CESRA 2023 Workshop

Abstracts

July 3–7, 2023

WG 1

Sun-Earth connection and the inner heliosphere

1.1 Multi-spacecraft observations of solar radio bursts and anisotropic scattering of radio waves [Invited]

S. Musset (1), L. Siebenaler (2), O. Witasse (1), B. Sanchez-Cano (3), S. Joyce (3), A. Vecchio (4,5), X. Bonnin (5), V. Krupar (6), M. Maksimovic (5), B. Cecconi (5), P. Zhang (7), E. Kontar (8) & N. Chrysaphi (5,9)

(1) ESA/ESTEC (2) University of Leiden (3) University of Leicester (4) Radboud University (5) LESIA, Observatoire de Paris, PSL (6) NASA GSFC (7) University of Helsinki (8) University of Glasgow (9) LPP, Sorbonne University

With the current fleet of heliospheric and planetary missions measuring the radio flux in the heliosphere, we are able for the first time to measure radio bursts simultaneously from multiple positions in the heliosphere. We present here how these measurements are used to calculate the directivity profiles and intrinsic radio burst intensity for a sample of events observed by four spacecraft: Solar Orbiter, Parker Solar Probe, STEREO-A and Wind. By comparing these observations to the predictions resulting from ray-tracing simulations of radio-wave propagation in the heliosphere, we are able to probe the importance of anisotropic scattering of radio-waves due to density fluctuations in the heliosphere. We will finally discuss how we can use planetary missions to enhance our set of measurements, with the example of radio bursts measured by the MARSIS instrument on Mars Express.

1.2 Understanding interplanetary radio emissions in the era of Parker Solar Probe and Solar Orbiter [Invited]

I.C. Jebaraj

University of Turku

Over the past two decades, space-based radio observations made by Wind, and STEREO A & B (Solar Terrestrial Relations Observatory Ahead and Behind) have given us the opportunity to study various aspects of different types of interplanetary radio emissions. However, the observations by the recently launched Parker Solar Probe (PSP) and Solar Orbiter (SolO) provide us, for the first time, a unique opportunity to study radio emissions at distances close to their source. Combining the observations from all spacecraft also makes it possible to study radio emissions as observed at different distances from the Sun and from different vantage points. In this talk, I will address different aspects of the generation of radio emission as observed by PSP, particularly focusing on the type III radio bursts, which are signatures of fast electron beams propagating along the open or quasi-open field lines. During the presentation, I will delve into the characteristics of the fundamental

and harmonic components of type III radio bursts, such as time-profile asymmetry, time-delay, and polarization. Through these observations, we gain further insight into the mechanisms behind the generation of these radio bursts. Additionally, I will present extraordinary observations of the structured type III radio bursts. Lastly, I will showcase how the new missions have revolutionized our capabilities to track radio sources through the heliosphere.

1.3 Solar energetic particle acceleration in CME-driven shocks: Insights from numerical simulations and data analysis [Invited]

A. Afanasiev (1), R. Vainio (1), N. Dresing (1), N. Wijsen (2,3), J. Gieseler (1), S. Nyberg (1), L. Annie John (1), C. Palmroos (1) & N. Talebpour Sheshvan (1)
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Solar flares and coronal mass ejections (CMEs) are often associated with fluxes of solar energetic particles (SEPs). The origin of SEPs as well as the conditions of their propagation in the coronal and solar wind plasmas have been thoroughly studied because, apart from the fundamental interest, they have important practical implications. The established understanding is that large, gradual SEP events originate from shock waves driven by CMEs. However, the detailed picture of particle acceleration in shocks is still elusive. At the same time, novel spacecraft observations by the recently expanded spacecraft fleet provide new opportunities to solve the puzzles of SEP acceleration and transport. This talk will address recent developments towards a better understanding of SEP acceleration in CME-driven shocks from the perspectives of numerical simulations and data analysis. More specifically, the focus will be given to the role of self-generated turbulence in the acceleration of ions (protons) and the stochastic shock drift acceleration (SSDA) mechanism of electrons. Furthermore, easy-to-use SEP data analysis tools recently developed in the framework of the SERPENTINE EU H2020 project will be outlined. Finally, application of the SEP acceleration and transport modelling in the space weather context will be briefly discussed. This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 (SERPENTINE).

1.4 First results on interplanetary electron events obtained by joint observations of remote-sensing and in-situ instruments on Solar Orbiter

A. Warmuth (1) on behalf of the joint STIX-EPD-RPW-EUI working group
(1) Leibniz Institute for Astrophysics Potsdam (AIP)

We present the first statistical results on impulsive electron events obtained by joint observations of remote-sensing and in-situ instruments on Solar Orbiter. We use the Energetic Particle Detector (EPD) to measure the properties of the electrons (time profile, anisotropy, maximum energy, inferring the injection time at the source, etc.), as well as to determine the particularities of the composition in the suprathermal energy range. Also, X-ray observations from the Spectrometer/Telescope for Imaging X-rays (STIX) constrain the energetic electrons in the solar flare in terms of timing, spectrum, and location. Type III radio bursts detected by the Radio and Plasma Waves (RPW) instrument are used to link the nonthermal X-ray peaks to the interplanetary electron beams. Finally, the Extreme Ultraviolet Imager (EUI) provides context on the flare evolution. We use a large event sample obtained during the first 2.5 years of the Solar Orbiter mission, which covers a wide range of radial distances ranging from as close as 0.33 au to 1.02 au.

1.5 Radio Triangulation of subsequent type III radio bursts

K. Deshpande (1, 2), J. Magdalenič (1, 2), I. C. Jebaraj (3) & V. Krupar (4, 5)

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Type III radio bursts are the signatures of fast electron beams travelling along open or quasi-open magnetic field lines. Although these bursts are studied for decades there are still many unknowns about the propagation of the fast beams and the associated emission processes. In this study we focused to type III radio bursts observed by the space-based instruments at frequencies below 30 MHz. We study the time profiles of these, so called interplanetary (IP) type III radio bursts, their spectral characteristics, and the positions of the associated radio sources in the 3D space. Some of the recent case studies indicate that the electron beams, associated with the IP type IIIs, do not always propagate along the Parker spiral, contrary to the usual widely accepted opinion. The only way to test that and map the propagation path of fast electron beams is while employing the so called direction-finding observations and the radio triangulation method. In this study we employ the radio triangulation to investigate how the proximity in the 3D space, of the subsequent radio bursts, and/or fundamental-harmonic burst pairs, influences the accuracy of the estimated radio source positions. We have analyzed the spectral and time profiles and the 3D source positions of the type III radio bursts appearing in several isolated groups observed in 2019, 2020 and 2021. Our first results indicate that in a case of subsequent (appearing within few minutes) type III bursts propagating along the closely spaced magnetic field lines the radio triangulation mostly provides the single radio source position in a 3D with the large source area. On the contrary, for the case of clearly isolated type III bursts the obtained radio source areas are significantly smaller. This effect is particularly accented at the higher direction-finding frequencies of 800 – 2000 kHz.

1.6 Mapping propagation of the type III radio bursts

J. Magdalenic (1,2), I. Jebaraj (3), S. Pavai Valliappan (1), P. Zucca (4), A. Kouloumvakos (5) & V. Krupar (6,7)

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The most frequently observed radio bursts are so called type III bursts, radio signatures of the very fast electron beams. It is generally considered that the type III radio bursts propagate alone the open and quasi open magnetic field lines roughly following the Parker Spiral. In order to test this hypothesis our study is focused on mapping the propagation path of the group of type III bursts using both, ground-based and space-based radio observations. During April, 2019, several groups of type III radio bursts were observed by LOFAR (Low Frequency Array), and by instruments on Stereo A, Wind and Parker Solar Probe (PSP). We studied a well observed group of type III bursts, during time interval 16:40-17:00 UT, on April 03. Employing radio triangulation method the 3D positions of the type III radio sources were obtained providing the trajectory of the associated fast electron beam. First results show that the type III bursts do not follow, as generally considered, Parker spiral but they propagate strongly southward from their source region. It is possible that this unusual propagation path is induced by the weak CME that preceded the radio bursts and disturbed the ambient solar conditions.

1.7 Observations of the Sun and heliosphere using LOFAR for a co-ordinated ground- and space-based approach to Space-Weather research.

P. Zucca (1), D. Morosan (2), M. Bisi (3), B. Dabrowski (4), P. Gallagher (5), K. Kozarev (6), A. Krankowski (4), J. Magdalenic (7), B. Matyjasiak (8), H. Rothkaehl (8), H. Reid (9) & C. Vocks (10)
(1) ASTRON, (2) University of Helsinki, (3) RAL, (4) University of Warmia, (5) DIAS, (6) BAS, (7) ROB, (8) CBK, (9) UCL, (10) AIP

Understanding and modelling the complex state of the Sun-solar wind-heliosphere system, requires a comprehensive set of multiwavelength observations. LOFAR has unique capabilities in the radio domain. Some examples of these include: a) the ability to take high-resolution solar dynamic spectra and radio images of the Sun; b) observing the ionospheric scintillation and the iterplanetary scintillation (IPS) of distant, compact, astronomical radio sources to determine the density, velocity and turbulence structure of the solar wind; and c) the use of Faraday rotation as a tool to probe the interplanetary magnetic-field strength and direction. However, to better understand and predict how the Sun, its atmosphere, and more in general the Heliosphere works and impacts Earth, the combination of in-situ spacecraft measurements and ground-based remote-sensing observations of coronal and heliospheric plasma parameters is extremely useful. The PSP mission is observing the solar corona and near-Sun interplanetary space. Two instruments on the spacecraft are of particular interest, FIELDS measuring the radio emission, electric and magnetic fields, and WISPR imaging coronal streamers, coronal mass ejections (CMEs), their associated shocks, and other solar wind structures in the corona and near-Sun interplanetary space. In this talk, the different observing modes of LOFAR and several results of the joint LOFAR/PSP campaign will be presented, including fine structures of radio bursts, localization and kinematics of propagating radio sources in the heliosphere, and the challenges and plans for future observing campaigns including PSP and Solar Orbiter.

