spectral density for each model, we identify the excited frequencies of these low-amplitude oscillations and show that the frequency of the fundamental standing kink mode is the dominant one. We also argue that both mechanisms are essentially self-oscillations, since the dominant excited frequencies are dependent upon the characteristics of the oscillating loops, and not those of the drivers. We thus present two models acting as a proof-of-concept for self-oscillations in coronal loops, and we propose them as possible mechanisms for interpreting the observed decay-less transverse loop oscillations.

Excitation of decay-less transverse oscillations of coronal loops by random motions (Contributed)

Andrey Afanasyev (LASP, University of Colorado Boulder)
Collaborators: T. Van Doorsselaere, V. M. Nakariakov, V. Pant

The relatively large-amplitude decaying regime of transverse oscillations of coronal loops has been known for two decades and has been interpreted in terms of magnetohydrodynamic kink modes of cylindrical plasma waveguides. Recent observations have revealed the so-called decay-less, small-amplitude oscillations, in which a multi-harmonic structure has been detected. Several models have been proposed to explain these oscillations. In particular, decay-less oscillations have been described in terms of standing kink waves driven with continuous mono-periodic motions of loop footpoints, in terms of a simple oscillator model of forced oscillations due to harmonic external force, and as a self-oscillatory process due to the interaction of a loop with quasi-steady flows. However, an alternative mechanism is needed to explain the simultaneous excitation of several longitudinal harmonics of the oscillation. We propose a mechanism that interprets decay-less transverse oscillations of coronal loops in terms of kink waves driven by random motions of the loop footpoints. We find the excitation of loop eigenmodes and analyse their frequency ratios as well as the spatial structure of the oscillations along the loop. The obtained results successfully reproduce the observed properties of decay-less oscillations. In particular, the excitation of eigenmodes of a loop as a resonator can explain the observed quasi-monochromatic nature of decay-less oscillations and the generation of multiple harmonics detected recently.

Coronal heating and implications of thermodynamic activity of the corona for MHD waves

Aspects of MHD wave heating in the complex solar atmosphere (Invited)

Ineke De Moortel (University of St Andrews, UK)

In a series of numerical experiments, we investigate the possible role of MHD waves in the energy and mass cycle in the complex solar corona. Using 3D MHD simulations of transverse, Alfvenic waves, we look at the role of chromospheric evaporation, the complexity of the magnetic field and the power spectrum of the wave driver. We focus on the efficiency of the wave-based heating in our models, in particular whether heating provided by the waves can balance coronal losses and whether proposed wave heating mechanisms are in fact self-consistent.

Evolution of coupled slow magnetoacoustic and entropy waves in a plasma with heating/cooling misbalance (Invited)

Dmitrii Zavershinskii (Samara National Research University and Lebedev Physical Institute, Russia)
Collaborators: D. Y. Kolotkov, N. E. Molevich, D. S. Ryashchikov

The processes of plasma heating and cooling may significantly affect the slow magnetoacoustic (MA) waves, causing amplification or attenuation, and also dispersion. However, the entropy mode is also excited in the plasma and is affected by heating/cooling misbalance. Unlike the plasma without heating/cooling misbalance the properties and evolution of slow MA and entropy waves are interrelated. The different regimes of misbalance lead to a variety of scenarios for the initial perturbation to evolve. In order to describe properties and evolution of slow MA and entropy waves in various regimes of misbalance we obtained exact solution of the linear evolutionary equation. Using the characteristic times and the obtained exact solution we identified different regimes with qualitatively different behavior of slow MA and entropy modes. For some regimes, the spatio-temporal evolution of the initial Gaussian signal is shown. It is found that in some regimes slow MA modes may have a range of non-propagating harmonics, and dispersion of the phase speed in those cases can be a non-monotonic function of the wavenumber. We also showed that the initial distribution of energy between slow MA and entropy mode depends on the heating and cooling process. Furthermore, the heating/cooling misbalance causes additional phase shifts between perturbations of different plasma parameters.

Will it rain in this loop? The role of asymmetries in coronal rain formation during thermal non-equilibrium cycles (Contributed)

Gabriel Pelouze (KU Leuven, Belgium)
Collaborators: F. Auchère, K. Bocchialini, C. Froment, Z. Mikić, E. Soubrié, A. Voyeux

Thermal non-equilibrium (TNE) results in several observables that can be used to constrain the spatial and temporal distribution of coronal heating. Its manifestations include prominence formation, coronal rain, and long-period intensity pulsations in coronal loops. The recent observation of periodic coronal rain associated with intensity pulsations by Auchère et al. allows to unify these two phenomena as the result of TNE condensation and evaporation cycles. However, not all TNE cycles result in the formation of coronal rain. Our goal is to understand why.
We perform 1D hydrodynamic simulations of the event reported by Auchère et al. We explore different heating parameters and variations of the loop geometry (9000 simulations in total). We compare the resulting behaviour to simulations of TNE cycles which do not form coronal rain realized by Froment et al. Our simulations show that both prominences and TNE cycles (with and without coronal rain) can form within the same loop geometry. We show that the formation of coronal rain during TNE cycles depends on the asymmetry of the loop and of the heating. Asymmetric loops are overall less likely to form coronal rain, regardless of the heating. In symmetric loops,

coronal rain forms when the heating is also symmetric. In asymmetric loops, rain forms when the heating is oppositely asymmetric.

Generation of solar spicules and subsequent atmospheric heating (Contributed)

Tanmoy Samanta (NASA Marshall Space Flight Center, Huntsville, AL 35812, USA)
Collaborators: H. Tian, V. Yurchyshyn, H. Peter, W. Cao, A. Sterling, R. Erdelyi, K. Ahn, S. Feng, D. Utz, D. Banerjee, Y. Chen

Rapidly evolving fine-scale jets known as spicules are the most prominent and dynamical phenomena observed in the solar chromosphere. At any given instant, around a few millions of these spicules shoot plasma material out from the Sun's surface. It is highly likely that these spicules play a crucial role in key solar physics mysteries, such as chromospheric and coronal heating and mass supply to the solar wind. Despite intensive delving in the past decades, still there is no clear consensus on how these small-jets of magnetized plasma originate from the solar surface, nor we understand how exactly they transfer energy into and possibly heat the solar atmosphere. The exact source of these small-scale jets is hard to observe due to the resolution limitations of earlier telescopes. Therefore, they remain poorly understood. Using unprecedented multi-wavelength and high-sensitive magnetic field observations from the world's largest Solar Telescope at the Big Bear Solar Observatory, we strive to reach conclusions on the possible scenario among the many proposed hypotheses of spicule's origin. We found that the dynamical interaction of magnetic fields in the partially ionized lower solar atmosphere is the precursor of these high-speed jets which subsequently energizes the upper solar atmosphere.

