SOLAR WIND 16

Asilomar, California
June 12 – 16 2023

June 9, 2023

Hello, everyone!

On behalf of the organizing committee, I would like to welcome you to the 16th Solar Wind Conference. We are delighted to have you here in Asilomar, California, for this exciting event.

The solar wind is a stream of charged particles that flows outward from the Sun. It is a major driver of space weather, and it plays an important role in the evolution of the heliosphere and the Earth's atmosphere.

This conference will bring together leading experts from around the world to discuss the latest research on the solar wind. We will cover a wide range of topics, including the origins of the solar wind, its dynamics, its interaction with the Earth's magnetosphere, and its effects on space weather.

We are confident that this conference will be a valuable opportunity for all of us to learn from each other and to advance our understanding of this important phenomenon.

We would like to thank the sponsors of this conference for their support. I would also like to thank the local organizing committee for their hard work in making this event possible.

We hope you enjoy your stay in Asilomar and that you find the conference to be stimulating and informative.

Thank you!

SOC/LOC

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Conference Abstracts

Studying the whole Sun: from small-scale heating to large-scale structure

Adam Finley
CEA Paris-Saclay

The Sun's large-scale magnetic field undergoes periodic reversals due to the activity of the dynamo within the solar interior. The cyclic evolution of the Sun's magnetic field has a clear impact on the structure of the corona which, due to active region emergence and disintegration, varies even more from rotation to rotation. In addition to temporal variation, it has become increasingly clear that understanding the solar wind necessitates connecting multiple scales in the solar atmosphere, from the buffeting of convective motions in the photosphere to the dissipation of Alfven waves in the solar wind. Each aspect of the Sun playing a role in sculpting the solar wind, and so requiring expertise in a range of subject areas. I will highlight some recent works driven by the WholeSun ERC Synergy grant (https://wholesun.eu), which combines expertise from five different host institutions across Europe. These works range from modelling small-scale energy transfer in the solar atmosphere, to mapping large-scale cyclic variation in coronal structure and rotation. I will also discuss the prospect of long-term monitoring of large active regions, and active nests of flux emergence, in the era of Parker Solar Probe and Solar Orbiter.

Propagation of solar energetic particles in 3D MHD simulations of the solar wind

Ahmed Houeibib

Ahmed Houeibib, LESIA, Observatoire de Paris, PSL Université, CNRS, Sorbonne Université, Université de Paris, 92195 Meudon, France

We propagate relativistic test particles in the field of 3D ideal MHD simulations of the solar wind in the inner heliosphere. We use the MPI-AMRVAC code (https://amrvac.org/) for the wind simulations and integrate the relativistic guiding center equations to solve the particle trajectories. To do so, following Mignone et al. (Comp. Phys. Comm., April 2023), we adopt a third order time step accurate prediction-correction method. Sample objectives are the propagation and diffusion of solar or extra-solar energetic particles in a stationary or in a CME perturbed wind.

Estimating spatial gradients using multi-spacecraft measurements

Alexandros Chasapis

Laboratory for Atmospheric and Space Physics - University of Colorado Boulder

We present a study evaluating the quality of spatial gradients estimated using the curlometer multi-spacecraft technique. We focus on spatial gradients of the magnetic field, where the results can be directly compared with the current density obtained independently from plasma measurements. This allows for a realistic evaluation of the accuracy and robustness of this technique with in situ spacecraft data. We use data from the Magnetospheric MultiScale mission, obtained in different regions of near-Earth space. MMS instruments provide both 4-point magnetic field measurements, as well as high resolution plasma moments, allowing for a direct comparison of independent estimates of the current density. Moreover, the MMS mission has now acquired a high volume of burst-resolution data, obtained in a variety of environments, covering a wide range of plasma parameters. We carry out a statistical analysis of the errors associated with curlometer multi-spacecraft gradient calculations. We then evaluate its performance as a function of spacecraft formation. Moreover, the change in size of the tetrahedron formation throughout the different phases of the mission allows us to understand how the associated errors depend on spacecraft separation. Finally, we examine the influence of varying plasma conditions, to better understand how this multi-spacecraft approach can be employed in different regions throughout the heliosphere. Such a qualitative analysis, enabled by MMS observations, is particularly relevant when this kind of independent evaluation of the quality of multi-spacecraft gradient estimates is not available. These results inform our approach for future large spacecraft constellations, that will involve highly variable configurations of multiple spacecraft across several scales, such as the upcoming HelioSwarm and the proposed Plasma Observatory.

Coherent structures from MHD to kinetic scales in solar wind turbulence at 0.17 and 1 au

Alexandrova Olga

O. Alexandrova (1), A. Vinogradov (1), A. Artemyev (2), P. Demoulin (1), M. Maksimovic (1), A. Mangeney (1), S. Bale (3); (1) LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, Meudon, France (2) Institute of Geophysics and Planetary Physics, University of California, Los Angeles, USA (3) Space Science Laboratory, Physics department, University of California, Berkeley, USA

We study magnetic turbulence in the solar wind from MHD to kinetic plasma scales at 0.17 au, using Parker Solar Probe measurements during its first perihelion and using Cluster and Wind data at 1 au. One of the inherent properties of the turbulent cascade is intermittency which is due to coherent structures. Coherent structures are localized in space and characterised by high amplitudes of magnetic fluctuations. We show presence of embedded coherent structures from MHD down to kinetic scales. Statistical study at 0.17 au shows that Alfven vortices are dominant at all scales. Co-existance of magnetic vortices from MHD to sub-ion scales is shown here for the first time. Current sheets are rare. Further away from the Sun, at 1 au, magnetic holes appear in the slow wind streams, as well as magnetic solitons and shocks. In the fast wind, Alfven vortices are the dominant events as is observed closer to the Sun.

Microstreams and mesoscale structures in the nascent solar wind

Alexis Rouillard

Alexis Rouillard (IRAP, France)

The past decade of remote-sensing observations and in situ measurements of the nascent solar wind by STEREO, Parker Solar Probe and Solar Orbiter have revealed its highly structured and dynamic nature at all observable scales. Specific scales and periodicities in the wind properties measured in situ can be related to similar ones observed remotely in the form of brightness variations triggered at different heights in the solar atmosphere. These fluctuations likely result from the effects of transport processes, magnetic flux emergence and their induced continual reconfiguration of the coronal magnetic field. In this presentation we will review recent research on the origin of mesoscale structures measured in the corona and the solar wind down to some of the smallest scales that are currently resolved remotely (microjets, small bright points, density fluctuations, streamer ejecta). We will consider microstreams, stream interfaces, patches of switchbacks, small flux ropes and more broadly mesoscales structures measured in situ. This scene-setting talk will raise a number of challenging questions on the mechanisms that drive solar wind variability with some important implications for our understanding of coronal heating, solar wind formation and acceleration. We will argue that joint observations and modelling of coronal and wind composition with Solar Orbiter could help resolve some of these mysteries. Upcoming high-cadence and high-resolution observations by PUNCH, MUSE and Proba-3 will also open new capabilities to monitor small-scale structures as they form in the low solar atmosphere and propagate in the corona and the solar wind.