1.8 C6.2 class flare parameters inferred with a 3D geometry of flare database

V. Cuambe (1,2,3), J. Costa (4) & P. Simões (5)
(1) AIR Centre, (2) RAEGE, (3) CICGE,DGAOT, FCUP, (4) INPE, (5) CRAAM

We analyzed a GOES C6.2 class flare on 27 October 2003 on the heliographic position S20E29. Based on the essential parameters of its microwave emission, we inferred a set of geometric and physical parameters to characterize a solar flare using a developed database of a simplified model of a 3D geometry of a magnetic loop. Based on the general properties of known solar flares and convoluted with the instrument resolution to replicate the observations from the Nobeyama radio polarimeter (NoRP) spectra and the Nobeyama radio-heliograph (NoRH) brightness maps. Observed spectra and brightness distribution maps were compared with the modeled spectra and images in the database, indicating a possible range of unknown parameters. We computed a weighted mean of one hundred best model parameters ordered by increasing χ^2. The solution was optimized as guess input to a final refinement with the Pikaia algorithm. We analyzed six different times, representing a flare's gradual, impulsive, and decay phases. We found at the time of burst maxima the energy spectral index $\sim$5.74, photospheric magnetic field $\sim$2543 G, non-thermal electron density$\sim 10^9$ cm^{-1}. We conclude that the physical parameters (magnetic field, energy spectral index, and non-thermal electron densities) are well recovered. However, the geometric parameters such as inclination, asymmetry, azimuth, loop radius, loop height, and foot separation are hard to fit due to a lack of instrument resolution of a precise geometry of a loop-like flare, eventually due to a loop-top emission or small-size loops that are not resolved.

1.9 Self-consistent modeling of particle acceleration in shocks [poster]

A. Afanasiev, S. Nyberg, L. Annie John & R. Vainio
University of Turku, Finland

By current understanding, large gradual solar energetic particle (SEP) events are caused by shock waves driven by coronal mass ejections (CMEs). While analytical solutions of particle distribution functions around shocks exist for one-dimensional steady-state theory, time-dependent and/or multi-dimensional systems cannot generally be solved analytically, motivating investigation of numerical models. In this poster we will present results from the self-consistent proton acceleration and Alfvén wave generation model SOLar Particle Acceleration in Coronal Shocks (SOLPACS) [Afanasiev et al. 2015], evaluate the role of energetic particle injection and particle focusing in correspondence between simulation results and observations, and outline ideas for improving the accuracy and performance of self-consistent numerical models of particle acceleration in shocks. This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 (SERPENTINE).

References:
Afanasiev, A., Battarbee, M., & Vainio, R. 2015: Astronomy & Astrophysics 584, id. A81

1.10 Open-Source Analysis Platform for Solar Energetic Particles provided by SERPENTINE [poster]

A. Afanasiev (1), C. Palmroos (1), J. Gieseler (1), N. Dresing (1), D. E. Morosan (2), E. Asvestari (2), A. Yli-Laurila (1), D. J. Price (2), S. Valkila (1) & R. Vainio (1)
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Combining remote sensing observations with in-situ measurements is key to fully comprehend solar eruptive processes. The recently expanded heliospheric spacecraft fleet gives unique opportunities to investigate these processes from multiple viewpoints. But combining all these distinct observations from various instruments onboard different spacecraft is a bothersome task. To achieve maximal impact for exploitation of this data by the wider scientific community, the EU Horizon 2020 project SERPENTINE aims at providing a versatile set of tools. They are provided as open-source Python Jupyter Notebooks and are aimed at non well-versed programming scientists. Next to extensive examples on how to use the multi-spacecraft spatial configuration and solar magnetic connection plotter Solar-MACH, an analysis platform for studying the energetic particle component of the in-situ observations of solar energetic particle (SEP) events has been developed. This analysis platform consists of plotting tools (e.g, energetic particle time series or dynamic spectra) as well as analysis software that allow to automatically derive SEP onsets or estimate the path length and injection time of these particles using a time-shift analysis approach. In this presentation, we will give an overview on the already available set of tools and instructions on how to use them, which is also possible completely in the cloud on SERPENTINE's own JupyterHub server. This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 (SERPENTINE).

1.11 Electron beam energy distributions, Langmuir waves and associated Type III radio bursts measured by Solar Orbiter

C. Y. Lorfing & H.A.S. Reid
University College London

Numerous solar electron events with associated type III solar radio bursts have recently been measured by Solar Orbiter's Energetic Particle Detector (EPD) and the Radio and Plasma Wave (RPW) in-situ instruments.

These exciting measurements allow us to probe and quantify beam-plasma interactions and how they modify the electron spectrum during the particles' transport in the heliosphere. Previous observations at 1 AU, and numerical simulations have investigated the electron beam energy spectrum, fitting the peak flux with a power-law and identifying a spectral break around 60 keV. The new, high-resolution Solar Orbiter data provides us with an excellent opportunity to identify which physical processes are responsible for the spectral break present in the electron spectra. We use a combination of EPD and RPW data products to analyse 43 events that occurred in the solar wind. Each electron event shows a varying number of spectral breaks, and we look at how the electron distribution function varies around these spectral breaks in the electron spectrum alongside evidence of Langmuir waves growth in the solar wind. As resonant interactions between the electron beam and the solar wind plasma happen during the beam's journey through the heliosphere, we observe the appearance of a plateau in energy space and a flattening of the electron distribution function, specifically around the spectral breaks. We find that for events with associated Langmuir wave growth, the energy range of electrons experiencing this quasi-linear relaxation due to wave-particle interactions also occurs around the spectral breaks. This work provides further understanding of how quasi-linear relaxation from wave-particle interactions shapes electron spectra as they travel through the solar wind.

1.12 STIX source imaging and magnetic connectivity for a large sample of SEP events

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(1) Leibniz Institute for Astrophysics Potsdam (AIP), (2) Institut de Recherche en Astrophysique et Planétologie (IRAP)

During the cruise phase and the first year of the nominal mission, the instrument EPD on board Solar Orbiter has detected more than 200 energetic electron events. Most of them can be associated with X-ray flares seen with the STIX instrument. For those events with enough counts in the non-thermal range (E ¿ 10 keV), X-ray images can be generated with high fidelity and a position accuracy much better than 1 arcmin. At the same time, the most likely region on the Sun that is magnetically connected with the spacecraft can be derived from models. Here we show the distribution of positions and morphologies for the flares that give rise to SEP events. We then discuss how this agrees with expectations from the magnetic connectivity tool developed at IRAP.

WG 2

Electron acceleration and radio emission in solar flares

2.1 An Overview of Particle Acceleration Modelling [Invited]

P.K. Browning
University of Manchester

It is generally accepted that flares are caused by a release of stored magnetic energy through magnetic reconnection, and that a substantial fraction of this released energy is transmitted to energetic (non-thermal) electrons and ions. However, modelling the processes by which these particles are accelerated is challenging - especially due to the requirement to encompass a vast range of spatial and temporal scales, from the global scales of Active region magnetic fields (well modelled by fluid approaches) to the microscopic plasma kinetic scales. Furthermore, reconnection in flares departs from classical models through being time-dependent and three-dimensional, and is likely to both cause, and be affected by, turbulence and waves. I will present an overview of the current understanding of particle acceleration processes and of modelling approaches which attempt to integrate fluid and kinetic scales. Forward modelling of emission - such as radio emission from non-thermal electrons – can assist in confronting models with observation data. As an illustration of this, I will describe some recent work predicting quasi-periodic pulsations in microwave emission arising from a simulated flaring twisted loop. I will also present recent data-driven modelling predicting particle precipitation and escape in some observed flares.

2.2 The Spectrometer/Telescope for Imaging X-rays: Solar Orbiter's X-ray Eyes on the Sun [Invited]

D. Ryan (1), S. Krucker (1) and the STIX team
(1) University of Applied Sciences Northwest Switzerland

The Spectrometer/Telescope for Imaging X-rays (STIX) is the X-ray spectroscopic imager onboard Solar Orbiter. It can produce simultaneous spectra and images in any energy band between 4 and 150 keV at cadences down to 0.5 seconds. This gives it access to valuable diagnostics of non-plasma heating and non-thermal electron acceleration in the low corona during solar flares. This is highly complementary to the physical processes probed by radio observations. In this presentation we outline the STIX instrument, its operations and data products and highlight how STIX can complement solar radio observations.

2.3 Imaging of Coherent Microwave Bursts with EOVSA

D.E. Gary (1), B. Couthino (1), G.D. Fleishman (1) & B. Chen (1)
(1) New Jersey Institute of Technology

We report microwave imaging of two bursts with coherent emission at unusually high frequencies, up to 12 GHz in one case. The two events are very different, with one associated with an erupting filament in a spotless region and the other a more typical flare. We compare the characteristics of the coherent burst source regions with those of the accompanying gyrosynchrotron sources, focusing on the magnetic field and plasma environments, to account for the escape of the coherent radiation.