Nonlinear effects of coronal MHD waves: observational manifestations and theoretical modelling

The role of nonlinear forces on the propagation of torsional polarized waves in the solar atmosphere (Invited)

Soheil Vasheghani Farahani (Tafresh University, Iran)

As the Alfven wave is known to be the one of the most decisive candidates regarding energy transfer in the solar atmosphere, various aspects in this regard are being taken under consideration. The fact of the matter is that the Alfven wave is an incompressive wave without perturbing the neighbouring sites. Now what if the transverse structuring of the plasma structure experiences shears either due to rotation or a flow with a shear at the boundary, or an equilibrium magnetic twist. It is then that the Alfven wave experiences a modification in its phase speed in the linear regime depending on the interplay of the equilibrium parameters may increase or decrease. This causes the density to be perturbed by the wave which is now in the category of a fast wave. However, in the nonlinear regime the Alfven wave actually does perturb the density and hence all other compressive perturbations namely the cross section acting in line with collimation. This is where special care must be paid where depending on the polarization of the Alfven wave different estimations regarding the energy transfer to

shorter scales due to the nonlinear cascade is observed. As the speed of the bulk regarding cylindrical structures is the tube speed while the speed of bulk in slab-like structures is the sound speed, a crucial difference is observed which is a singularity due to the equality of the sound and the plane Alfven speeds in some height of the solar atmosphere which is never observed for torsional wave since the tube speed is always lower than the torsional Alfven speed. The forces that play decisive roles in the propagation of the Alfven wave are affected by the plasma conditions and parameters where in case of a steady flow with a shear at the boundary, the interplay of the nonlinear forces is highly affected. This influences the collimation features of for instance a solar jet, the shock formation of waves inside a jet, and finally the energy transfer to smaller scales inside the jet. This is while the nonlinear forces connected with torsional waves are also imbalanced for solar tornadoes.

Nonlinear effects of kink MHD waves in coronal loops: observations and modelling (Invited)

Norbert Magyar (University of Warwick, UK)

The displacements in observed kink oscillations of coronal loops, especially in the impulsively-triggered standing waves, are usually on the same order as the loop cross-sectional radius or even higher. Analytical theories suggest that for displacements comparable to the loop radius, the kink wave dynamics are well in the nonlinear regime. When compared to properties inferred from linear analysis, nonlinearities can substantially change the appearance and dynamics of waves. They usually lead to a redistribution of wave energy throughout the spectral k-space, i.e. nonlinear coupling to different eigenmodes and forced modes of the system. In this sense, care should be taken when applying coronal seismology based on linear wave models to observed nonlinear oscillations. I will present the different observational manifestations of nonlinearities in coronal waves and the effects they induce, which could be relevant for coronal seismology. Then I will focus on the theoretical modelling of these nonlinearities and ways they could be accounted for when applying coronal seismology.

On the lookout for TWIKH rolls in the solar atmosphere with the help of forward modelling (Invited)

Patrick Antolin (Northumbria University, UK)

Numerical simulations in the last decade have strongly pointed to the presence of dynamic instabilities, such as Kelvin-Helmholtz, accompanying the ubiquitously observed transverse MHD waves. Known as TWIKH rolls for Transverse Wave-Induced Kelvin-Helmholtz instability rolls, they are expected across a wide variety of waveguides, from spicules and fibrils in the chromosphere, to prominences and coronal loops in the corona. Yet, this phenomenon has so far eluded direct observations. In this talk I will review the indirect observations and the probable reasons for this conspicuous absence based on the main observational signatures expected from forward modelling of 3D MHD simulations of this phenomena.

Properties of Uniturbulence (Contributed)

Rajab Ismayilli (CmPA, KU Leuven, Belgium)
Collaborators: T. Van Doorsselaere

We are investigating turbulence in the theoretical model with inhomogeneity (in the density, in magnetic field etc.) across the background magnetic field. In other words, we take gradients of the Alfven speed perpendicular to the field into account. This generates turbulence which is termed as 'Uniturbulence' because it can be generated by unidirectionally propagating waves. The idea of Uniturbulence is that you do not need counterpropagating waves (colliding waves) to generate turbulence anymore, if you have an inhomogeneous Alfven speed perpendicular to the direction of the magnetic field. In this case waves propagating through a perpendicularly inhomogeneous field will deform non-linearly.

Coronal MHD waves and magnetic reconnection in the solar atmosphere

MHD wave propagation in the neighbourhood of coronal null points (Invited)

James McLaughlin (Northumbria University, UK)

Coronal null points are locations where the magnetic field, and hence the local Alfven speed, is zero. The behaviour of all three MHD wave modes, i.e. fast and slow magnetoacoustic waves and the Alfven wave, has been investigated in the neighbourhood of 2D, 2.5D and (to a certain extent) 3D magnetic null points, for a variety of assumptions, configurations and geometries. These studies contribute to our understanding of MHD wave propagation in inhomogeneous media, and this talk will review some specific findings in this area, in particular the results that have led to critical insights into reconnection, mode-coupling, and quasi-periodic pulsations.

MHD waves behaviour around a magnetic null point (Contributed)

Somaye Sabri (The University of Tabriz, Iran)
Collaborators: H. Ebadi, S. Poedts

We performed numerical studies for interpreting the behaviour of MHD waves behaviour in interaction with the magnetic null point in solar coronal condition. A shock capturing Godunov type PLUTO code is used to solve MHD equations. It is found that Alfven waves propagate toward the magnetic null point with inducing magnetoacoustic waves perturbations and also plasma flows. Besides the transfer of the energy from the nonlinear Alfven wave during the propagation toward the magnetic null point is investigated. Moreover the behaviour of the initial fast magnetoacoustic wave is studied. It is found that due to the interaction of magnetoacoustic wave with the null point oscillatory magnetic reconnection takes place. This interaction also contributes to the significant creation of inflows and outflows that are possible candidates for the creation of solar jets which has important contribution towards coronal seismology.