Parker Solar Probe Detection of Energized Protons Upstream of Venus

Ali Rahmati

SWEAP and FIELDS teams

Parker Solar Probe (PSP) has been in orbit around the Sun since its launch in August 2018 and has so far performed five Venus gravity assist maneuvers in order to bring the spacecraft's perihelion closer to the Sun. During the first three flybys of Venus, the SWEAP (Solar Wind Electron, Alpha, Proton)/ SPAN-I (Solar Probe Analyzer-ion) instrument detected energized proton distributions in the upstream region of the Venusian bowshow. In this work, we closely examine the spatial and velocity distributions as well as the time variation of the detected protons and investigate two possible sources for the observed ions: 1) Pickup process by the solar wind of the ionized neutral hydrogen exosphere of Venus 2) Venusian bowshock accelerated solar wind protons. For studying the pickup process, we analytically solve the trajectories of the presumed pickup protons and convolve their fluxes at PSP with the instrument Field of View (FOV) to construct a model of the pickup proton distributions and compare the model results with the measured pickup ions fluxes. Using these model-data comparisons, the hydrogen neutral densities upstream of Venus can be reconstructed at distances on the order of a few proton gyro-radii, which would help constrain the hydrogen escape rates from Venus. Our pickup ion model employs the measured vector components of the solar wind velocity and interplanetary magnetic field (IMF) to simulate the trajectories of pickup ions. A key data input in calculating the trajectories of pickup ions is the three components of the IMF, measured in the solar wind by the MAG instrument on PSP. Due to the sensitivity of pickup ion trajectories to the direction and magnitude of the magnetic field, the accuracy of the measured components of the IMF plays a key role in determining what part of the pickup ion ring-beam distribution would be in the FOV of SPAN-Ion.

Preliminary analysis of the simulated pickup protons indicates that the measured proton 3D distributions do not perfectly match the modeled pickup ion distributions. This points to the 2nd proposed energization process, i.e., shock drift acceleration of solar wind protons due to their interaction with the Venusian bowshock. We study this energization process by using a model of the Venusian bowshock and track the trajectories of the solar wind protons as they reach the bowshock and are reflected and subsequently energized by the motional electric field of the solar wind. The results of this work would enhance our understanding of the processes that affect the interaction of the solar wind with Venus.

The interplay between magnetic switchbacks and solar wind turbulence in the inner heliosphere

Andrea Larosa

A. Larosa, Queen Mary University of London, London, UK C. H. K. Chen, Queen Mary University of London, London, UK V. J. Jagarlamudi, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA J. McIntyre, Queen Mary University of London, London, UK

One of the most intriguing discoveries of the Parker Solar Probe mission is the presence of magnetic field reversals, known as Switchbacks (SBs), in the near Sun environment. Their origins are still unclear and many mechanisms for their generation have been proposed. On top of that their interactions with the background solar wind turbulence is not yet understood. In this work we investigate whether the SBs can be considered as part of the background solar wind turbulence or as a population of separate structures. We address this problem by studying the distributions of the magnetic field increments and rotations and their radial evolution. We show that switchbacks do not arise clearly as a separate population of structures in the rotation distributions and that the magnetic field vector increments evolve with increasing radial distance towards a lognormal shape. Our results suggest a complex interplay between expansion and turbulence that causes the formation and evolution of magnetic field rotation, switchbacks included.

Temperature inversion in a bound plasma atmosphere: the case of the solar corona

Andrea Verdini

Luca Barbieri, Lapo Casetti, Andrea Verdini and Simone Landi Dipartimento di fisica e astronomia. University of Florence, Italy

The solar atmosphere is the most notable example of temperature inversion, that is, a system in which temperature and density have an opposite profile: density decreases while temperature jumps to million degree in the outermost corona. Understanding how such a profile is obtained is known as the coronal heating problem and usually requires finding a suitable mechanism for transporting energy to the outer layers of the atmosphere and a dissipation mechanism capable of heating the coronal plasma. If, however, thermal equilibrium is not enforced, coronal heating is not necessary, as first recognised by Scudder in the late 90s. Following this approach, we present a kinetic model of a collisionless plasma confined in a semicircular tube subjected to the gravity of the Sun and in thermal contact with the chromosphere, modelled as a collision-dominated plasma, i.e. a thermostat. Using numerical simulations we show that temperature inversion naturally forms if the chromospheric temperature varies rapidly enough to hold out of equilibrium the plasma inside the loop. In particular, the temperature and density profiles are strikingly similar to those observed in the Sun atmosphere, including the formation of a thick transition region, if temperature increments in the chromosphere reach million degrees, lasting less than a second, and having an occurrence rate of less than 1%. The numerical results can be explained with a theoretical model that returns analytical predictions for the plasma distribution functions at various heights. We discuss how observations of the dynamic chromosphere compare to the required temperature distribution and how this approach can be extended to magnetically opened region and the solar wind.

Deformed and distorted flux rope models

Andreas Weiss

Andreas Weiss, NASA Postdoctoral Program Fellowship, NASA Goddard Space Flight Center, Greenbelt, MD, USA Teresa Nieves-Chinchilla, Heliophysics Science Divsion, NASA Goddard Space Flight Center, Greenbelt, MD, USA

We present ongoing work and results regarding the construction of a more general and complex analytical flux rope model., These new types of analytical models allow for the deformation of the flux rope axis so that the geometry is no longer limited to either a cylinder or torus. We can now combine this deformation of the axis with the distortion of the cross-section beyond circular or elliptical shapes., The result is a highly flexible new flux rope model allowing for practically any arbitrary geometry while still being divergence-free and conserving the axial flux. We also study additional degrees of freedom, with which we can significantly change the internal magnetic field structure within the flux rope without changing the geometry. The hope is that these new models will allow the characterization of atypical or more complicated in situ signatures that are hard to reconstruct using contemporary models.

Ancillary and Ephemeris Data for Solar Orbiter

Andrew Walsh

A. Escalante Lopez, R. Valles, A. De Groof, H. R. Middleton, P. Osuna, D. R. Williams.

ESA/ESAC

The Solar Orbiter SOC, together with the ESA SPICE Service, is responsible for providing Ancillary and Ephemeris data for the mission to the instrument teams and the broader scientific community, making available the orbit, spacecraft pointing and attitude in various ways. Ancillary data are provided based on the NAIF/SPICE toolkit and as CDF files. They are distributed through the Solar Orbiter Archive as well as via dedicated channels. Here we will introduce the various predicted and as-flown ancillary data products that are available, where to get them, and some tips and tricks to make the most of the available data.