2.4 Detailed look at the temporal correlation between hard X-ray flare and type III radio bursts

S. Bhunia (1,2), L. Hayes (3), S. Maloney (1) & P. T. Gallagher (1)
(1) Dublin Institute for Advanced Studies, (2) Trinity College Dublin, (3) European Space Agency, ESTEC

It is well known that flare-accelerated electrons can produce both hard X-ray (HXR) emission and Type-III radio bursts. The HXR emission is produced by the accelerated electrons propagating towards the chromosphere where they deposit their energy while Type-III radio bursts are produced by the accelerated electron beams traveling towards the outer solar atmosphere. Hence a temporal correlation between these two kinds of emission may imply a common origin of the accelerated electrons providing insight into the acceleration process, and allows us to connect electrons at the Sun to those in the heliosphere On 2022-Nov-11 11:30 - 12:00 UT, the Spectrometer Telescope for Imaging X-rays (STIX) on Solar Orbiter observed a highly energetic flare event with an excellent time resolution of 0.5 s. Simultaneously there were observations of multiple coronal and interplanetary Type-III radio bursts from several instruments such as WIND/WAVES, NENUFAR, I-LOFAR and ORFEES spanning the frequency range from 1 - 1000 MHz. I-LOFAR provides high-sensitivity imaging spectroscopy in the range of $\sim$10-240 MHz with a time resolution of 1.31 ms and a frequency resolution of 195 kHz. We examine the temporal correlation between the X-ray and radio time series and discuss the relationship between the two and what it implies about the origin of the electron populations producing these two kinds of radiation. We also do multiwavelength imaging analysis using AIA, STIX and NRH to understand the evolution of the magnetic field topology before and during the eruption.

2.5 Statistical study of type III bursts and associated HXR emissions

N. Vilmer (1) & T. James (on leave from 1)
(1) LESIA, Observatoire de Paris

Energetic electrons may produce closely temporarily related hard X-ray (HXR) emission while interacting with the dense solar atmosphere and radio type III bursts when propagating from the low corona to the interplanetary medium. We present here new results on the correlation between the number and spectrum of HXR-producing electrons and the type III characteristics (flux, starting frequency). This new study is based on thirteen years of data between 2002 and 2014 and is based on $\approx$200 events with a close temporal association between HXR emissions and radio type III bursts in the 450-150 MHz range. We used X-ray flare observations from RHESSI and FERMI/GBM to calculate the number of electrons giving rise to the observed X-ray flux and observations from the Nançay Radioheliograph to calculate the peak radio flux at different frequencies in the 450-150 MHz range. Under the assumption of thick-target emissions, the number of HXR-producing electrons and their energy spectra were computed. The correlation between electron numbers, power-law indices, and the peak radio fluxes at different frequencies were analysed as well as potential correlations between the electron numbers and starting frequency of the radio burst. We shall present the results of this analysis and discuss them in the framework of results from previous studies and in the context of numerical simulations of bump-in-tail instabilities and subsequent radio emissions.

2.6 Imaging a Large Coronal Loop Using Type U Solar Radio Burst Interferometry

J. Zhang (1), H.A.S. Reid (1), E. Carley (2), L. Lamy (3,4), P. Zucca (5), P. Zhang (6) & B. Cecconi
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Solar type U radio bursts are generated by electron beams that travel along closed magnetic loops in the solar corona. The low-frequency (¡100 MHz) U-bursts are powerful diagnostic tools for studying large-sized coronal loops that reach the middle and upper corona. The descending leg (the component drifting from low to high frequency) of U-bursts, which is weaker and more diffuse than the ascending leg (high to low frequency), has been less studied due to observational limitations. However, new-generation radio interferometers, such as the Low-Frequency Array (LOFAR), provide imaging spectroscopy of U-bursts with higher frequency and temporal resolution than before. In this study, we analyzed LOFAR interferometric data of a U-burst observed on June 5, 2020, which has a bright and clear 'U'-shaped structure between 10 to 90 MHz. We found that the velocity of the electron beam decreased while traveling up the ascending leg and down the descending leg of the loop. We also found evidence supporting symmetry in physical parameters, including density, temperature, and pressure, as well as symmetry in the flux tube size of the coronal loop.

2.7 Can a deep learning approach of detecting solar radio bursts perform better than the interquartile range threshold outlier detection method?

A. Gunessee, C. Marqué, A. Martinez Picar, L. Dolla & V. Delouille
Royal Observatory of Belgium

Anyone familiar with the field of solar radio burst detection and classification knows the cumbersome task of having to go through daily observations and manually recording the type of solar radio burst occurring in the spectrograms. Past non-AI based approaches have been applied to avoid or reduce that particular hindrance but with mixed results. One of these methods is an outlier detection rule, namely the interquartile range (IQR) threshold method which is currently running on the spectrograms of the CALLISTO instrument of the Royal Observatory of Belgium. Briefly, this method registers a burst when the brightness distribution over time of the spectrogram is higher than the sum of the third quartile with the product of 1.5 and its IQR. This simple criterion can be subject to many false positives and false negatives too, where false positives would be mainly due to RFIs. With the recent rise of big data and AI, we present a prototype model of detecting solar radio burst using YOLOv5. The initial prototype was trained on 306 images and resulted in a precision of 59.5% and a recall of 65.9%. This prototype also made us aware that this initial model iteration was susceptible to falsely detecting lightning strikes as bursts. Following these promising results and valuable lessons learnt, another round of annotations was just completed with roughly 1300 new images, and another class being added to the annotated data, that is, lightning strikes. The new annotations will allow the prospective model to not only detect if and how many solar radio bursts are present in a spectrogram but also classify which types are there. Ultimately, being able to correctly differentiate between genuine solar radio bursts and RFIs, and further classifying them into their different solar radio bursts types would be beneficial to monitoring solar activity and useful to the space weather community.

2.8 Non-thermal and thermal electron signatures during a type IV burst

K.-L. Klein, C. Salas Matamoros & A. Hamini
Observatoire de Paris, LESIA

We report on spectro-heliographic observations of a particularly well-observed type IV radio burst with the ORFEES Radiospectrograph and the refurbished Radioheliograph of the Nançcay Radio Observatory. The type IV burst displays two phases of moving sources, each lasting several tens of minutes. We compare the evolution of the moving type IV sources with SDO/AIA images and conclude that the non-thermal electrons emitting the radio bursts are confined in the erupting flux rope, with a prominent source at the apex of the flux rope. At some time during the event a type III burst is seen on the low-frequency side of the moving type IV emission, and a small electron event is observed aboard Solar Orbiter. We employ combined multi-frequency radio spectrography to investigate the origin of these escaping electrons and their relationship with the confined ones in the moving type IV source. Besides non-thermal electrons the radio images also show a deep depression of the underlying thermal emission of the corona. We investigate the spectral shape of the brightness depression and discuss the implications on the plasma ejected in the prominence under the assumption that the absorbing material is this plasma.

2.9 Flare-accelerated electrons and the evolution of the associated active region

M. Broese & C. Vocks
Leibniz Institute for Astrophysics Potsdam

A multi-wavelength analysis is conducted to study flare signatures both in the low and higher corona. LOFAR, STIX/Rhessi, and AIA data provide an extensive picture about different aspects of flare characteristics. The active region and its thermal evolution are studied through Differential Emission Measure (DEM) reconstructions from AIA data. Flare-accelerated electrons and their radio traces are observed with STIX and LOFAR, respectively. These are in principal all associated with the energy release during the flare process. We focus on fluctuations of the radio sources and the thermal evolution of the active region, and their possible relations. Solar magnetic fields are a binding element between low and high corona, accelerated electrons, and heated flare loops. They are included in the analysis via a Potential Field Source Surface (PFSS) model.

2.10 Fundamental and harmonic emission in LOFAR solar type III radio burst images

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(1) Leibniz Institute for Astrophysics Potsdam (AIP), (2) ASTRON, (3) RAL Space, (4) University of Warmia and Mazury, (5) University of Helsinki, (6) Dublin Institute for Advanced Studies, (7) Royal Observatory of Belgium, (8) Polish Academy of Sciences

LOFAR spectroscopic imaging observations of solar type III radio bursts during an M class flare on 7 September 2017 show distinct compact sources with variations in their positions and intermittent dual structures over a wide range of frequencies. These are interpreted as fundamental and harmonic emission, with the one or other being dominant at times. Sources of fundamental emission at one observed frequency, and harmonic emission from a coronal region where the local plasma frequency is half the observed frequency, can be clearly separated. Thus, it is possible to yield separate lightcurves and to compare the flux evolution of fundamental - harmonic pairs, e.g. 35 MHz and 70 MHz. Both fundamental and harmonic emission should originate simultaneously from the same coronal source region. Variations in burst onset times and apparent source position then provide information on transport effects, like scattering and refraction, of radio waves in the solar corona.

Furthermore, harmonic sources at the lowest observable frequencies are relevant for the transition into the solar wind, and especially useful for combining LOFAR observations with data from the spacecraft currently exploring the inner heliosphere, like Solar Orbiter and Parker Solar Probe.