MHD waves in a lower solar atmosphere

Seismology of sunspot umbrae and bright points in the photosphere based on the theory of slow magnetoacoustic waves (Invited)

Il-Hyun Cho (Kyung-Hee University, South Korea)
Collaborators: V. M. Nakariakov, Y.-J. Moon, K.-S. Cho, S.-C. Bong

We performed seismological determinations of Alfvén speeds and plasma-beta of photospheric magnetic flux tubes of sunspot umbrae and bright points. The seismology was based on the dispersion relation of the slow magnetoacoustic wave in a non-isothermal and stratified atmosphere in a uniform vertical magnetic field. The dispersion relation has a form of a third-order polynomial as a function of cutoff frequency and squared ratio of the tube speed to sound speed. For a given flux tube observed in the continuum, we estimated a weighted frequency of the intensity fluctuation, and use it to determine the cutoff frequency. The sound speed is determined from the continuum intensity. By solving the polynomial equation, we obtained the Alfvén speed and plasma-beta. The Alfvén speeds for bright points, small, and large umbrae were calculated to be 9.68 km/s, 8.73 km/s, and 8.63 km/s, respectively. The calculated plasma-beta was 0.93 for bright points, 0.86 for small umbrae, and 0.83 for large umbrae. For the sunspot umbrae, the observed quantities are found to be affected by the geometrical Wilson depression. Based on the results, we concluded that the theory of slow waves in a non-isothermal and stratified atmosphere with a uniform vertical magnetic field provides the proper interpretation for the observed continuum oscillations in the photospheric magnetic flux tubes. We also introduce an observational property of slow waves in coronal plumes, which exhibits accelerations with supersonic speeds.

Possible evidence of sausage waves associated with photospheric bright points (Contributed)

Yuhang Gao (Peking University, China)
Collaborators: H. Tian, Y. Li

Sausage waves have been frequently reported in solar magnetic structures such as sunspots and flaring loops. However, they have not been reported in photospheric bright points (PBPs). Using high-resolution TiO images obtained with the Goode Solar Telescope at the Big Bear Solar Observatory on 2018 Aug 6, we have analyzed several isolated PBPs, and found correlated changes of the area and average intensity. The in-phase fluctuation likely suggests the presence of sausage waves in these PBPs.

Oscillation dynamics in short-lived faculae during their lifetime (Contributed)

Andrei Chelpanov (Institute of Solar-Terrestrial Physics, Irkutsk, Russia)
Collaborators: N. Kobanov, V. Tomin, A. Kiselev

We performed a multiwave study of the oscillation dynamic in short-lived faculae during their lifetime. We consider a facula short-lived if it forms and decays during one passage through the disk, i.e. under 14 days. We found that at the formation phase, low-frequency (1-2 mHz) oscillations concentrate in the central areas of faculae, while higher-frequencies (5-7 mHz) group at the periphery of the active region. We suggest that the appearance of low frequencies may serve as a precursor of the coronal loop system development. At the later stages of the facula development, five-minute oscillations dominate its photosphere and chromosphere, while the low-frequency areas shrink. At the same time, low frequencies prevail in the coronal frequency distributions. These results support the version that the sources of the low-frequency oscillations in loops lie in the lower layers of the solar atmosphere.

Waves propagation above a plage as observed by IRIS and SDO (Contributed)

Pradeep Kumar Kayshap (Vellore Institute of Technology VIT, Bhopal University, Kothri Kala, Sehore, M.P., India)
Collaborators: A. K. Srivastava, S. K. Tiwari, P. Jelinek, and M. Mathioudakis

In the current era, it is widely accepted that magnetohydrodynamic waves transport energy from the photosphere to heat the transition region (TR) and corona. Therefore, understanding of the wave's propagation is very crucial for the coronal heating problem. We have investigated the propagation of waves within an active region (AR) plage to understand the relationship between photospheric and TR oscillations. We applied wavelet analysis with a customized noise model on photospheric (i.e., AIA 1700) and TR (i.e., IRIS/SJI 1400) intensity time-series deduced from the vertical magnetic flux tubes within the plage region.
We found that a broad-range of wave-periods (i.e., from 2.0 to 9.0 minutes) have correlated between the photosphere and TR. The comparison between TR sound speed and estimated propagation speed predicts that these waves are slow magnetoacoustic waves. Most importantly, almost all locations show correlation/propagation of waves over a broad range of periods from the photosphere to TR. It suggests the wave's correlation/propagation spatial occurrence frequency is high within the plage area.

Effect of electrical resistivity on the damping of slow sausage modes (Contributed)

Michaël Geeraerts (KU Leuven, Belgium)
Collaborators: T. Van Doorsselaere, S.-X. Chen, B. Li

Recent observations of slow surface sausage modes in a photospheric magnetic pore have been shown to be heavily damped. Numerical calculations have shown that electrical resistivity plays a significant role in this damping process. The aim of the present paper is to make an independent analytical derivation that would confirm the importance of electrical resistivity in the damping of these modes. An analytical dispersion relation in the framework of resistive magnetohydrodynamics is derived for sausage modes in a straight cylinder with a circular cross section and a discontinuous boundary. The effect of electrical resistivity on the damping of slow sausage modes in photospheric pore conditions is then studied, by solving the obtained dispersion relation numerically. The obtained results agree with those from the numerical calculations.

FIP and inverse FIP effects in solar flares (Contributed)

Martin Laming (Naval Research Laboratory, USA)

The Inverse FIP Effect, the depletion in corona abundance of elements like Fe, Mg, and Si that are ionized in the solar chromosphere, has been identified in several solar flares. We give a more detailed discussion of the mechanism of fractionation by the ponderomotive force associated with magnetohydrodynamic waves, paying special attention to the conditions in which Inverse FIP fractionation arises in order to better understand its relation to the usual FIP Effect, i.e. the enhancement of coronal abundance of Fe, Mg, Si, etc. The FIP Effect is generated by parallel propagating Alfven waves, with either photospheric, or more likely coronal, origins. The Inverse FIP Effect arises as upward propagating fast mode waves with an origin in the photosphere or below, refract back downwards in the chromsphere where the Alfven speed is increasing with altitude. We give a more physically motivated picture of the FIP fractionation, based on the wave refraction around inhomogeneities in the solar atmosphere, and inspired by previous discussions of analogous phenomena in the optical trapping of particles by laser beams.