Solar Orbiter's Coordinated Science Operations: Tailoring 10 instruments' operations to truly unique encounters with our home star

Anik De Groof

Anik De Groof(1), David Williams(1), Andrew Walsh(1), Pedro Osuna(1), Daniel Müller(2), Yannis Zouganelis(2), Miho Janvier(2) and Luis Sánchez(1) (1) European Space Agency (ESA), European Space Astronomy Centre (ESAC), Madrid, Spain (2) ESTEC, European Space Astronomy Centre (ESAC), Noordwijk aan Zee, The Netherlands

Solar Orbiter has, by its nature, a long mission. During the 10 years of its Cruise, Nominal and Extended phases, it will sample a vast array of phenomena in the solar wind, and record their source on the Sun, across a large parameter space: different parts of the solar cycle; a range of distances, latitudes, inclinations; and a variety of longitudinal separations with both Earth (+ Hinode, IRIS, SDO and Cluster) and other deep-space missions like STEREO, BepiColombo and its closest cousin, Parker Solar Probe.

Its unique trajectory around the Sun means that there are whole host of precious, often unique opportunities to study particular science topics with Solar Orbiter. Much of this uniqueness is because Solar Orbiter's need to progressively incline its trajectory means that its highly elliptical orbit resonates not with Earth but with Venus.

To fulfil its main goal, studying the connection between the Sun's activity and its effects in the heliosphere, the mission goals hinge on coordinated observations of the full payload, six remote-sensing telescopes observing the dynamic Sun and four in-situ instruments measuring the solar wind surrounding the spacecraft. Instrument observations cannot be planned in isolation but are grouped in so-called Solar Orbiter Observing Programmes (SOOPs) tailored to the science questions we want to address during a particular opportunity. Also, Solar Orbiter's unique orbit around the Sun implies that mission resources like downlink speed greatly vary throughout the operations phase. This means that science planning needs careful coordination and resource optimisation, in order to fully exploit the capabilities of this exciting mission.

In this poster, we present the Mission's science operations concept, and take the reader through the steps taken by the Science Working Team and Science Operations Working Group to go from the Mission's objectives to a detailed schedule of coordinated science campaigns tailored to answering Solar Orbiter's science questions, as best it can. By the time of the Solar Wind 16 conference, Solar Orbiter will have finished its third close encounter and will be observing the far side of the Sun.

Evolution of switchbacks in the solar wind and dispersive effects

Anna Tenerani

Anna Tenerani, The University of Texas at Austin

Alfvénic wind streams are those solar wind streams that are permeated by large amplitude Alfvénic fluctuations, including switchbacks. What is the origin and evolution of switchbacks, and what is their contribution to solar wind energetics, remain important open questions. In this talk we discuss observational data from PSP, Helios and Ulysses providing evidence that switchbacks' evolution is scale-dependent and suggesting that in-situ generation and decay mechanisms are both at play in the inner heliosphere. We then focus on two possible mechanisms that affect the radial evolution of switchbacks, depending on their spatial scale: parametric decay and dispersion. By comparing MHD, Hall-MHD and hybrid kinetic simulations, we show that switchbacks can contribute to solar wind internal energy due to coupling with compressible fluctuations and phase-space mixing. Implications of our results for solar wind energetics are also discussed [References: Tenerani et al ApJL 2021, Tenerani et al PoP 2022].

The Solar Wind defines Space Weather Safety Zones

Arik Posner
Arik Posner, NASA HQ

During the ARTEMIS era, humans again will venture beyond the protection of the Earth's atmosphere and magnetosphere into the solar wind. It is now well established that the solar wind is responsible for carving out a cavity in cosmic ray flux in the inner heliosphere. The resulting reduction in blood-forming organ dose rate basically enables human exploration. Lesser known or acknowledged is the important role the solar wind plays in shaping the directivity and extents of solar energetic particle events. This influence leads to an effective offset of the source location of the Sun that has the most potential to harm explorers through radiation exposure from major solar eruptions. This presentation will discuss how the solar wind influence renders current measures ineffective but instead demands new and immediate strategies to protect human explorers over the first decades of ARTEMIS exploration missions.

A first observational characterization of the isotropization mechanism of solar wind's suprathermal electrons

Arnaud Zaslavsky

Arnaud Zaslavsky, LESIA, Observatoire de Paris (et al.)

The solar wind suprathermal electrons are usually separated into two main populations, based on their pitch angle distribution : an isotropic component, called the halo, and a magnetic field aligned component, usually referred to as the strahl. The strahl is completely dominent close to the Sun, and gets fainter (and angularly broader) with increasing distances, until it nearly completely vanishes at distances of a few AU.

Here we adopt a slightly different perspective, and aim at reproducing the suprathermals pitch angle distributions without making use of strahl/halo categories. To do so, the radial evolution of electrons pitch angle distributions are modelled by a Fokker-Planck equation (FPE) describing the competition between magnetic focusing tending to move the electrons VDFs away from isotropy, and a random process tending to bring them back to it.

We compare steady-state solutions of this FPE to data provided by the recently launched Solar Orbiter (SO) and Parker Solar Probe (PSP) missions, and find that the measured velocity distribution functions can be, with a very high precision, and at all distances from the Sun, fitted by solutions of the FPE, varying the isotropization mean-free path as the only free parameter of the model. Mean free paths obtained are of the order of the AU, and appear to only weakly depend on the electrons energy in the 100eV - 1keV range. This value is far below the Coulomb collisions estimates, but quite consistent with observed mean free paths of SEP events of low energies, known to result from angular scattering by the solar wind's turbulent magnetic field fluctuations.

A consequence of this study is that the strahl/halo picture appears as a steady state feature emerging from the random walk, on heliospheric scales, of the suprathermal electrons in velocity space. In particular we show that the strahl, and its radial evolution, is essentially independent from the boundary conditions imposed for the VDF at the Sun level, but only determined by the interplanetary magnetic field radial profile and by the mean-free path of the isotropization process.

Parallel adiabaticity of protons in the solar wind

Arnaud Zaslavsky
Arnaud Zaslavsky, LESIA, Observatoire de Paris

The data provided by the Helios spacecraft allowed the first reconstruction of the density and temperature radial profiles of different populations of particles constituting the solar wind. Discrepancies between these profiles and the ones predicted for an adiabatic expansion were observed, and naturally interpreted as due to energy flowing into the plasma along its expansion. The identification of the energy source and mechanisms of heating requires the heating rates to be carefully derived from the spacecraft data.