2.11 Estimating the total energy content in escaping accelerated solar electron beams

A.W. James & H.A.S. Reid
University College London

Quantifying the energy content of accelerated electron beams during solar eruptive events is an outstanding objective that must be constrained to refine particle acceleration models and understand the electron component of space weather. In this study, we deduce properties of a rapid sequence of escaping electron beams that were accelerated during a solar flare on 22 May 2013 and produced type III radio bursts. We use extreme-ultraviolet observations to infer the magnetic structure of the source active region NOAA 11745, and Nançay Radioheliograph imaging spectroscopy to estimate the speed and origin of the escaping electron beams. Using the observationally inferred electron beam properties from the type III bursts and co-temporal hard X-rays, we used simulations of electron beam properties to estimate the electron number density and energy in the acceleration region. We find an electron density (above 30 keV) in the acceleration region of 10^4 cm^{-3} and an energy density of 4.55×10^{-4} erg cm^{-1}. Radio observations suggest the particles travelled a very short distance before they began producing radio emission, implying a very thin acceleration region. A short but plausibly wide slab-like acceleration volume of 10^{26} cm^3 could contain a total energy of 10^{24} erg ($\sim$100 beams), which is comparable to energy estimates from previous studies.

2.12 Nonlinear Diffusion with Advection of Flare Accelerated Electrons and Langmuir Wave Generation: Implications of Quasilinear Time Evolution

E.P. Kontar (1), O. Sirenko (2) & F. Azzolini (1)
University of Glasgow (1), Main Astronomical Observatory, Kyiv, Ukraine (2)

Electrons accelerated by solar flares and observed as type III solar radio bursts are not only a crucial diagnostic tool for understanding electron transport in the inner heliosphere but also an early indication of potentially hazardous space weather events.

Up until now, previous studies have assumed the characteristic time of interaction between the flare-generated electron beam and the surrounding plasma (quasilinear time) to be constant. However, in the present work, we introduce a novel approach where we consider quasilinear time as a function of space and time, and we develop a self-consistent theory describing Langmuir wave generation and electron transport guided by the magnetic field over heliospheric distances.

By solving the governing equations, we can predict the evolution of electron beam density, spectral energy density and brightness temperature of radiation in time and space and, to corroborate the validity of our analytical solution, we compare it to the outcomes of numerical simulations in the small quasilinear time limit.

2.13 Type III burst fine structure driven by Langmuir wave motion in turbulent plasma

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Type III burst fine structure in frequency space has been observed for decades. The formation and motion of type III fine frequency structures is a puzzle, but is commonly believed to be related to plasma turbulence in the solar corona and solar wind. This work combines a theoretical framework with kinetic simulations and high-resolution radio type III observations using the Low-Frequency Array, we quantitatively show that the observed fine structures are caused by the moving intense clumps of Langmuir waves in the turbulent solar corona. Our results show how type III fine structure can be used to remotely analyse the intensity and spectrum of compressive density fluctuations, and can infer ambient temperatures in both coronal and solar wind plasma, substantially expanding the current diagnostic potential of solar radio emission.

2.14 Data-constrained 3D modeling of a solar flare evolution: acceleration, transport, heating, and energy budget

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Solar flares are driven by release of the free magnetic energy and its conversion to other forms of energy—kinetic, thermal, and nonthermal. Quantification of partitions between these energy components and their evolution is needed to understand the solar flare phenomenon including nonthermal particle acceleration, transport, and escape and the thermal plasma heating and cooling. The challenge of remote sensing diagnostics is that the data are taken with finite spatial resolution and suffer from line-of-sight (LOS) ambiguity including cases when different flaring loops overlap and project one over the other. Here we address this challenge by devising a data-constrained evolving 3D model of a multi loop SOL2014-02-16T064620 solar flare of GOES class C1.5. Specifically, we employed a 3D magnetic model validated earlier (Fleishman et al. 2021) for a single time frame and extended it to cover the entire flare evolution. For each time frame we adjusted the distributions of the thermal plasma and nonthermal electrons in the model, such as the observables synthesized from the model matched the observations. Once the evolving model has been validated this way, we computed and investigated the evolving energy components and other relevant parameters by integrating over the model volume. This approach removes the LOS ambiguity and permits to disentangle contributions from the overlapping loops. It reveals new facets of electron acceleration and transport, as well as heating and cooling the flare plasma in 3D. We find signatures of substantial direct heating of the flare plasma not associated with the energy loss of nonthermal electrons.

Fleishman, G. D., Kleint, L., Motorina, G. G., Nita, G. M. & Kontar, E. P. 2021, ApJ, 913, 97

2.15 Statistical studies and correlation investigation between solar flares occurrences and Active Regions' radio spectral evolution

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A wide variety of solar eruptive phenomena such as flares and coronal mass ejections severely shape the interplanetary environment and strongly interact with the Earth magnetic field, posing interesting scientific issues and turning into a possible hazard for space missions and ground facilities.

It has been shown in several studies that there is a correlation between changes in the magnetic field configuration of the solar active regions (ARs) and the eruptive events, up to two days prior to the event. In our studies we are investigating a possible correlation between the ARs' spectral index temporal variation and the eruptive phenomena in the K-band range (18-26 GHz). Our work is conducted in the context of the SunDish project, which aims to map and monitor the Sun at high radio frequencies with the Italian Sardinia (64-m) and Medicina (32-m) Radio Telescopes. To date, we acquired more than 350 solar maps filling the observational gap in the field of chromospheric imaging at these frequencies.

Thanks to the first early science results of the project, we compiled a first catalog of radio continuum solar imaging observations including the multi-wavelength identification of ARs, their brightness and spectral characterization. We are comparing our results with the GOES catalog to correlate our AR data with the flares detections. We initially focused on individual specific cases: for example on November 23rd 2020 we observed an unusual and very soft spectrum (gyroresonance emission component enhancement?) in one of the ARs and just a few hours later a C-class flare occurred arising from the same AR. We are now developing new analysis tools to find and study such interesting cases over a period of a few years on a wide ARs sample. Moreover, we are performing multi-wavelength statistical studies in order to characterize the features of the eruptive events/AR associations and precursors as global phenomena.

2.16 Hot Onset Precursor Events viewed at cm-mm wavelengths

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The GOES soft X-ray data have recently been interpreted to show a "hot onset precursor event"(HOPE for short) phenomenon prior to the impulsive phase of a flare (2021MNRAS.501.1273H). During the HOPE development, which occurs in most flares and lasts for tens of seconds to minutes, the GOES isothermal fits show a smooth increase of emission measure in the range 0.001 to 0.1 $\times 10^{49}$ cm^{-3}, which corresponds to a negligible microwave (free-free) flux level for whole-Sun observations such as the RSTN and NoRP data, ieat levels below one SFU. The HOPE normally appears as a gradual increase, rather than a discrete event or set of events. We have found that the most powerful events may have cm-mm HOPE counterparts ranging up to 100 SFU, with microwave spectra peaking in the few GHz range, but extending to 15.4GHz in SOL2002-07-23. The few events we have studied show no obvious circular polarization. We tentatively interpret them as thermal gyroresonance emission resulting from the hot-onset process operating in strong magnetic fields near major sunspots.

2.17 First detection of the magnetic component of a type III radio burst

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(1) LPC2E - CNRS & Université d'Orléans, (2) LESIA - Observatoire de Paris, (3) IAP - Czech Academy of Sciences, (4) Space Sciences Laboratory - University of California

On October 28, 2021, a powerful flare occurred on the Sun, which accelerated energetic electrons into interplanetary space. The beam of energetic electrons, interacting with the surrounding plasma as it propagated, produced electromagnetic waves at the local plasma frequency in the kHz - MHz range. This type III radio burst has been observed by various spacecrafts and on Earth. RPW and its search coil magnetometer SCM measured the magnetic component of the electromagnetic wave at frequencies between 140 kHz and 450 kHz. Simultaneously, the SCM of FIELDS on Parker Solar Probe also detected the magnetic component of the radio wave at similar frequencies. To our knowledge, this is the first detection in space of the magnetic signature of a radio wave which is not emitted by a planet. These measurements allow to estimate the refractive index of the wave, and to infer the direction of the wave vector.

2.18 Type III radio burst locations and propagation in the solar corona as interpreted with LOFAR interferometric observations

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Radio bursts produced by non-thermal electrons provide unique insights into the complex processes that govern the acceleration and propagation of energetic particles in the Sun's atmosphere and are a vital tool for advancing our understanding of space weather. The acceleration of non-thermal electrons occurs in the vicinity of magnetic reconnection sites in the corona associated with coronal mass ejections and flares. Type III radio bursts are among the most common and intense types of radio bursts, generated by the acceleration of electrons in the solar corona that travel along open and quasi-open magnetic field lines. The acceleration occurs through several types of plasma wave-particle interaction, which can take place in various regions such as magnetic reconnection sites, shock fronts, and coronal holes. The open magnetic field lines allow the energetic electrons to escape from the solar corona and propagate outward into interplanetary space. With state-of-the-art radio instruments such as LOw Frequency ARray (LOFAR), it has now been possible to study these bursts and the structures within them at their origin close to the Sun, in great spectral, temporal, and spatial resolutions. In this paper, we focus on the intrinsic radio source sizes and shapes of individual type III bursts and type III groups. For this, we use the type III bursts observed with LOFAR in interferometric mode between 10-90 MHz. To infer the sizes and shapes (ellipticities) of these radio sources, we use a 2D Gaussian approximation. We investigate the sizes and shapes of fine structures in a type III burst and their variation with frequency. Additionally, we study the propagation of electron beams in the middle corona using radio images.