Influence of waveguide cross-sectional shape on the spatial structure of MHD wave modes (Invited)

Gary Verth (University of Sheffield, UK)

The cross-sectional shape of a waveguide fundamentally determines the spatial structure of the eigenfunctions. This is known from the membrane solutions of the wave equation, which is equivalent to solving two Helmholtz equations if separation of variables is possible. Well known cases produce, e.g., sinusoidal solutions for a rectangular membrane in Cartesian coordinates and Bessel functions for a circular membrane in polar coordinates. In the linear approximation, assuming the vertical wavenumber is constant, all MHD perturbed variables are governed by a Helmholtz type equation which depends on the particular geometry. It is found that, for photospheric conditions, the internal part of the slow body mode eigenfunctions, are to good approximation, described by solutions of the Helmholtz equations where the boundary values of the perturbed variables are fixed to be zero. We discuss two sunspot case studies where the observed slow body modes are decomposed with Proper Orthogonal Decomposition and compared with the modelled eigenfunctions.

MHD waves in open coronal structures and global wave phenomena

MHD Waves in open coronal structures (Invited)

Dipankar Banerjee (Aryabhatta Research Institute of Observational Sciences, India)

Modern observations have revealed the ubiquitous presence of magnetohydrodynamic waves in the solar corona. The propagating waves (in contrast to the standing waves) are usually originated in the lower solar atmosphere which makes them particularly relevant for coronal heating. Furthermore, open coronal structures are believed to be the source regions of solar wind, therefore, the detection of MHD waves in these structures is also pertinent to the acceleration of solar wind. Besides, the advanced capabilities of the current generation telescopes have allowed us to extract important coronal properties through MHD seismology. The recent progress made in the detection, origin, and damping of both slow mangetoacoustic waves and Alfv\'{e}nic waves will be presented especially in the context of open coronal structures.

Observations of small and large scale MHD waves from Polar Coronal Hole (Invited)

Kyungsuk Cho (Korea Astronomy and Space Science Institute, South Korea)
Collaborators: I.-H. Cho, V. Nakariakov, M. S. Madjarska, V. B. Yurchyshyn, H. Yang, E.-K. Lim

In the first part of this talk, we report a high-resolution observation of a small surge observed with 1.6m Goode Solar Telescope (GST). Characteristics of plasma motions in the surge are determined with the normalizing radial gradient filter and the Fourier motion filter. We find a propagating kink oscillation of the surge, with the period of ~2 minutes. As the height increases, the initial amplitude of the wave increases, and the oscillation damping time decreases from 5.13 to 1.18 minutes. In the second part, we will focus on the nature of propagating intensity disturbances (PIDs) in plumes located in the northern polar coronal hole observed during the 2017 total solar eclipse. We find that the PIDs in the higher temperature SDO/AIA channels, 193 and 211 A, are faster than that of the cooler SDO/AIA 171 A channel. This tendency is more significant for the active plumes than the quiet ones. Our results support the idea that PIDs in plumes represent a superposition of slow magnetoacoustic waves and plasma outflows that consist of dense cool flows and hot coronal jets.

Diagnostics of flare core region by propagating fast mode waves (Invited)

Ding Yuan (Harbin Institute of Technology, Shenzhen, China)

Diagnostics of a solar flaring region by bidirectional quasi-periodic propagating fast magnetosonic waves (Contributed)

Yuhu Miao (Institute of Space Science and Applied Technology, Harbin Institute of Technology, Shenzhen, China)
Collaborators: D.Yuan

Most of the observed QFP wave events present an unidirectional wave trains along the funnel-like coronal loops. We report a simultaneously bidirectioanl wave trains. This event provides a chance to study the nature of the trigger mechanism and could be applied in diagnosing the flares. I will also talk about my work in the past two years. It helps us to understand the trigger mechanism of the QFP waves.

Instability of triangular jets in the solar atmosphere (Invited)

Teimuraz Zaqarashvili (IGAM, Institute of Physics, University of Graz, Austria)

It is known that hydrodynamic triangular jets are unstable to antisymmetric kink perturbations. The inclusion of magnetic field may lead to the stabilisation of the jets. Jets and complex magnetic fields are ubiquitous in the solar atmosphere, which suggests the possibility of the dynamic kink instability in certain cases.
We found that MHD triangular jets are unstable to the dynamic kink instability depending on the Alfv\'en Mach number and the ratio of internal and external densities. When the jet has the same density as the surrounding plasma, then only super Alfv\'enic flows are unstable. However, denser jets are unstable also in sub Alfv\'enic regime. Jets with an angle to the ambient magnetic field have much lower thresholds of instability than field-aligned flows.

Capability of a coronal mass ejection (CME) scenario to drive a Moreton wave (Contributed)

Mariana Cécere (Instituto de Astronomía Teórica y Experimental (CONICET/UNC), Observatorio Astronómico de Córdoba (UNC), ARGENTINA)
Collaborators: G. Krause, E. Zurbriggen, A. Costa, C. Francile, and S. Elaskar

It is known that coronal mass ejections (CMEs) are impulsive coronal events capable of producing large-scale coronal shocks and therefore it is a potential trigger of Moreton waves, but not all CMEs are capable of producing the chromospheric wave. We examine, by performing 2D compressible magnetohydrodynamics simulations, the capability of a CME scenario to drive a Moreton wave. We found that light and hot flux ropes and relatively strong magnetic fields are able to provoke the CME lift-off and significant expansion to produce an intense shock leading to a high-speed Moreton wave. Also, we present arguments to explain why Moreton waves are much rarer than CME occurrences.