The spread in the plasma data collected at a given distance from the Sun is usually very important, implying large uncertainties on the calculated radial gradients, and therefore on the calculated heating rates. In order to overcome this problem, the procedure adopted in most previous works consisted in fitting plasma and magnetic field data with a set of model (typically power-law) functions, and to derive the heating rates from these fittings.

In this work, we show that the rates obtained by such an approach strongly depend on the rather arbitrary choice one makes for these model functions, which makes this commonly used method unreliable. An alternative approach, consisting in monitoring the radial evolution of the CGL adiabatic invariants, based on locally measured plasma and magnetic field parameters, is free from such a flaw.

We apply this technique to a recently released Helios proton dataset, and confirm the existence of a clear perpendicular heating of solar wind's protons. On the other hand, no significant change in the parallel adiabatic invariant is visible in the data. This contradicts the conclusion of several previous works, based on the "power-law fitting approach", that solar wind's protons would undergo a parallel cooling close to the Sun, and a parallel heating farther away from it.

A recent work on PSP data by Mozer et al. (2023) showed that the parallel CGL invariant is also essentially constant from 20 Rs to 120 Rs. We conclude that to date, and from 20 Rs to 1 AU, no deviation of solar wind's protons from parallel adiabaticity has yet been observed.

Observations of Wave-Particle Interactions Leading to Dissipation of Turbulent Energy in Magnetosheath Plasma

Arya Afshari

Arya Afshari, University of Iowa Greg Howes, University of Iowa Jason Shuster, University of Maryland, College Park Kris Klein, University of Arizona Dan McGinnis, University of Iowa Mihailo Martinovic, University of Arizona Scott Boardsen, NASA GSFC Colin Brown, University of Iowa Rui Huang, University of Iowa Craig Kletzing, University of Iowa David Hartley, University of Iowa

Turbulent energy in space plasmas has been studied in the interplanetary medium (both near the Sun and as far as the outer planets), as well as in the near-Earth space regions (foreshock, magnethosheath). Yet few of these studies link the dissipation of turbulent energy with the mechanism responsible for removing this energy from the turbulent fields and transferring it to the plasma particles at kinetic scales. Ion-cyclotron waves are one such mechanism that couple the turbulent field energy to ions at ion kinetic scales, resulting in the dissipation of turbulent energy and the subsequent energization of the ions. We use data from the Magnetospheric Multiscale (MMS) mission from when the spacecraft were located downstream of the Earth's bowshock, in the magnetosheath, and analyze the data using the field-particle correlation (FPC) technique. Using single-point spacecraft measurements, we identify ion-cyclotron waves and quantify the energy density transfer rate from the waves to the particles. Combining our new results with previous studies, we quantify the dissipation of turbulent energy due to ion-cyclotron damping and electron Landau damping, which together serve as a means of diagnosing various channels of energy dissipation.

The role of flux emergence rate in the formation of coronal jets and Alfvénic perturbations

Bahaeddine GANNOUNI

Bahaeddine GANNOUNI ;Victor Réville; Alexis P. Rouillard; Kévin Dalmasse; Institution: IRAP, Université Toulouse III - Paul Sabatier, CNRS, CNES, Toulouse, France

Coronal holes (CHs) are well-known source regions of the solar wind that is channeled along magnetic field lines rooted in these holes that extend out into the interplanetary medium. While CHs appear as dark regions in extreme ultraviolet (EUV) images of the solar disk due to their cooler prevailing temperatures, spectroscopic and imaging observations of the regions situated off-limb just above CHs reveal persistent ray-like structures embedded in these CHs. These rays, called "coronal plumes", form and disappear over timescales of a few days and their formation is often concomitant with jet-like activity. The latter is triggered by magnetic flux emergence and flux cancellation. The plume main phase is then observed as a brightening in ultraviolet images. The aim of the present study is to model the small-scale activity triggered during the formation of a plume by using a high-resolution 2.5 MHD model of the solar corona. We model the emergence process of a bipole in an open field region from 1 to 20 $R_\odot$ that triggers interchange reconnection and the formation of plasmoid sequences. We then track the propagation of these plasmoids in the forming solar wind as they trigger compressive modes and subsequently evolve into packets of Alfvénic perturbations. We discuss these findings in terms of recent solar wind measurements made in the solar corona by Parker Solar Probe (PSP). In particular, PSP has shown that the solar wind is continually perturbed by strong Alfvénic perturbations often associated with a reversal of the radial component of the magnetic field. These so-called magnetic switchbacks have been interpreted as fossil signatures of an interchange reconnection process occurring in CHs. Although no magnetic reversals are observed outside the plume structure in our simulations, we speculate that these jets could be the source of part of the observed switchbacks.

An Approximate Analytic Solution to the Coupled Problems of Coronal Heating and Solar-Wind Acceleration

Ben Chandran

Benjamin Chandran, University of New Hampshire

Observations from Parker Solar Probe and other spacecraft suggest that the solar wind is powered to a large extent by an Alfven-wave energy flux that is generated by photospheric motions and/or magnetic reconnection. The solar wind and solar corona are also affected by the flux of heat, including conductive losses into the radiative lower solar atmosphere. In this presentation, I will describe an approximate analytic solution to the coupled problems of coronal heating and solar-wind acceleration that accounts for this Alfven-wave energy flux and heat flux. This solution includes analytic formulas and intuitive explanations for the solar mass-loss rate, the solar-wind speed far from the Sun, the coronal temperature, the heat flux from the corona into the lower solar atmosphere, and the plasma density at the base of the corona. Analytic treatments such as this one are useful because they can deepen our understanding by distilling complex processes into their most essential elements, show how different quantities scale with one another, and encapsulate our understanding into a portable form that can be applied to other systems and used by anyone.

Mass-per-Charge Depending Heating of Iron at a Collisionless Shock

Benjamin Alterman

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On March 11, 2022 Solar Orbiter encountered a CME-driven shock at 0.44 AU during the inbound portion of its orbit. Using high time resolution observations from the Heavy Ion Sensor (HIS), we report on the heating of iron 8+ to 12+ across and downstream of this collisionless CME-driven shock. We show that this heating increases with iron charge state. Our results are only in partial agreement with simulations. We show that changes in the shock normal may be one piece of the puzzle underlying the charge-dependent heating observed in this paper.