2.19 Radio and EUV emission from MHD simulations of coronal jets

C. E. Alissandrakis, V. Archontis, S. Patsourakos, K. Moraitis, J. Zhuleku & A. Nindos
University of Ioannina

We performed full 3D MHD simulations of emerging flux, which show the formation and develoment of a jet, which is driven by an eruption. We further computed the expected thermal microwave and mm-lambda emission, as well as the emission in the AIA EUV bands. We will present our initial results and compare them with obsevations. This work was supported in part by the ERC synergy grant 'The Whole Sun'.

2.20 Utilizing a warm-target algorithm to analyze the electron acceleration during the impulsive phase of a solar flare

Y. Luo & E.P. Kontar
University of Glasgow

Solar flares are the most explosive solar activities and are believed to be efficient electron accelerators. However, how those electrons are accelerated remains an outstanding question; one of the obstacles is the limited observational information from the major acceleration site. Hard X-ray (HXR) bremsstrahlung emission and radio gyrosynchrotron emission have demonstrated powerful diagnostics of accelerated electrons during solar flares. Kontar et al. 2023 analyzed the RHESSI HXR and SDO/AIA EUV observations of the well-studied 2017

September 10 flare to obtain the fraction of the accelerated ambient electron population during the impulsive phase. Here, we suggest the derived electron distribution information also satisfies the thick-target model. For an improved estimate of the electron acceleration condition during the impulsive phase of the flare, we utilize the warm-target algorithm for further study. We also compare the results with the previous results based on the thin-target model and those inferred from the microwave emissions.

2.21 Fraction of Electron Accelerated above 20 keV during the Impulsive Phase of a Solar Flare [poster]

E.P. Kontar (1), A.G. Emslie (2), G.G. Motorina (1) & B.R. Dennis (3)
(1) University of Glasgow, (2) Western Kentucky University, (3) NASA/GSFC

Understanding the nature of the process that accelerates particles to high energies is a key question in solar physics and the ratios of the number densities of non-thermal and thermal electrons to the total number density of background electrons in coronal flaring regions is thought to be direct diagnostics of acceleration processes. However, observations of coronal Hard X-ray sources in solar flares are rare and often incomplete. Here, we show, for a well-observed flare on 2017 September 10, that a combination of RHESSI HXR and and the Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) EUV observations provides a robust upper limit of the fraction of the ambient electron population that is accelerated at a given time on the number density of non-thermal ($\geq$20 keV) electrons, expressed as a fraction of the number density of ambient protons in the same volume. This upper limit is about 2 orders of magnitude lower than previously inferred from OVSA microwave observations of the same event. The results indicate that the fraction of accelerated electrons in the coronal region at any given time is relatively small but also that the overall duration of the HXR emission requires a steady resupply of electrons to the acceleration site. Simultaneous measurements of the instantaneous accelerated electron number density and the associated specific electron acceleration rate provide key constraints for a quantitative study of the mechanisms leading to electron acceleration in magnetic reconnection events. Further details are online: https://ui.adsabs.harvard.edu/abs/2023ApJ...947L..13K/abstract

2.22 Study of electron acceleration in interplanetary shocks through in situ observations and simulations [poster]

A. Afanasiev, N. Talebpour Sheshvan, N. Dresing, S. Nyberg & R. Vainio
University of Turku, Finland

Coronal mass ejections (CMEs) are powerful outbursts of plasma and magnetic field from the surface of the Sun to the Interplanetary (IP) space. This study focuses on whether shocks driven by fast CMEs can accelerate electrons to relativistic energies up to 1 AU distance. Time series analysis of High Energy Telescope (HET) observations on board the STEREO spacecraft is used to identify electron energetic storm particle (ESP) events associated with intense IP shocks. We apply a new filtering technique to the whole in-situ shock list of the STEREO mission and find nine cases with significant increases in MeV electron intensities, mostly in the highest energy channel of HET (2.8-4.0 MeV), during the IP shock crossing time. All nine events are associated with IP shocks generated by CMEs traveling at transit speeds of over 900 km/s. Additionally, we will present preliminary results on our modeling efforts of electron acceleration by stochastic shock drift acceleration (SSDA). This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004159 (SERPENTINE).

2.23 Electron and ion-rich X-ray solar flares, and solar radio bursts detected with STIX, EPD and ground-based radio telescopes in December 2022 [poster]

O. Dudnik (1), G. Mason (2), G. Ho (2), R. Allen (2), R. Wimmer-Schweingruber (3), J. Rodriguez-Pacheco (4), F. Espinosa Lara (4), R. Gomez Herrero (4), T. Mrozek (5), A. Awasthi (5) & M. Karlicky (6)

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The solar flares are being characterized by X-ray emission originated due to thermal and non-thermal processes. Sun in X-ray wavelengths is observed by the Spectrometer-Telescope for Imaging X-rays (STIX) onboard the Solar Orbiter mission. A strong non-thermal counterpart of X-ray emission (Hard X-rays/HXR) as observed during the flares is also indicative of the detection of high-energy electron and ion beams that have escaped the coronal loops during the magnetic reconnection process. When flares with strong HXR are detected solar type III radio bursts are registered frequently with their numerous modifications. The e-CALLISTO and specialized worldwide radio telescopes allow us to characterize the non-thermal components in the energy spectra of X-ray flares. At the same time, some X-ray flares are accompanied by ejections of energetic ions starting from He-3 up to Fe-26. We present some preliminary results of a combined study of observations of energetic electron and ion fluxes, X-ray flare parameters, and solar radio bursts in a wide waveband for the events recorded in December 2022. The analyzed period was unique in terms of producing moderate to high solar activity. We noted the presence of three periods with enhanced electrons, light, and heavy-ion fluxes: at the beginning of the month, in the middle, and on 24-26 December. We demonstrate also the presence of extremely anisotropic electron beams detected by the Electron Proton Telescope (EPT) of the Energetic Particle Detector (EPD) for selected events mentioned above and heavy ions detected by the Suprathermal Ion Spectrograph (SIS) of EPD.

WG 3

Coronal mass ejections and associated radio emissions

3.1 Observations of the Radio Emission Associated with CME Shocks and Properties of Acceleration Regions [Invited]

D.E. Morosan (1), J. Pommel (1), A. Kumari (1), R. Vainio (2) & E.K.J. Kilpua (1)

(1) University of Helsinki, (2) University of Turku

Energetic particle populations are ubiquitous throughout the Universe and often found to be accelerated by astrophysical shocks. One of the most prominent sources for energetic particles in our solar system are huge eruptions of magnetised plasma from the Sun called coronal mass ejections (CMEs), which usually drive shocks that accelerate charged particles up to relativistic energies. Accelerated electrons, in particular, can

be observed remotely as low-frequency radio bursts or in situ as large particle fluxes detected by spacecraft. However, it is currently unknown where electrons accelerated in the early phases of such eruptions propagate and when they escape the solar atmosphere. The study of radio emission associated with CMEs can shed some light on these unknowns by tracking the location of these radio emitting electrons in the corona. Here, we present recent results from the field on the acceleration, escape, and propagation directions of radio-emitting electrons during the early evolution of strongly expanding coronal shock waves. We also present new studies that use a three-dimensional (3D) representation of the radio emission locations in relation to the overlying coronal magnetic field, CME or shock wave propagation, magneto-hydrodynamic (MHD) models of the solar corona, and radio spectropolarimetric and imaging observations from ground-based observatories. These recent studies indicate that the first radio emission in the CME eruption, which usually manifests as type II radio bursts, comes from electrons that initially propagate in regions of low Alfvén speeds and mostly along closed magnetic field lines

3.2 Type II Radio Bursts and Other Heliophysical Phenomena [Invited]

N. Nitta
Lockheed Martin Advanced Technology Center

Type II radio bursts are characterized by a relatively slow drift from higher to lower frequencies in a radio dynamic spectrum in metric and longer wavelengths. It is generally agreed that type II bursts come from shock-accelerated electrons, irrespective of the frequencies at which they are observed. Therefore they are supposed to provide useful information on the properties of shock waves that accompany solar transient phenomena. This talk reviews how observations of type II bursts have improved, over the several decades in the past, our understanding of solar flares and large-scale eruptions that may lead to coronal mass ejections. Various relationships are discussed, including metric vs decametric-hectometric (DH) type II bursts, metric type II bursts vs coronal shock waves, type II bursts (metric and DH) vs solar energetic particles, DH and kilometric type II bursts vs sustained gamma-ray emission.

3.3 Space weather and solar radio emissions [Invited]

N. Gopalswamy
NASA Goddard Space Flight Center

A whole host of radio bursts (millimetric to kilometric wavelengths) caused by nonthermal electrons occur during solar eruptions. Radio bursts at low frequencies (¡ 15 MHz) are of particular interest because they are associated with energetic eruptions involving fast and wide coronal mass ejections (CMEs) and large solar flares. Therefore, the low-frequency radio bursts are indicative of CMEs with significant space weather consequences. Three types of low-frequency nonthermal radio bursts are associated with CMEs: Type III bursts due to accelerated electrons propagating along open magnetic field lines, type II bursts due to electrons accelerated in shocks, and type IV bursts due to electrons trapped in post-eruption arcades behind CMEs. Type II bursts are indicative of CME-driven shocks that accelerate protons to high energies that can pose radiation hazard to humans and their technology in space. If Earth-directed, CME-driven shocks compress Earth's magnetosphere causing storm sudden commencement, which is often followed by intense geomagnetic storms. Type III and type IV bursts are also indicative of energetic eruptions. This paper presents a summary of key findings obtained by combining white-light coronagraphic observations with radio dynamic spectra.