Generation mechanisms of low-frequency waves in the solar corona (Invited)

Yuandeng Shen (Yunnan Observatories, China)
Collaborators: Y. Liu, K. Shibata, P. Chen, Y. D. Liu, and J. Su

The generation mechanisms of low-frequency wave in the solar corona will be introduced in detail, especially advances in recent years based on high temporal and high spatial resolution observations. The talk mainly introduces the generation mechanisms of two kinds of low-frequency coronal waves including the large-scale extreme ultraviolet (EUV) waves and the quasi-periodic fast-propagating magnetosonic waves. The large-scale EUV waves were discovered twenty years ago in the SOHO era, but question about their generation mechanism is still not completely understood. The main discrepancy about the driving mechanism of EUV waves is whether they are driven by flare pulses or coronal mass ejections (CMEs). Many previous studies have suggested that EUV waves are not driven by flare pulses; therefore, their driver should be CMEs. Many recent high resolution observations did support the CME driven theory. Nevertheless, there should have other driving mechanisms of large-scale EUV waves, because any disturbance would launch waves in the solar corona in theory. By searching the 7-years database of SDO/AIA, we did find new driving mechanisms of EUV waves in some non-CME-association eruptions. For example, large-scale EUV waves can be driven by coronal jets directly, sudden loop expansions due to the impingement of other disturbances, and periodic expanding motion of the unwinding helical structure of erupting solar filaments. These new results enhanced our understanding of coronal EUV waves. The quasi-periodic fast-propagating waves were detected by the SDO/AIA, and they are tightly associated with quasi-periodic pulsation in solar flares. We will introduce the several possible excitation mechanisms in theory and the corresponding observation evidences.

Oscillations in coronal filaments and prominences

Confined jets in a filament-channel and its interaction with a prominence: large-amplitude oscillations (Contributed)

Manuel Luna (Universitat de les Illes Balears, Spain)
Collaborators: F. Moreno-Insertis

Large-amplitude oscillations in solar prominences are triggered by several mechanisms including eruptions, Moreton waves, and jets among others. In this work, we study the triggering of large-amplitudes oscillation by jets. We numerically simulated the formation of a jet in a filament channel structure that hosts a solar prominence. We have found that there are two reconnection phases producing two differentiated jets. In addition, there is an Alfvénic disturbance that precedes the jets. The Alfvénic disturbance and both jets collide with the prominence producing large-amplitude oscillations with different polarizations.

Simultaneous longitudinal and transverse oscillations in filament threads after a failed eruption (Contributed)

Rakesh Mazumder (Indian Institute of Astrophysics, Bangalore, India)
Collaborators: V. Pant, M. Luna, and D. Banerjee

Longitudinal and transverse oscillations are frequently observed in the solar prominences and/or filaments. These oscillations are excited by a large-scale shock wave, impulsive flares at one leg of the filament threads, or due to any low coronal eruptions. We report simultaneous longitudinal and transverse oscillations in the filament threads of a quiescent region filament. We observe a large filament in the northwest of the solar disk on July 6, 2017. On July 7, 2017, it starts rising around 13:00 UT. We then observe a failed eruption and subsequently the filament threads start to oscillate around 16:00 UT. We analyse oscillations in the threads of a filament and utilize seismology techniques to estimate magnetic field strength and length of filament threads. We placed horizontal and vertical artificial slits on the filament threads to capture the longitudinal and transverse oscillations of the threads. Data from Atmospheric Imaging Assembly onboard Solar Dynamics Observatory were used to detect the oscillations. We find signatures of large-amplitude longitudinal oscillations (LALOs). We also detect damping in LALOs. In one thread of the filament, we observe large-amplitude transverse oscillations (LATOs). Using the pendulum model, we estimate the lower limit of magnetic field strength and radius of curvature from the observed parameter of LALOs. We show the co-existence of two different wave modes in the same filament threads. We estimate the magnetic field from LALOs and suggest a possible range of the length of the filament threads using LATOs.

Slow magnetoacoustic waves in coronal loops

Topics on active region oscillations (Invited)

Andrea Costa (IATE-CONICET, Argentina)
Collaborators: M. Cécere, E. Zurbriggen, V. Sieyra, H. Capettini, A. Esquivel, G. Stenborg

I will present a review of recent works on active region oscillations. In one case we numerically analyze the capability of different type of perturbations -associated with usual environment energy fluctuations of the solar corona- to excite slow and sausage modes in solar flaring loops. We find that local loop energy depositions of typical microflares are prone to drive slow shock waves that induce slow mode patterns. The slow mode features are obtained for every tested local energy deposition inside the loop. Meanwhile, to obtain an observable sausage mode pattern a global perturbation, capable of modifying instantaneously the internal loop temperature, is required, i.e. the characteristic conductive heating time must be much smaller than the radiative cooling one. In other case, assuming a thin flux tube approximation, the cut-off periods of slow-mode magnetoacoustic-gravity waves that travel from the photosphere to the corona are analytically obtained considering a non-isothermal gravitationally stratified atmosphere in hydrostatic equilibrium; we also include the variation of the mean atomic weight. We discuss the cut-off results varying the intensity and the magnetic scale height of the magnetic field for different transition region profiles. We show that the cut-off periods obtained are consistent with observational results of a particular active region.
Within the limitations of our model, we show that slow monochromatic oscillations of the solar atmosphere are the atmospheric response, at its natural frequency, to random impulsive perturbations, and not a consequence of the forcing from the photosphere. A final reflection about the relation between coronal and chromospheric mutual influences is offered.

Determination of transport coefficients by coronal seismology of slow-mode waves observed with SDO/AIA (Invited)

Tongjiang Wang (CUA and NASA-Goddard Space Flight Center, USA)
Collaborators: L. Ofman and S. Bradshaw

Longitudinal intensity oscillations generated in flare-heated coronal loops were recently observed with SDO/AIA in 94 and 131 A channels. These oscillations have been interpreted as standing or reflected propagating slow magnetoacoustic waves. The propagation, damping, and excitation mechanisms of such slow-mode waves in flaring loops are still poorly understood. In this presentation, we present an overview of recent results on determination of effective transport coefficients from observed oscillations by coronal seismology techniques based on linear theory and 1D MHD simulations. We also discuss the role of modified transport coefficients in the quick formation of fundamental modes by impulsive heating based on 1D and 2D modeling.

Compressive oscillations in hot coronal loops (Contributed)

Krishna Prasad Sayamanthula (KU Leuven, Belgium)
Collaborators: T. Van Doorsselaere

Compressive plasma oscillations are routinely observed in flare-related hot coronal loops since their initial discovery as Doppler shift oscillations within SUMER spectra. Based on the observed properties, they are interpreted as standing slow waves. They are often associated with a small confined flare or other reconnection event near one of the foot points of a coronal loop which is believed to trigger these oscillations. Recent high-resolution imaging observations reveal reflected propagating (or sloshing) oscillations which also display similar characteristics. Additionally, separate evidences are also found for standing waves. It has been theorized that depending on the physical conditions within the coronal structure, the sloshing oscillations maybe transformed into standing waves. However, the observations so far uncover only their independent presence without any obvious relation. In this talk, we revisit some of the old data to show that such a transition is indeed existent and discuss the consequences of these new results along with possible seismological applications.