On the Relationship Between the Separatrix Web Magnetic Structure of the Corona and the Resulting In-situ Solar Wind Properties

Benjamin Lynch

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Connecting the solar wind observed throughout the heliosphere to its origins in the solar corona is one of the central aims of heliophysics. The variability in the magnetic field, bulk plasma, and heavy ion composition properties of the slow wind are thought to result from magnetic reconnection processes in the solar corona. We present a detailed analysis of the solar wind and its source regions during Carrington Rotation (CR) 2002. We characterize some of the bulk plasma and turbulence properties during these specific solar wind intervals and examine their relationship to the source region topologies described by the separatrix web/squashing factor formulation that quantifies coronal magnetic connectivity and its complexity. We will discuss a slightly improved version of the "standard" heliospheric back-mapping techniques and present preliminary results for several additional CRs representing solar minimum (2007—2010) and solar maximum configurations (2001—2003) and Parker Solar Probe Encounter 10.

Parker Solar Probe observations of Quiescent Regions and modeling their solar surface connections.

Benjamin Short

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During each close approach to the sun, the Parker Solar Probe (PSP) mission has observed regions of solar wind which exhibit low magnetic field fluctuation and magnetic field geometry in line with the Parker Spiral called Quiescent Regions. In this study, we identify all Quiescent Regions for PSP orbits 1 through 12 by examining the z-parameter, the normalized deflection angle of the magnetic field to the local Parker Spiral, and its variance to determine Parker-like field orientation and field stability. After identification, we examine Quiescent Region bulk properties and compare them to bulk properties for non-quiescent solar wind. We then use a PFSS model to trace magnetic field lines from PSP down to the solar surface. Once traced, Quiescent Region foot point locations are compared to the locations for supergranulation network boundaries which are located via a ball-tracking algorithm. By comparing the foot point locations modeled for Quiescent Regions, this study can probe the solar origins of these regions and explore the role that quiescent regions play in the evolution of the solar wind.

UCSD Time-Dependent 3-D Reconstructions Using Thomson Scattering Data and Interplanetary Scintillation Observations

Bernard Jackson

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From the year 2000, UCSD's time dependent three dimensional (3-D) reconstruction program has characterized the topology throughout the inner heliosphere based on interplanetary scintillation (IPS) observations. Now also incorporating Solar Mass Ejection Imager (SMEI), and STEREO Heliospheric Imager (HI), imagery and available in-situ measurements from any spacecraft, we have worked to combine all of these observations into a comprehensive analysis system. This takes advantage of the benefits of each data source to provide plasma densities, velocities, and extrapolations of solar surface magnetic fields. Most recently we have certified our kinematic 3-D reconstructions by matching inner heliospheric spacecraft in-situ measurements to UCSD CME forecast analyses prior to CME arrivals at Earth, and STEREO. In a complementary way, we have also helped provide a calibration for the electron plasma monitor on the BepiColombo spacecraft during its cruise phase to Mercury. Until now there has not been an attempt to reconstruct the propagation of heliospheric plasma much beyond Earth's orbit. We have now rectified this and use our comprehensive 3-D reconstruction program to map plasma velocities, densities and fields globally and have extended our recent forecasts past Mars, and as distant from the Sun as Jupiter. This effort is enhanced by ingesting these tomographic inputs into the ENLIL 3-D MHD model, so that now more of the known plasma physical properties can be included to these solar distances. Most of these analyses are available now in near real time and archived on our UCSD website: https://ips.ucsd.edu.

Solar Wind Time-Dependent 3-D Reconstructions of Mesoscale Structures

Bernard Jackson

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We now use the University of California, San Diego (UCSD) iterative tomography analyses to provide high-resolution Solar Mass Ejection Imager (SMEI) and STEREO Heliospheric Imager (HI) 3-D reconstructed plasma densities in the inner heliosphere. These analyses also include Earth-based interplanetary scintillation (IPS) instrumentation data from the Institute for Space-Earth Environmental Research (ISEE), Japan, to help provide more refined high-resolution plasma densities and velocities. Because we use both SMEI and STEREO HI data with a long temporal base removed, we can study the morphology of Stream Interaction Regions (SIRs) as well as that of Interplanetary Coronal Mass Ejections (ICMEs). Here we present reconstructed densities at one-hour cadences, and with latitude and longitude resolutions at Earth of a few degrees, and solar distance resolution of 0.02 AU. These are well within the regime of mesoscale structures that take up to a half a day to pass over an observer near Earth. The analyses show that the larger mesoscale structures that propagate past Earth are often very "corrugated" and "patchy" in our analyses. These 3-D reconstructions can explain some of the differences inherent in multipoint in-situ measurements from spacecraft near Earth and further afield (e.g., at the STEREO spacecraft). Patchy structures are poorly represented by many current heliospheric modeling techniques that assume smooth structures propagate outward from the solar surface. This simplification also presents difficulties for most forecasting techniques that require a smooth outward-moving front for ICME arrival timing, unlike those revealed by our analyses.

The Big Picture: The 3D Solar Wind over the Solar Cycle

Bob Leamon

Bob Leamon, UMBC/NASA GSFC; Scott McIntosh, NCAR

While we all talk about the 11-year solar cycle, the fundamental mode of solar activity is the 22-year Hale Cycle: that is, 11 years of one leading sunspot polarity in each hemisphere and 11 years of the other. Similarly, the polar fields reverse close to solar maximum. The difference between odd and even numbered Schwabe (11-year) cycles in terms of cosmic rays (global solar dipole being parallel or antiparallel to the local ISM field) is well known. Here we show that differences exist in various other activity measures and proxies, including flare occurrence rates, solar wind parameters and geomagnetic indices. These differences are best viewed through the prism of the Extended Solar Cycle framework, whereby we recently (https://doi.org/10.3389/fspas.2022.886670) constructed a new solar activity "clock" which maps all solar magnetic activity onto a single normalized epoch based on the Terminators of Hale Magnetic Cycles. Defining phase $0*2\pi$ on this clock as the Terminators, then solar polar field reversals occur at $\sim 0.2*2\pi$, and the geomagnetically quiet intervals centered around solar minimum start at $\sim 0.6*2\pi$ and end at the terminator, thus lasting 40% of the cycle length.

We will show that the large-scale behaviour of the bulk solar wind (speed & streams, composition, magnetic field…) over the solar cycle is predictable from the global-scale magnetic systems of the Hale Cycle, both in the ecliptic and in the 3D heliosphere. We will also show the different behaviours of odd and even cycles as seen in the tilt of the heliospheric current sheet, the sector structure of the solar wind and the solar wind speed itself, and of course the cosmic ray flux.