3.4 Sources of a “framed” type II radio burst in the corona—An evidence of multiple coronal shock waves

S. Feng (1,2,3), B. Wang(1), L. Wu (2,3), X. Zhao (2,3), Y. Yang (2,3), Y. Chen (1), J. Yan (2,3), J. Wu (2) & C. Wang (1)
(1) Shandong University at Weihai, (2) State Key Laboratory of Space Weather, National Space Science Centre, (3) Yading Space Weather Science Centre, National Space Science Centre

Solar type II radio bursts are due to plasma emission excited by energetic electrons accelerated by shock waves during solar eruptions, and are tracers of shock wave propagation in the corona and inner heliosphere. For interplanetary type II bursts, they are produced by interplanetary coronal mass ejections (CMEs)-shock-accelerated energetic electrons, while in the solar corona the origin of type II bursts and their associated shocks remains an open question and has become a hot research topic. Here we present a typical solar type II radio burst. On the solar radio dynamic spectrum, the harmonics of this type II burst show three nearly parallel branches—two well-defined “fringed” branches (named “F1” and “F2”) and a middle branch (named “MAIN”) with a higher brightness temperature and a larger bandwidth. The observational data show that the sources of F1 are correlated with an ascending coronal loop in terms of appearance time, location, local electron number density, and propagation velocity, the MAIN and F2 are associated with another distinct coronal loop, and all the three are not significantly related to the CME’s leading shock. Our analysis suggests that at least three coronal shocks existed simultaneously during this solar type II burst, i.e. there are multiple shocks in the corona.

3.5 DSRT: A meter wavelength radio interferometer for solar observation

J. Yan, L. Wu, Y. Yang, J. Wu & C. Wang
National Space Science Center, Chinese Academy of Sciences

The Daocheng Solar Radio Telescope (DSRT) is an instrument of the Meridian Project, China’s major national science and technology infrastructure. The principal scientific driver of the DSRT is to monitor the highly dynamic solar activity in the corona, through which coronal mass ejections (CMEs) escape into interplanetary space. Once strong CMEs arrive in the vicinity of Earth, there is a risk of severe space-weather events, and modern high-tech infrastructure and spacecraft may malfunction or even be damaged. Observations with the DSRT will help scientists understand solar bursts and improve the prediction accuracy of catastrophic space-weather events. DSRT is a circular array of 1 km diameter with 313 element antennas, each with an aperture of 6 m. The nominal receiver band is 150–450 MHz, the frequency of solar radio emissions from the high corona. DSRT’s circular array produces a dish-like u–v coverage of $\sim$100,000 independent samples, and samples are distributed quasi-uniformly within the dish. Such coverage can produce a snapshot of $\sim$70,000 pixels every 5 ms in a field of view of $7° \times 7°$ in the 450 MHz channel. The DSRT was proposed in 2013 and approved in 2019. A pair of experimental antennas was built in August 2021, and spectra and interferometric patterns of solar bursts were obtained. In March 2022, a 16-element array was constructed along the circle, and radio images of solar bursts and strong astronomical sources were retrieved. The hardware of the full array and the calibration tower was completed in November 2022. A set of customized processing pipelines, quick-look pipelines, and post-processing software are iterating with the real system. It is expected that the DSRT will switch to the test operation phase in June 2023.

3.6 Deciphering Faint Gyrosynchrotron Emission from Coronal Mass Ejection using Spectro-polarimetric Radio Imaging

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ogy, Newark, USA

Measurements of the plasma parameters of coronal mass ejections (CMEs), particularly the magnetic field and non-thermal electron population entrained in the CME plasma, are crucial to understand their propagation, evolution, and geo-effectiveness. Spectral modeling of gyrosynchrotron (GS) emission from CME plasma has been regarded as one of the most promising methods to estimate spatially resolved CME plasma parameters remotely. The very low flux density of CME GS emission, however, makes this rather challenging. This challenge has recently been overcome using the high dynamic range imaging capability of the Murchison Widefield Array (MWA). Although the detection of GS is now possible routinely, the large number of free parameters of the GS models and some degeneracies between the values of these parameters make it hard to estimate all of them from the observed spectrum alone. These degeneracies can be broken using polarimetric imaging. In this work, we demonstrate this using our newly developed capability of robust polarimetric imaging on the data from the MWA. Very interestingly, we find that spectro-polarimetric imaging not only breaks the degeneracies but also provides tighter constraints on a larger number of plasma parameters than possible with total intensity spectroscopic imaging alone.

3.7 Energetic electron beam traces in CME revealed by interferometric imaging of Herringbone structure in CME

P. Zhang & Diana Morosan
University of Helsinki

Coronal Mass Ejection (CME) is one of the most energetic phenomena on the Sun that have been studied for decades. However, the details of their energy release and associated particle acceleration processes remain unclear. Radio imaging spectroscopy is a powerful tool for tracing signatures of energetic electrons in the solar atmosphere. The fine structures in solar radio bursts (such as herringbone bursts) correspond to the impulsive acceleration of electron beams during a CME eruption. In this work, we present for the first time a high-resolution imaging spectroscopy observation of herringbones accompanying a type II radio burst that occurred on October 16th, 2015. From the imaging analysis of several herringbone group structures, we found that there are herringbone lanes with single-peak and point-like sources, as well as herringbone lanes with multiple-peaks and extended sources. Our observations suggest that numerous complex processes contribute to electron acceleration during the CME eruption.

3.8 Multiwavelength observations of a metric type-II event

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(1) University of Ioannina, (2) University of Athens

We have studied a complex metric radio event that originated in a compact flare, observed with the ARTEMIS-JLS radiospectrograph on February 12, 2010. The event was associated with a surge observed at 195 and 304 A and with a coronal mass ejection observed by instruments on board STEREO A and B near the eastern and western limbs respectively. On the disk the event was observed at ten frequencies by the Nancay Radioheliograph (NRH), in Halpha by the Catania observatory, in soft X-rays by GOES SXI and Hinode XRT, and in hard X-rays by RHESSI. We combined these data, together with MDI longitudinal magnetograms, to get as complete a picture of the event as possible. Our emphasis is on two type-II bursts that occurred near respective maxima in the GOES light curves. The first, associated with the main peak of the event, showed an impressive fundamental-harmonic structure, while the emission of the second consisted of three well-separated bands with superposed pulsations. Using positional information for the type-IIs from the NRH and triangulation from STEREO A and B, we found that the type-IIs were associated neither with the surge nor with the disruption of a nearby streamer, but rather with an extreme ultraviolet (EUV) wave probably initiated by the

surge. The fundamental-harmonic structure of the first type-II showed a band split corresponding to a magnetic field strength of 18 G, a frequency ratio of 1.95 and a delay of 0.23–0.65 s of the fundamental with respect to the harmonic; moreover it became stationary shortly after its start and then drifted again. The pulsations superposed on the second type-II were broadband and had started before the burst. In addition, we detected another pulsating source, also before the second type-II, polarized in the opposite sense; the pulsations in the two sources were out of phase and hence hardly detectable in the dynamic spectrum. The pulsations had a measurable reverse frequency drift of about 2 s^{-1}.

3.9 Imaging an Unusual High frequency Type-II Solar Radio Burst and their features in Lower Corona

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(1) Astronomical Observatory of Jagiellonian University, (2) Institute of Space Sciences, Shandong University

High frequency type-II solar radio burst is rarely observed at frequencies larger than ¿ 300 MHz. Here, we present the first radio imaging study of one such event with frequencies extending from 30 MHz up to $\sim$600 MHz. In addition to its unusually high-frequency, the type-II burst presents other distinct features such as a wide-band continuum, and discontinuous band split. The type-II burst is associated with a solar coronal mass ejection (CME) that has been well captured by the AIA/SDO. The burst is also imaged by NRH at different pass-bands. We found that the burst originates from the top front of a steeping shock structure driven by the dome-like CME. Our main purpose is to investigate the nature of emission features and their association with the EUV eruptive structures so to uncover the physical origin of this unusual type-II radio burst, on the basis of these multi-wavelength data.

3.10 Forecasting CME arrival time to Earth using EUHFORIA and radio observations

A. Valentino (1) & J. Magdalenic (1, 2)
(1) KU Leuven, (2) Royal Observatory of Belgium

We present the study of two CME/flare events observed on December 7th 2020 and October 28th 2021. Both of the studied CMEs were full halo CMEs with the velocity of about 1400 km/s. The events were associated with the long duration GOES C7.4 and the X1.0 flare, respectively. Both of the events were also associated with the radio signatures of the shock wave, so called type II radio bursts, and in situ shock signatures observed by the ACE spacecraft. This study is focused on estimating the influence of the main CME propagation direction on the accuracy of forecasting the CME and CME-driven shock wave arrival time at Earth. Therefore, we have chosen CME with strongly non radial propagation direction. We compare the results of forecasting of the CME-driven shock wave and the CME arrival time at Earth, using two different methods. For the first method we employed the 3D MHD model of the CMEs and the solar wind EUHFORIA and for the second method we used the drift rate of the type II radio bursts and the radial coronal electron density model Saito. In order to obtain the CME characteristics that were used in the modeling with EUHFORIA we employed the EUV and coronagraphic observations. First results show that the forecasted shock arrival time, for both studied events, using the type II radio bursts was about 24h before the shock observed in situ. The CME-driven shock wave arrival time to Earth, as modeled by EUHFORIA, shows about 12h of latency in comparison with the observed in situ shock. We discuss obtained results in the dependence of used different forecasting methods, i.e., on one hand the relative position of the type II emission and the CMEs leading edge and on the other the inability to implement in EUHFORIA and similar MHD models the non-radial direction of the CME propagation.