Observations of slow modes above a sunspot: multi-thermal structuring of a coronal loop? (Contributed)

Timothy Duckenfield (KU Leuven, Belgium)
Collaborators: L. Fryer, V. Nakariakov

Considerable advances have been made recently in our understanding of the physics of wave processes in the coronal part of active regions, above sunspots. It is known that significant oscillations of ~3 minutes are prevalent above sunspot umbra, and from observations in different wavelengths there is evidence for the gradual upward propagation of slow magnetoacoustic waves (with the phase speed close to that expected for the sound speed). Essentially vertical wave propagation from the photosphere to the chromosphere is detected in many observations, though fewer data exist for propagation through the transition region to the corona, and in particular the role of the local magnetic geometry is not clear. Nonetheless because coronal loops act as waveguides for these slow magnetoacoustic modes, and their propagation speed depends on temperature, these waves may be used to probe the thermal structure of the loops.

In this talk I will outline some observations in which we find evidence that supports the idea of coronal loops having a multi-thermal structure, as opposed to a monolithic homogeneous plasma. I will also speculate on the rapid damping of these waves, which are an intrinsic trait of these waves and may be indicative of wave-induced thermal misbalance and thermal conduction.

Evidence of a periodic propagating signal in an active region (Contributed)

María Valeria Sieyra (KU Leuven, Belgium)
Collaborators: G. Stenborg, A. Costa, E. Zurbriggen, M. Cécere, A. Esquivel

On 2011 July 6 high spatial resolution images of the solar corona recorded in the extreme ultraviolet (EUV) channels of the Atmospheric Imaging Assembly (AIA) instrument onboard the Solar Dynamics Observatory (SDO) detected a recurrent, arc-shaped intensity disturbance over a sunspot in NOAA AR 1243. The intensity fronts were observed to propagate along a coronal loop bundle rooted in a small area of the dark umbra of the sunspot. Neither signatures of flare activity nor of a coronal mass ejection event were observed in association with the phenomenon. A preliminary analysis suggests that the fronts 1) are accelerated in 171 Å and propagate with a projected, average phase velocity of about 50 km/s, for the other coronal channels the values are of about 40 km/s; 2) the upper photosphere and chromosphere exhibit typical decelerated profiles with speed values according to running penumbral waves 3) all the wavelengths exhibit a pseudo-periodic recurrence with a period of about 3 minutes in the umbra. To shed light on the physical nature of the event, we performed 2D numerical simulations based on a simple potential magnetic field configuration embedded in a gravitationally stratified atmosphere in hydrostatic equilibrium. We perturb the atmosphere forcing a wave below the photosphere with a period of 3 min. We also considered the injection of a periodic flow. In this presentation, we 1) report on the kinematical properties and frequency characterization of the event as observed at the different temperature regimes covered by the SDO/AIA images, and 2) compare them with the results from the numerical simulations carried out. The speed values obtained from numerical simulations are similar to those estimated from observations for 171 Å and we reproduce the periods observed in coronal umbra. In brief, the analysis suggests that we can not distinguish if the recurrent fronts are a signature of a propagating slow-mode magnetoacoustic wave or a periodic flow.

Novel techniques and approaches in coronal seismology

Studying vertical wave propagation using the p-modes modulated by flares (Contributed)

Andrei Chelpanov (Institute of Solar-Terrestrial Physics, Irkutsk, Russia)
Collaborators: N. Kobanov

A small solar flare modulates 3.3 and 5.6 mHz oscillations, which are typically present in the lower layers of the solar atmosphere. The amplitudes of the oscillations increase up to five times their normal amplitudes. Such a brief and well-pronounced wave train serves as a means to probe the speeds of the magnetohydrodynamic waves as it helps avoid the phase lag mismeasurements that occur under regular conditions. The use of the small-flare amplitude modulation allows us to probe the solar atmosphere under conditions close to those in the non-disturbed atmosphere.

A novel approach to calculation of the magnetized plasma dispersion relation (Contributed)

Vladimir V. Annenkov (Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia)
Collaborators: I. V. Timofeev, E. P. Volchok

Electron beam interactions with plasma are considered as the most probable cause of type II and III solar radio bursts. An important tool for studying the physics of beam-plasma interaction is the solution of the dispersion equation of the concerned system. In this report we present a novel approach to dispersion equation solving within the framework of the exact kinetic theory of magnetized plasma, taking into account relativistic effects. In particular, this approach has allowed us to find the regime of enhanced second harmonic EM emission during the coupling of oblique oscillations excited in a plasma by counterstreaming electron beams (V. V. Annenkov et al 2020 ApJ 904 88). The further development of this approach involves the study of low-frequency plasma oscillations, such as Alfvén oscillations and magnetoacoustic waves, and the comparison of the results obtained with the predictions of the MHD theory. It can also be used in the context of studying type III solar radio bursts in a plasma with local density inhomogeneities caused by the propagation of MHD waves.

Modern diagnostic techniques for the solar corona (Invited)

David Pascoe (KU Leuven, Belgium)

The high spatial and temporal resolution provided by the Atmospheric Imaging Assembly of the Solar Dynamics Observatory has allowed the development of advanced observational techniques to probe the solar atmosphere. Forward modelling of the EUV intensity of coronal structures and the seismological analysis of kink oscillations provide powerful diagnostics to constrain properties such as the plasma density and magnetic field strength. Results of numerical simulations can be directly incorporated into our methods. We also increasingly employ Bayesian analysis and Markov chain Monte Carlo sampling to increase the robustness and accuracy of our analysis. These techniques are also being applied to study quasi-periodic pulsations associated with solar and stellar flares.