Simultaneous Imaging and In-situ Observations of a CME by Parker Solar Probe

Brian Wood

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On 2021 April 24-25, Parker Solar Probe (PSP) simultaneously imaged and was hit by a CME, a mission first. We perform a full 3-D reconstruction of the event based on the available imagery, which unfortunately is limited to STEREO/COR2-A and PSP/WISPR. The activity consists of six little CMEs seen by COR2-A erupting sequentially from the solar corona, and we connect these transients with fronts observed by WISPR, and in situ signatures observed locally. We use an automated magnetic flux rope (MFR) finding routine to identify MFR candidates within the PSP in situ data. The MFRs have orientations roughly consistent with PSP encountering the right sides of roughly E-W oriented MFRs, which are sloping back towards the Sun. The multiple eruptions seen by COR2-A are suggestive of intermittent reconnection occurring near the heliospheric current sheet. It is becoming more popular to envision microscale interchange reconnection as being responsible for both the ubiquitous switchback structures observed by PSP, and potentially for the solar wind as a whole, so activity such as the 2021 April 24-25 transients could provide a useful way to study this important process on a more macroscopic scale.

Proposed Resolution to the Solar Open Magnetic Flux Problem

C. Nick Arge

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The solar magnetic fields emerging from the photosphere into the chromosphere and corona are comprised of a combination of “closed” and “open” fields. The closed magnetic field lines are defined as those having both ends rooted in the solar surface, while the “open” field lines are those having one end extending out into interplanetary space and the other rooted at the Sun’s surface. Since the early 2000’s, the amount of total unsigned open magnetic flux estimated by coronal models have been in significant disagreement with in situ spacecraft observations, especially during solar maximum. Estimates of total open unsigned magnetic flux using coronal hole observations (e.g., using extreme ultraviolet (EUV) or Helium (He) I) are in general agreement with the coronal model results and thus show similar disagreements with in situ observations. While several possible sources producing these discrepancies have been postulated over the years, there is still no clear resolution to the problem. This paper provides a brief overview of the problem and summarizes some proposed explanations for the discrepancies. In addition, two different ways of estimating the total unsigned open magnetic flux are presented, utilizing the Wang-Sheeley-Arge (WSA) model, and one of the methods produce surprisingly good agreement with in situ observations. The findings presented here suggest that active regions residing near the boundaries of mid-latitude coronal holes are the probable source of the missing open flux. This explanation also brings in line many of the seemly contradictory facts that have made resolving this problem so difficult.

Sol0HI Living catalogue

Cecilia Mac Cormack

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Multi-viewpoint and multipoint studies of the inner heliosphere are improving the understanding of coronal mass ejections (CME) and other structures. Combining in situ measurements and high-resolution remote sensing observations, the Solar Orbiter mission is a valuable new tool in the study of the inner heliosphere and solar corona. Among the six remote sensing instruments on Solar Orbiter, the Solar Orbiter Heliospheric Imager (SoloHI) studies the inner heliosphere by observing photospheric visible light scattered by electrons in the solar wind. This heliospheric imager is operated by the U.S. Naval Research Laboratory (NRL) and has a field of view that spans roughly between 5 and 45 degrees in elongation to the east of the Sun, relative to the spacecraft. With the Solar Orbiter mission predicted to reach a minimum perihelion of 0.28 AU and an inclination angle of at least 30 degrees above the orbital plane, SoloHI can complement previous heliospheric imagers at 1 AU.

In this work, we present a living catalog of Sol0HI structures observed during the initial remote sensing windows. We describe the CME geometry and the sources, where possible. We also present all remote sensing observations and in situ measurements collected by other spacecraft for the same event and complement them with the event modeled by the Space Weather Database Of Notifications, Knowledge, Information (DONKI) developed at the Community Coordinated Modeling Center (CCMC).

Wind Spacecraft Charging: Estimates of the Photoelectron Current and its Variability

Chadi Salem

Chadi Salem, University of California, Berkeley, CA, USA John Bonnell, University of California, Berkeley, CA, USA Marc Pulupa, University of California, Berkeley, CA, USA

We present a statistical analysis of solar wind electrons at 1AU using several years of accurate core, halo and strahl electron parameters from the Wind spacecraft to investigate the properties and variability of the spacecraft floating potential as well as the total photoelectron current on Wind.

This work is based on the comprehensive analysis of electron data from the EESA electrostatic analyzers of the Wind 3D-Plasma experiment. We developed a comprehensive and sophisticated algorithm for a non-linear fitting analysis of the structure of the eVDF in the solar wind using data from both 3DP/EESA-Low and 3DP/EESA-High electrostatic analyzers, with the aim of producing large data sets of accurate and reliable total and core-halo-strahl electron parameters over the entire Wind mission: the first ever such analysis for that instrument suite (Salem et al., A&A, 2023).

The important component of the technique is how we estimate the spacecraft potential of the Wind spacecraft, a crucial unknown parameter that distorts the thermal part of the distribution severely. The spacecraft floating potential is initially estimated using a current balance model, and relies on the use of completely independent measurements of the electron density obtained from the fit of the spectrum of quasi-thermal noise around the electron plasma frequency measured by the Wind/Waves electric field antennas. This "quasi thermal noise" (QTN) technique is immune to spacecraft potential and therefore offer an independent and highly accurate measure of electron density and temperature, which we use as reference. Final "fit" values of the spacecraft potential are obtained by comparing the total density of the eVDF fit to the QTN density; the algorithm requires that they are equal.

We discuss the properties and variability of this "measured" spacecraft potential, in comparison to the potential determined as a solution of a comprehensive current balance model between photoelectrons, and solar wind electrons and ions, taking into account both their thermal and bulk motions. We use this current balance model to derive an estimate of the unknown photoelectron current and we discuss its properties and variability.

Moving-Window Cross-Correlation for the analysis of heavy ion signatures in solar wind and Interplanetary Coronal Mass Ejections

Chaoran Gu

Chaoran Gu, Verena Heidrich-Meisner and Robert F. Wimmer-Schweingruber, Institute of Experimental and Applied Physics (IEAP), Kiel University, Kiel, Germany

Coronal Mass Ejections~(CMEs) are extremely dynamical large scale events in which plasma-not only the coronal plasma-is ejected into the interplanetary space. Their interplanetary counterparts measured in-situ are Interplanetary Coronal Mass Ejections (ICMEs), which is also an important part of space weather.

Even though the kinetic properties of the plasma might change because of dynamic effects occurring during the expansion of the CME, the heavy ion characteristics remain unchanged after it leaves the low corona. Charge states of heavy ions reflect important information about the coronal temperature profile due to the freeze-in effect, while elemental abundances indicate potential source regions of the plasma.

We apply a newly developed Moving-Window Cross-Correlation(MWCC) analysis method to a long-term in-situ solar wind data and several recorded ICME events. Heavy ion data sets are obtained from the Pulse Height Analysis (PHA) data from the Solar Wind Ion Composition Spectromet (SWICS) on board the Advanced Composition Explorer (ACE).

Time periods with unusual heavy ion signatures are identified in solar wind, and we found a rich internal structure within individual ICME events. Boundaries of those time periods are given by the MWCC method. This method efficiently identifies segments within in-situ solar wind data that warrant further investigation and serves as a reference for determining the start and end times of ICMEs in future work.