3.11 Towards a Next-Generation e-Callisto Network

J. Bussons, M. Prieto & M. Fernández
e-Callisto Collaboration

Since 2012, e-Callisto keeps playing a significant role in round-the-clock monitoring of solar radio emission. Its native 45–870 MHz dynamic range can be extended down to 20 MHz with enough sensitivity to detect important events, e.g. reverse-drift and J bursts in the 20–85 MHz range not covered by other types of instruments. Worldwide low-cost geo-coverage and geo-redundancy make it an excellent tool for cross-match studies between ground-based and satellite-borne detectors. Yet its full potential is far from being reached and recognized. A brainstorming process is currently taking place within the e-Callisto Network with the goal of making it a more efficient Space Weather Instrument with updated instrumentation, data quality assessment and user-friendly open-access services for scientists and space-weather operators.

We present progress and plans in topics such as data archiving and processing, absolute calibration; automatic identification and classification of Solar Radio Bursts (SRBs), SRB catalogues, production of merged data files combining multiple stations, prompt alert system and other real-time products, instrumental developments, science case update and international capacity-building workshops. We also invite an updated summary of ongoing discussions on the coordination, funding, maintenance and expansion of ground-based observational networks –such as eCallisto Next Generation– which are taking place in the framework of E-SWAN and other transnational forums.

3.12 Introduction of DSRT Data Processing Pipeline

L.Wu, J.Y.Yan, Y.Yang, & J.Wu
National Space Science Center, Chinese Academy of Sciences

The Daocheng Solar Radio Telescope (DSRT) is a symbolic instrument of the Meridian Project, a major national science and technology infrastructure of China. The principal scientific driver of the DSRT is to monitor the highly dynamic solar activity in the high coronal regions, through which coronal mass ejections (CMEs) escape into interplanetary space. DSRT data processing is a major issue for Scientific requirements. The DSRT data processing pipeline will be introduced, including the data processing method, procedure and scientific data format, etc.

3.13 Radio observations of type II solar burst with a mixture of spectral morphological patterns

A. Koval (1), A. Stanislavsky (2,3), M. Karlicky (1), B. Wang (4), S. Yerin (2), A. Konovalenko (2), M. Barta (1)
(1) Astronomical Institute of the Czech Academy of Sciences, (2) Institute of Radio Astronomy of the National Academy of Sciences of Ukraine, (3) Wroclaw University of Science and Technology, (4) Institute of Space Sciences, Shandong University

Type II solar bursts are radio signatures of shock waves in the solar corona driven by solar flares or coronal mass ejections (CMEs). Therefore, these bursts present complex spectral morphologies in solar dynamic spectra. Here, we report about meter-decameter radio observations of the type II burst on 2014 July 25th with Ukrainian radio telescopes UTR-2 (8.25-33 MHz) and GURT (8.25-78 MHz). The burst demonstrates fundamental-harmonic components, band-splitting, herringbone structure, and spectral break. These specific spectral features, observed jointly in a single type II burst, are rarely detected. To contribute to understanding of such puzzling type II events, we carried out a detailed analysis of the recorded type II dynamic spectrum. In particular, the herringbone pattern has been exploited to study electron density turbulence in the solar corona. We calculated power spectral densities of the flux variations in selected herringbones. The spectral index is in the range of α= -1.69 to -2.00 with an average value of -1.897 which is slightly higher than the Kolmogorov spectral index of -5/3 for fully developed turbulence. We also recognized the second type II burst consisting of three drifting lanes. The lanes onsets coincide in time with the spectral break in the first type II burst. We suppose that the CME/shock passage through a streamer caused the spectral break and triggered the multi-lane type II radio emission. Thus, we support one of the proposed scenarios of type II bursts occurrence as a result of the CME/shock-streamer interaction.

WG 4

Solar atmosphere, radio wave propagation and turbulence

4.1 Scattering in solar radio bursts: implications for the observed properties [Invited]

N. Chrysaphi
Sorbonne Université

A large arsenal of space-based and ground-based instruments is dedicated to the observation of radio emissions, whether they originate within our solar system or not. Any photon whose frequency is close to the fundamental plasma frequency of the heliosphere will interact with density fluctuations, and its trajectory will be altered, influencing properties deduced from observations. Such interactions include absorption, refraction from large-scale density fluctuations, and the most severe of all, scattering on small-scale density fluctuations. I will demonstrate using observations of solar radio bursts, that not only is this scattering anisotropic, but its significance is so large that the true nature of the observed radio sources is distorted. As a result, observations must be corrected before any meaningful properties of the radio exciters or their local environment can be obtained. A combination of observations and advanced radio-wave propagation simulations will be used to illustrate the multitude of propagation effects, as well as to address several long-standing debates related to solar radio busts.

4.2 Active region and solar flare modelling with GX Simulator [Invited]

G. Nita, on behalf of the GX Simulator Team
New Jersey Institute of Technology

To facilitate the study of solar flares and active regions, we have created a modeling framework, the freely distributed GX Simulator IDL package, that combines 3D magnetic and plasma structures with thermal and non-thermal models of the chromosphere, transition region, and corona. Its object-based modular architecture, which runs on Windows, Mac, and Unix/Linux platforms, offers the ability to either import 3D density and temperature distribution models, or to assign numerically defined coronal or chromospheric temperatures and densities, or their distributions, to each individual voxel. GX Simulator can apply parametric heating models involving average properties of the magnetic field lines crossing a given voxel, as well as compute and investigate the spatial and spectral properties of radio, (sub-)millimeter, EUV, and X-ray emissions calculated from the model and quantitatively compare them with observations. The package includes a fully automatic model production pipeline that, based on minimal users input, downloads the required SDO/HMI vector magnetic field data, performs potential or nonlinear force free field extrapolations, populates the magnetic field skeleton with parameterized heated plasma coronal models that assume either steady-state or impulsive plasma heating, and generates non-LTE density and temperature distribution models of the chromosphere that are constrained by photospheric measurements. The standardized models produced by this pipeline may be further customized through specialized IDL scripts, or a set of interactive tools provided by the graphical user interface. In this presentation, I will describe the GX Simulator framework and its applications.

4.3 Recent Spike Burst Observations and CMEs [Invited]

D. L. Clarkson
University of Glasgow

Solar radio spikes are signatures of rapid energy release in the corona on millisecond timescales. Observations indicate that spike occurrences can be associated with fragmented post-flare magnetic reconnection, with numerous events linked to coronal mass ejections (CME). Recent advancements in imaging observations provided by LOFAR have enabled the tracking of individual, decametre sub-second spike sources over tens of millisecond scales. These observations suggest that the spikes were triggered following frequent magnetic reconnection in multiple sites driven by perturbation of the field by a CME, and exhibited a superluminal displacement of their apparent centroids over time. The results are consistent with the spike emission arising from regions with anisotropic density inhomogeneities, with their true source location never observed in radio imaging. Decoupling the apparent sources from the scattering component suggests shorter emission timescales at decametre wavelengths, which could be excited via non-thermal electron beams interacting with coronal turbulence.

4.4 Sizes and shapes of spike radio sources

M. Gordovskyy (1), D. Clarkson (2) & E.P. Kontar (2)
(1) University of Hertfordshire, (2) University of Glasgow

Solar radio spikes can be indicators of short impulses of energy release and particle acceleration in the corona. Therefore, their geometry (sizes, orientations, apparent motion) can be used to understand energetic particle transport and magnetic field structure in the corona. We use a new deconvolution technique to derive sizes and shapes of the spike radio sources observed by the Low-Frequency Array (LOFAR) in the tied array beam mode. We will discuss geometric properties of the spike sources and compare them with the geometric properties of type III emission sources observed in the same events.

4.5 Bohr-van Leeuwen Paradox

K. Shibasaki
Solar Physics Research Inc.

High-energy electrons generated by solar flares concentrate near the top of the magnetic loop and emit microwaves and X-rays. The concentration is due to the mirror force acting on the magnetic moment caused by the motion of the electrons. On the other hand, it has been believed that according to classical physics, thermal electrons do not have a magnetic moment. This is known as the Bohr-van Leeuwen theorem, which states that all magnetism in the matter is a quantum mechanical effect. Magnetohydrodynamics does not include magnetic moments because plasmas are treated in classical physics. We thought this was very unnatural and investigated the basis of Bohr-van Leeuwen's theorem in detail to show that this theorem is wrong. The thermal plasma has a magnetic moment and the Kelvin force acting on it causes an up-flow of plasma along the magnetic field lines, which leads to a concentration of plasma near the top of the closed magnetic field lines and a longer scale height of the atmosphere, etc., as predicted and observed.

4.6 The first measure of the solar radius and the evidence of the coronal physical emission in the centimetric range with the Italian INAF radio telescopes

M. Marongiu (1), A. Pellizzoni (1), S. Mulas (1), S. Righini (2), E. Egron (1) & M. N. Iacolina (3)

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The Sun is an extraordinary workbench to accurately calculate several fundamental stellar parameters. Among these parameters, the solar radius R have been the subject of increasingly accurate measurements and investigations. To date several models (both analitical and physical) were constructed in order to reproduce quantitatively the solar disk and the corona region from radio observations. Despite the importance of having an accurate measurement of R and a deep knowledge of the corona, these subjects are still a matter of debate in the literature.