Legolas - Opening the door to modern MHD spectroscopy (Contributed)

Niels Claes (KU Leuven, Belgium)
Collaborators: J. De Jonghe, R. Keppens

Magnetohydrodynamic spectroscopy can be a powerful tool in astrophysical disciplines, since it quantifies all linear wave modes (including growing and damped modes) for a certain configuration that satisfies thermodynamic and force balance, essentially allowing one to predict the reaction of a given state to perturbations. Obtaining these wave modes is no easy task however, especially when the medium is not spatially homogeneous or when various physical effects are included, both of which are the case in virtually all astrophysical configurations. This is why we developed Legolas, a brand new, modern MHD spectral code, which can calculate the full spectrum of 3D equilibria with 1D variation that balance pressure gradients, Lorentz forces, centrifugal effects and gravity, enriched with non-adiabatic effects in both Cartesian and cylindrical geometries. In this talk I will show how Legolas can be readily applied to a plethora of physical configurations, thereby able to reproduce a great deal of well-established results ranging from p- and g-modes in stratified atmospheres to modes relevant in coronal loop seismology, non-ideal quasi-modes and resistive tearing/rippling modes. Legolas is the first modern linear MHD code to investigate fully realistic astrophysical plasmas, opening the door to high-resolution studies of non-ideal equilibria ranging from loops and jets to stratified atmospheres and accretion disks.

Solar coronal loop oscillations: The fast MHD wave perspective (Invited)

Rekha Jain (University of Sheffield, UK)

Many observed oscillations of solar coronal loops have either *decaying amplitudes* or low-amplitudes that do not exhibit any temporal decay. One of the interpretations is fast MHD modes as superposition of waves generated by localised sources of short impulsive nature and continuous stochastic sources. The oscillatory signal arising from a localised, short-duration source is interpreted as a pattern of interference fringes produced by waves that have travelled different routes and hence different path-lengths through the waveguide. In this talk I will demonstrate how this scenario can lead to waveforms that resemble the observed oscillations. The talk will also address how fast waves can resonantly couple to the Alfvén waves, leading to resonant absorption.

Putting MHD waves in context: the full ion-electron wave diagrams (Contributed)

Rony Keppens (Centre for mathematical Plasma Astrophysics, KU Leuven, BE)
Collaborators: J. De Jonghe

While MHD wave theory has been essential to many success stories in solar coronal seismology, the single fluid MHD description "only" approximates the low frequency, long wavelength behavior of all actual waves in plasmas. If we concentrate on the slow, Alfvén and fast wave pairs - where a pair implies both a forward and a backward propagating version - a true ion-electron plasma actually supports a total of six wave pairs, namely S (slow), A (Alfvén), F (fast), M (modified Langmuir), O and X (electromagnetic). Even in a static and uniform ion-electron plasma, the S, A and F modes are dispersive, in contrast to the non-dispersive MHD limit. I will highlight recent findings concerning the full ion-electron wave dispersion diagram, to appreciate how the MHD limit extends to Hall-MHD, to dispersion relations for cold to warm plasmas, and to generic whistler waves. Phase and group diagrams at varying wavenumbers generalize the phase and Friedrichs diagrams from all MHD textbooks (e.g., “Magnetohydrodynamics of Laboratory and Astrophysical Plasmas”, 2019, Cambridge University Press). This two-fluid wave theory forms the basis for plasma wave spectroscopy, computing all waves and instabilities for a given configuration, beyond the one realized by linear MHD.

Multi-wavelength observations (from radio to gamma-rays) and modelling of quasi-periodic pulsations in solar and stellar flares

On probing the solar and stellar atmospheres by magnetohydrodynamic (MHD) waves (Invited)

Abhishek Kumar Srivastava (Department of Physics, Indian Institute of Technology BHU, Varanasi-221005, India)

The high resolution imaging and spectroscopic observations have revealed ubiquitious presence of magnetohydrodynamic waves in a variety of solar magnetic structures at diverse spatio-temporal scales. These wave modes play a significant role in diagnosing the local plasma and magnetic field properties of the solar atmosphere by the mean of solar MHD seismology. Moreover, their analogy can also serve as a diagnostics tool to the stellar coronae of distant similar stars. In the present talk, I will review the key developments about the observations of MHD waves in the solar and stellar atmospheres since last two decades. The potential role of MHD waves in probing crucial properties of solar/stellar coronae, possible clues about some heating candidates as well as dynamical plasma processes, will be elucidated.

Features and mechanism of the 4-8 GHz emission of weak solar flares (Contributed)

Maria Toropova (Institute of Solar-Terrestrial Physics, Russia)
Collaborators: L. Kashapova, E. Kupriyanova

Nowadays main interest to weak solar flares and microflares, which GOES class is from C down to below A relates to heating of the chromosphere and coronal plasma. However, such events could also be a source of accelerated particles generating microwave emission and propagating through interplanetary space. We present the analysis of the plasma properties of solar flares which GOES class was less than C4.3, but they had a detectable response in the 4-8 GHz range. The considered events occurred in AR 12565 and 12567 on July 20, 2016, and were detected by a new generation instrument, the Siberian Radioheliograph 4-8 GHz (SRH). We analysed flare plasma parameters (temperature, emission measure and spectral index, thermal energy) using microwave data (SRH, Siberian Solar Radio Spectropolarimeter (SSRS) 4-8 GHz and RSTN) and X-ray data (RHESSI, FERMI, GOES). The time profiles of microwave flux from AR 12565 and 12567 were tested for the presence of an oscillatory pattern related to occurrence and features of flares. In particular, we looked for quasi-periodic pulsations demonstrating amplification of their amplitudes or wave trains before the flares.Results of the statistical study and oscillation analysis are discussed.

Quasi-periodic pulsations in circular ribbon flare on 5 March 2014 (Invited)

Elena Kupriyanova (Pulkovo Observatory of RAS, Russia)
Collaborators: L. K. Kashapova, Z. Xu, H. A. S. Reid, D. Y. Kolotkov

The fan-spine magnetic topology and presence of remote sources assume simultaneous operation of different mechanisms of the charged particles acceleration and energy transfer during the circular ribbon solar flares. All of these make the circular ribbon flare an attractive object for investigation, but with difficulties of splitting processes of particle acceleration and plasma heating in different parts of the flare because of the projection effect. We present results of the circular ribbon flare study focusing on the quasi-periodic pulsations (QPPs) observed in different ribbons of this event and in hard X-rays, $H\alpha$, and microwaves. The event was located in the central part of the solar disk and observed with minimal projection effects. We found multi-wavelength QPPs with three significant periods around 150 s, 125 s, and 190 s appearing in different flare ribbons and spectral ranges and having a different origin. As the dominant 150 s period co-existed in $H\alpha$, hard X-ray, and microwave emissions, we associate it with the electron acceleration process in the site of the primary flare energy release. The 190 s period is associated with the three-minute sunspot oscillations. We assume that the 125 s period can be caused by a kink oscillation of the outer spine, connecting the primary reconnection site with the remote footpoint. Methods of the period detection and analysis are discussed, and the interpretation of the results and the flare energy release scenario are presented.