Keywords Sun: coronal mass ejections (CMEs) – Heavy ions

Evolution of weak MHD turbulence in the expanding solar wind: anisotropy, residual energy, and intermittency

Chen Shi

UCLA

We carry out 3D magnetohydrodynamic (MHD) simulations of weak, decaying turbulence. Expanding box model is implemented so that spherical expansion of the solar wind is accounted. The turbulence is anisotropic along the three axes. We show that negative residual energy is produced whenever nonlinear interaction exists regardless of the normalized cross helicity σ_c, and the spherical expansion facilitates the process. The residual energy is mainly distributed in the perpendicular direction with $Er \propto l \perp$ or equivalently $Er \propto k_{\perp}^{-2}$. The magnetic field develops a second-order structure function $S2(\boldsymbol{b}) \propto l \perp^{1/2}$ ($Eb \propto k \perp^{-3/2}$). The velocity's second-order structure function $S2(\boldsymbol{v})$ is systematically shallower than $S2(\boldsymbol{b})$, consistent with in-situ observations of the solar wind. We show that higher-order statistics of the turbulence, proxy of intermittency, depends strongly on the initial σ_c as well as whether the expansion effect is present. In general, the fluctuation is more multi-fractal when expansion effect exists and is more multi-fractal when the initial fluctuation is imbalanced $\sigma_c \approx 1$ than the balanced case ($\sigma_c \approx 0$).

chin-chun Wu

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Coronal mass ejections (CMEs) and their driven shock are a major source of large geomagnetic storms due to the large and long-lasting, southward component of magnetic field downstream of the shock (e.g. sheath) and within the flux rope (e.g., magnetic cloud). Predicting the southward field and its arrival time accurately thus plays a key role in space weather predictions. A new model, which combines the global three-dimensional, time-dependent, magnetohydrodynamic (MHD), data-driven model (G3DMHD) with a self-contained magnetic flux-rope model [Chen, 1996], is developed to address this problem. Here we simulate the evolution of a Sun-Earth-directed CME that erupted on 2012-July-12 to demonstrate the model capability. The computational domain spans from 2.5 solar radii (Rs) from the surface of the Sun, where the flux rope is injected, to 245 Rs. We compare the time profiles of the simulated MHD parameters (Density, velocity, temperature, and magnetic field) with in situ solar wind observations acquired at ~1 AU by the Wind spacecraft and the result is encouraging. The model successfully reproduces the shock, sheath, and flux rope similar to those observed by Wind. Detailed results will be presented and discussed.

IS⊙IS Observations of the 5 September 2022 SEP Event at 15 Rs – An Overview

Christina Cohen

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On 5 September 2022, Parker Solar Probe was near perihelion during its 13th orbit when the Integrated Science Investigation of the Sun (IS⊙IS) observed a large solar energetic particle (SEP) event. The event was associated with a large flare, estimated to be M9-X2 class, and an extremely fast coronal mass ejection, traveling ∼2600 km/s when it passed over the spacecraft. The time profile of the energetic protons exhibits numerous changes in intensity, spectral hardness and anisotropy, some of which correspond to structures and signatures identified in the solar wind data. We provide a brief overview of the event, its temporal evolution, and highlight unique aspects of observing a large SEP event at 15 Rs.

Parker Solar Probe Observations of Turbulence in the Near-Sun Solar Wind and Solar Corona

Christopher Chen

Christopher Chen (QMUL), PSP FIELDS & SWEAP Teams

Since its launch, Parker Solar Probe has allowed us an unprecedented opportunity to understand how solar wind turbulence works up close to the Sun, and the role that it plays in shaping the solar wind that we see. In this presentation, I will discuss what we have learnt from the most recent orbits where PSP crossed several times into sub-Alfvenic wind and saw clear changes in the turbulence properties. In particular, we see a change in the evolution of turbulence amplitudes that allow testing of the WKB vs non-WKB evolution of the fluctuations. We see a clear decrease of amplitudes in the sub-Alfvenic wind, as expected, that shows up prominently in the normalised amplitude dB/B - this is compared to theoretical predictions, allowing us to study the processes responsible for the fluctuations growing to the large amplitudes seen in the super-Alfvenic wind (dB/B$\sim$1, also known as "switchbacks"). We also discuss how other turbulence properties change in the sub-Alfvenic wind, including the magnetic compressibility, cross-helicity, and Elsasser spectra. These results will be discussed in the context of understanding the mechanisms for both the acceleration of the solar wind and the generation of the magnetic switchbacks.

On the regulation of solar wind Alfvénic pulsations by fine-scale solar magnetic activities

Chuanpeng Hou

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Parker Solar Probe has detected abundant magnetic switchbacks and velocity spikes in the young solar wind, the origins of which are still highly debated. Some studies based on observational data and numerical simulations argue that these perturbations are produced through interchange magnetic reconnection close to the Sun while other studies suggest that they result from transport processes involving for instance velocity shears and the development of solar wind turbulence. Interchange magnetic reconnection can occur during the eruption of small bipoles in pre-existing open magnetic field regions such as coronal holes. This process is known to drive the formation of plumes and pseudo-streamer-like structures and potentially mesoscale structures measured in the solar wind as well as velocity spikes. Using velocity measurements from Solar Orbiter, we infer the magnetic origin of mesoscale structures and velocity spikes measured by Solar Orbiter. We find that the footpoints of the magnetic lines associated with these spikes are located at the boundary of a coronal hole, where the imaging instruments aboard the Solar Dynamics Observatory (SDO) record many brightening structures, which number changes periodically. The time series of the number of bright structures, total magnetic flux below bright structures and in-situ velocity spikes show a similar period and a strong positive correlation. We speculate that the small-scale magnetic flux emergence in coronal hole contributes to the interchange reconnection processes, which are observed as the small brightness enhancements, and outward fluctuations/jets may act as a mediator between interchange reconnection and the formation of velocity spikes/magnetic switchbacks.

Imaging the Solar Wind in 3-D, with PUNCH

Craig DeForest

C.E. DeForest, S.E. Gibson, R. Killough, A.M. Henry, M. Beasley, R. Colaninno, G. Laurent, D. Seaton, and the PUNCH Team

The Polarimeter to UNify the Corona and Heliosphere (PUNCH) is a NASA Small Explorer mission to view and understand the corona and solar wind as a single system. Launching in 2025, PUNCH will image the young solar wind in three dimensions, from 6 to 180 solar radii from the Sun. Four synchronized satellites in low-Earth orbit will photometrically image visible light Thomson-scattered by the solar wind, measuring density, flow, and structure on a global and time-dependent basis. The ground system combines and background-subtracts the data from all four cameras, merging the observatories into a single polarimetric "virtual camera" with a 90 degree field of view and four minute cadence; and routine analysis tools extract the three-dimensional structure of the wind, without stereoscopy, from the polarization signal.