In this talk we present our first results about the measure of the solar radius and the evidence of the coronal physical emission in the 18-26 GHz band (up to 100 GHz in perspective) with the large single-dish radio telescopes of the Italian National Institute for Astrophysics (INAF), throughout 5 years, from 2018 to early 2023. The coverage of the entire solar disk, the low noise, the accurate absolute calibration, and the great sensitivity of INAF radio telescopes make these data crucial to accurately observe the solar corona. Using about 300 radio solar maps obtained in the context of the SunDish project, devoted to the radio imaging and monitoring of the solar atmosphere through the INAF radio telescopes (Medicina 32-m and SRT 64-m), we describe our methods to calculate the solar radius and to prove the physical origin of the coronal emission; finally, we discuss and comparate our results with respect to the literature.

4.7 Single-Dish Radio Monitoring of the Solar Atmosphere with INAF Radiotelescopes: Early Scientific Results and Future Challenges

A. Pellizzoni (1), M. Marongiu (1), S. Mulas (1), S. Righini (2), M.N. Iacolina (3), E. Egron (1) on behalf of the SunDish Team

(1) INAF-Osservatorio Astronomico di Cagliari, (2) INAF-Istituto di Radioastronomia, (3) Italian Space Agency (ASI)

In the frame of the SunDish program we are developing and exploiting innovative single-dish radio imaging techniques at high-frequencies up to 100 GHz. We obtained so far more than 300 calibrated images of the solar atmosphere in 18-26 GHz frequency range, in perspective covering the entire current solar cycle (see https://sites.google.com/inaf.it/sundish for details). Early science results included the first accurate measurements of the quiet Sun brightness level and a catalogue of the energetics and spectra of active regions in the above frequency range. We present an overview of the project status and its scientific challenges involving e.g. (1) the study of the solar radius and the coronal emission tails observed beyond the solar disk limb; (2) statistical studies on the correlation between short-time spectral evolution of ARs and flare/CMEs occurrences (for Space Weather science and forecast); (3) study of the peculiar features on the solar disk as polar brightening and coronal holes; (4) development of new solar imaging systems and receivers including new instrumentation able to perform nearly h24 solar monitoring at 100 GHz in polar sites (e.g. Solaris project in Antarctica).

4.8 Using ALMA as a prominence thermometer

M. Barta (1), P. Heinzel (1,2) & A. Berlicki (2,1)
(1) Astronomical Institute of the Czech Academy of Sciences, (2) University of Wroclaw

Temperature of the partially ionized plasmas in prominences belongs insofar to not really reliably determined parameters. Its value estimated by various authors in the hitherto published studies varies in a broad range of 6000K – 10000K. At the same moment, this parameter plays a significant role in the whole prominence physics, namely in the crucial question, whether the colder prominence gas merely drops into the magnetic field dips preformed by a system of external electric currents, or whether it itself contributes to the dip formation by its own gravity. Traditionally, the temperature of prominences is determined spectroscopically, inverting the lines in visible and UV/EUV domains. Complicated formation of the lines by non-LTE radiative transfer together with the other unknown parameters of the model lead to the above mentioned uncertainty in the temperature determination. Ascent of the solar ALMA observations in 2017 has, however, allowed an independent measurement of the plasma temperatures based on brightness temperature of the millimeter radiation emitted by the prominence. Heinzel et al. (2015) have developed a method of determination of the brightness temperature from the plasma kinetic temperature and the optical depth of prominence in each point inferred from integral emission of the Hα line in the corresponding pixel. The simultaneous images in Hα and at mm wavelengths (ALMA) can be thus in principle used (via inversion) to determination of the kinetic plasma temperature. This new method has been for the first time ever applied to the prominence observed simultaneously by ALMA and the MSDP instrument at the University of Wroclaw on April 18th, 2018. As a result of this study the authors obtained a temperature map of the prominence with resolution ~ 1". The results have been recently published in The Astrophysical Journal (Heinzel et al., 2022). This contribution aims at briefly summarizing the method and obtained results with emphasis on the non-trivial analysis of the complex data obtained by the ALMA observatory.

4.9 Triangulation of Type III solar radio bursts using the BayEsian LocaLization Algorithm (BELLA)

L. Alberto Canizares (1,2), S.T. Badman (3), S.A. Maloney (1), D.M. Weigt (4,1), M.J. Owens (5), E. Carley (1) & P.T. Gallagher (1)
(1) Dublin Institute for Advanced Studies, (2) Trinity College Dublin, (3) Harvard & Smithsonian, (4) Aalto University, (5) University of Reading

Solar radio bursts such as Type IIs and IIIs are emitted by electrons propagating through the corona and interplanetary space. Tracking such bursts is key to understanding the properties of accelerated electrons and radio waves, together with the local plasma environment that they propagate through. Here, we present the BayEsian LocaLization Algorithm (BELLA), a Python-based algorithm that evaluates radio burst positions and uncertainties using multilateration and Bayesian methods. BELLA was validated using simulations and a Type III solar radio burst observed by STEREO A and STEREO B (at $\pm$116 degrees) and WIND (at L1). BELLA successfully tracked the Type III from $\sim$3–140 Rsun (2–0.15 MHz) along a spiral trajectory. This also enabled us to derive a solar wind speed of $\sim$420 km/s, consistent with simulations of the solar wind and interplanetary magnetic field from the Heliospheric Upwind Extrapolation with time dependence (HUXt). BELLA results were also compared with positions derived from a time-difference-of-arrival (TDOA) method and the Solar radio burst Electron Motion Tracker (SEMP).

4.10 Density turbulence from the Sun to the Earth

E.P. Kontar (1), A.G. Emslie (2), D.L. Clarkson (1), X. Chen (1), N. Chrysaphi (3), F. Azzolini (1), N.L.S. Jeffrey (4) & M. Gordovskyy (5)

(1) University of Glasgow, (2) Western Kentucky University, (3) Sorbonne University, (4) Northumbria University, (5) University of Hertfordshire

Solar and interplanetary radio bursts are strongly affected by radio wave scattering on density fluctuations, so that the time characteristics, source sizes and positions are substantially enlarged. Similarly, galactic and extragalactic compact radio sources observed via solar atmosphere show anisotropic angular broadening. Using large scale simulations of radio wave transport in anisotropic turbulent plasma, the characteristics of density turbulence required to explain both solar and extra solar observations are determined. The simulations suggest that both fundamental and harmonic emissions should have similar source sizes emitted from the same plasma frequency (location) and have virtually co-spatial apparent positions radially away from the emission sources. The density turbulence provides fundamental limitation on the shortest time observed from the Sun, which match the shortest bursts observed at fundamental or harmonic.

4.11 OVRO Long Wavelength Array–a New Solar-Dedicated Meterwave Radio Spectral Imaging Facility

D.E. Gary

New Jersey Institute of Technology

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) all-sky imager, operating in the range 15-90 MHz, has recently been upgraded to add longer baselines and implement a new solar-dedicated backend to provide commensal daily solar imaging observations. The 352 antenna elements provide baselines to 2.6 km (5 arcmin resolution at 80 MHz). Modes include (1) a beamformed solar-dedicated beam at 3072 frequencies (24 kHz resolution) over the entire band at 1 ms time resolution, (2) a slow-visibility interferometric imaging mode at 10 s time resolution on all baselines for extremely sensitive imaging of slowly varying emission, and (3) a fast-visibility interferometric imaging mode at 0.1 s time resolution on baselines with 48 selected antennas for stronger bursts of more rapid variability. These capabilities are designed to fulfill the goals of the low-frequency part of the Frequency Agile Solar Radiotelescope (FASR-C), and being co-located with the Expanded Owens Valley Solar Array (EOVSA), provides unique simultaneous coverage of metric and microwave emission from the Sun. Recent examples of spectra and images from OVRO-LWA are shown, and plans for daily automated pipeline processing are discussed.

4.12 Millimeter Wavelength Observations of Solar Spicules in a Polar Coronal Hole [poster]

C.E. Alissandrakis (1), T.S. Bastian (2), A. Nindos (1) & M. Shimojo (3,4)

(1) University of Ioannina, (2) National Radio Astronomy Observatory (NRAO), Charlottesville, (3) National Astronomical Observatory of Japan, (4) Department of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), Mitaka, Japan

We report observations of solar spicules at millimeter wavelengths using the Atacama Large Millimeter/submillimeter Array (ALMA). These are supplemented by observations in ultraviolet, extreme ultraviolet and optical wavelengths using the Interface Region Imaging Spectrometer (IRIS), the Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) and Hα images from the GONG network. The observations were made on 2018 December 25 in the northern polar coronal hole present at that time. ALMA obtained time-resolved imaging observations at wavelengths of 3 mm (100 GHz; 2 s cadence) and 1.25 mm (239 GHz; $\sim$2 min cadence) with an angular resolution of 2.2 x 1.3" and 1.5" x 0.7", respectively. We discuss the numerous challenges to the data

reduction and analysis of these observations. We then discuss the structure of the chromosphere at the limb, limits on the temperature and density of spicules, and their kinematics. The limited angular resolution make it difficult to isolate individual spicules. Nevertheless, examples are shown of spicules that display transverse motions, rising and falling motions, and those which simply fade.