Inexplicit quasi-periodic pulsations during a triple-ribbon solar flare (Invited)

Ivan Zimovets (Space Research Institute IKI of RAS, Russia)
Collaborators: I. N. Sharykin

We report observations of quasi-periodic pulsations (QPPs) with an average period of about 50 s, found in the RHESSI data during a moderate M1.1 triple-ribbon solar flare on July 5, 2012. The pulsations manifest themselves in the temporal profiles of temperature (T) and emission measure (EM) of superhot plasma (kT ~ 3-6 keV), when approximating the flare X-ray spectrum by the bremsstrahlung spectrum of a double-temperature thermal plasma. The pulsations of T and EM are in antiphase - the peaks of T are ahead of the EM peaks by about half a period. Also, QPPs with a similar period are found in the spectral index of nonthermal electrons, if the observed X-ray spectrum is fitted with the bremsstrahlung spectrum of a single-temperature Maxwellian plasma and accelerated electrons with a very soft (-7-9) power-law energy spectrum. The pulsations are not noticeable in the X-ray flux according to RHESSI and GOES data, as well as in the radio data. The pulsations are emitted by a "single" X-ray source that shifts during a flare at a speed below 120 km/s (an average speed is about 14 km/s) along the central flare ribbon located in a narrow (< 5000 km) tongue of negative magnetic polarity between two areas of positive polarity. We interpret the observed QPPs as a result of successive episodes of energy release in different loops of the flare region. Possible triggers of the “propagating” energy release front are discussed, as well as the possibility of an instrumental origin of the QPPs.

Quasi-periodic pulsations in flares: A tool to study the solar-stellar connection (Invited)

Anne-Marie Broomhall (University of Warwick, UK)
Collaborators: the Solar & Stellar QPP Flares ISSI Team, L. Kashapova, A. Larionova & E. Kupriyanova

Flares are observed on the Sun and other stars and despite clear similarities between the two, one important disparity is their energies, with stellar flares predominantly being orders of magnitudes more energetic than solar flares. It is therefore natural to ask whether our Sun is capable of producing one of these so-called superflares, how often other solar-like stars produce superflares and whether those superflares create the same space weather that we see on Earth, as this will impact the habitability of stellar systems. Quasi-periodic pulsations (QPPs), which are quasi-periodic modulations observed in the lightcurve of a flare, appear to be a common, if not intrinsic, feature of both solar and stellar flares. QPPs, therefore, have the potential to provide a solid link between the physics of solar and stellar flares and to advance our understanding of stellar magnetism in general. However, QPPs are notoriously difficult to detect reliably and robustly. To stress-test current state-of-the-art detection mechanisms, as part of an ISSI team, we produced a database of artificial stellar flare lightcurves that both did and did not contain QPPs. Cutting-edge detection techniques, including robust Fourier and wavelet methodologies, Empirical Mode Decompositions, MCMC flare lightcurve fitting, and Gaussian process modelling, were used to determine which light curves contained QPPs, with the aim of establishing a list of recommendations of usage of each of these methods. Here I will describe the results of this exercise, focusing on the strengths and weaknesses of each method. An important aspect of the exercise was utilising an appropriately selected underlying flare shape as this could impact a user's ability to detect QPPs depending on method. One of the shapes we used was based on the flare template found by Davenport et al (2014) to aptly describe flares observed in white light on an M dwarf. We have since extended the results of Davenport to solar flares, looking at the average flare morphology in three SDO/AIA channels. I will describe subtle differences that are found between the solar and M dwarf flare profiles, which, if not properly accounted for in QPP-detection techniques, could lead to false detections.

New insights into quasi-periodic pulsations in solar and stellar flares from recent statistical surveys (Invited)

Andrew Inglis (NASA-Goddard Space Flight Center, USA)

Quasi-periodic pulsations (QPPs) are a fundamental feature of both solar and stellar flares. In the solar domain, QPPs have been observed across a wide variety of wavelengths for several decades, and have been extensively studied on an individual basis. However, until relatively recently there have been few attempts to perform large sample size analyses of this phenomenon. Fortunately, in the last several years the availability of robust analysis techniques coupled with large observational datasets has enabled a number of large-sample studies of QPPs in flares in both the solar and stellar domains. In this talk, I present an overview of these recent results, and explore the key insights that have been gained from this type of approach. This type of analysis can help us to answer some fundamental questions regarding QPPs, such as how often they occur in flares, how they are linked to their source active regions, whether there is a relationship between key flare parameters and QPP properties, and finally the nature of the solar-stellar QPP connection.

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Topical Collection of Solar Physics on "Magnetohydrodynamic (MHD) Waves and Oscillations in the Sun's Corona and MHD Coronal Seismology"

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New observational capabilities for studying quasi-periodic pulsations with the Siberian Radioheliograph

Sergey Anfinogentov (Institute of Solar-Terrestrial Physics, Irkutsk, Russia)

Observations of solar flares in the microwave band is a crucial source of information about the plasma parameters, dynamics, and energy release rate in the flare. It is important for studying quasi-periodic pulsations (QPP) associated with magnetohydrodynamic oscillations. In this talk, we present observational capabilities provided by Siberian Radioheliograph (SRH) operating in the 3-24 GHz range. The instrument will consist of three antenna arrays operating in 3-6 GHz, 4-12 GHz and 12-24 GHz bands. The first 3-6 GHz array is planned to be commissioned by the end of 2020. The data products of SRH include correlation curves and multiwavelength radio-images of the Sun. The individual frequencies can be dynamically tuned allowing for trading spectral versus temporal resolution. For instance, solar flares can be observed with the high cadence of about 1 seconds but limited number of frequency channels, while for the observing active regions in their quiet stage the number of channels can be substantially increased with longer imaging interval (i.e. 10 seconds). To give an idea of future observational possibilities, we present examples of QPP light-curves and images observed by 48-antenna SRH prototype which is routinely observing the Sun at 32 frequencies within 4-8 GHz band (5 frequencies before 2018) since 2016 with the cadence about 10 seconds. The radio images can be synthesized by request for almost any observational day since 1 January 2016, and are ready to use for scientific purposes.