Anticipated results on the ambient solar wind include global, time-dependent maps of solar wind flow and interaction on timescales of hours; measurements of the onset and development of large-scale turbulence; clear determination of the source(s) of solar wind variability through direct tracking; and understanding of the global physics of the poorly-explored "Alfvén Zone" where wave speed is comparable to flow speed. PUNCH will also track the trajectory, structure, and evolution of CMEs in 3-D, identify the origins and evolution of stream interaction regions, and explore the large-scale and cross-scale physics of shocks in the solar wind.

As a white-light imager, PUNCH is sensitive to density structure in the solar wind at scales from ∼100 Mm to ∼100 Gm, throughout the entire outer corona and inner heliosphere simultaneously. This complements in-situ measurements, which can measure "ground truth" of many parameters at a single moving point in space, to yield a true cross-scale and unified view of the solar wind.

PUNCH is now in assembly, integration, and test; environmental testing of integrated Observatories is scheduled for late 2023. PUNCH will ride-share with the SPHEREx mission, launching from Vandenberg SFB in Spring of 2025. PUNCH science team meetings are open to all; the next is 6-7 July 2023 in Boulder, Colorado. The PUNCH website is "https://punch.space.swri.edu".

We present an overview of the PUNCH science, potential synergies with existing missions, and how to get involved with PUNCH.

A New Map of the Three-Dimensional Boundary of the Heliosphere

Dan Reisenfeld

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We present new advances in mapping the 3D structure of the heliosphere using ENA flux observations from the Interstellar Boundary Explorer (IBEX) mission. IBEX has shown that variations in the ENA flux from the outer heliosphere are associated with the solar cycle and longer-term variations in the SW. In particular, there is a strong correlation between the dynamic pressure of the outbound SW and variations in the later-observed IBEX globally distributed ENA flux (GDF). The time difference between observations of the outbound SW and the heliospheric ENAs with which they correlate ranges from approximately two to six years or more, depending on ENA energy and look direction. This time difference can be used as a means of "sounding" the heliosheath, that is, finding the average distance to the ENA source region in a particular direction.

Reisenfeld et al. 2021 applied this method to build for the first time a three-dimensional map of the heliosphere. We now utilize a number of improvements in the means of rendering ENA sky maps from the raw IBEX-Hi data. These include: (1) a newly developed IBEX data product that reduces the statistical uncertainty of ENA fluxes by nearly a factor of two, (2) a newly developed 2D surface estimation technique for rendering higher resolution ENA sky maps and removing the blurring effect of the instrument angular response, and (3) a new statistically rigorous method to separate the ribbon from the GDF. The original 3D map was based on dividing the sky into 56 "macro-pixels", driven by the need to reduce the statistical uncertainty within a pixel to a reasonable level. Inclusion of the improved ENA sky maps allows for a more than 10-fold increase in the resolution of the 3D heliosphere map. The map shows a heliosphere compressed in the upwind direction (in good agreement with the heliopause crossings of Voyagers 1 & 2), and a flaring to the poles and along the flanks. Because charge-exchange loss of hot ions limits the ability to determine the downwind extent of the heliosphere, we conservatively place a lower limit on the heliotail extent at ~300 AU, but it could stretch much further. The higher resolution of the new 3D map also brings out articulations in the shape of the heliopause not previously observed.

Predicting the Global Structure of the Slow Solar Wind using Machine Learning and Artificial Intelligence

Daniel Carpenter

Liang Zhao (University of Michigan), Henry Han (Baylor University), Daniel Carpenter (University of Michigan) and Sue Lepri (University of Michigan)

The topology of HCS varies dramatically along solar cycle. Previous by Zhao et al. (2013) introduced a pair of HCS parameters, the latitudinal standard deviation (SD) and the slope (SL) of the HCS, which can evaluate the latitudinal deviation and global waviness of the HCS on Carrington synoptic maps of the 2.5 R s surface (the so-called "source surface"). In addition, the long-term fraction of the high O 7+ /O 6+ ratio wind (O 7+ /O 6+ >0.145, slow proton speed is usually less than 500 Km/s, HOR wind hereafter) is found to be correlated with SD and SL by ACE observations. Therefore, the association between the global structure of HOR wind and the HCS topology is confirmed (Zhao et al. 2009, 2014 and 2017). This connection of the HOR wind fraction with the HCS topology implies that we can predict the global HOR solar wind structure if SD and SL indexes can be predicted. With the development of the sophisticated prediction ability achieved by the ML and AI techniques, we can now for the first time predict the SD and SL indexes of the HCS, so that to predict the global solar wind structure with great confidence, by estimating the HOR wind fraction in the heliosphere. In this work, we first examine the current HCS topology and its relation to the equatorial solar wind. We analyze the Sun's source surface synoptic maps (calculated by PFSS) to examine the evolution of the topology of HCS through the recent three solar cycles. We investigate how the changes of HCS topology affect the equatorial solar wind structures. Then, we used a state-of-the-art ensemble learning method: extremely randomized trees (extra trees) to predict the SD and SL indexes. As an enhanced version of the widely used random forest method, the extra tree model has the advantage in low variance, better precision, and good generalization besides its low complexity. Our results indicate that the extra tree model demonstrates quite good and robust performance in predicting the SD and SL indexes. The regression score (R 2) of the extremely randomized tree method achieves 91.90% for SD and 74.33% for SL, which outperforms the results from other peer models (e.g., deep neural networks (DNN)). The strong performance under the SD index suggests its strong confidence in predicting the topology of the HCS. This prediction will become a useful tool for the prediction of the future equatorial solar wind structure.

Revealing the Coronal Origins of the Slow Solar Wind using the Dependences of its Properties on the Oxygen and Carbon Charge State Ratios measured by ACE/SWICS and SOLO/HIS

Daniel Carpenter

Liang Zhao (University of Michigan), Sue Lepri (University of Michigan), Enrico Landi (University of Michigan), and Daniel Carpenter (University of Michigan)

The exact coronal origin of the slow-speed solar wind has been under debate for decades. Besides the solar wind speed, the heavy ion composition, including the elemental abundances and charge state ratios, are widely used as diagnostic tools to investigate the coronal origins of the slow wind. In this study, we continue the previous work by Zhao et al. (2017 and 2022) examining the distributions of the physical properties (such as proton speed, density and heavy ion elemental abundances) of the solar wind on the O^{7+}/O^{6+} versus C^{6+}/C^{5+} frame (O-C frame, hereafter) using ACE and Solar Orbiter data. We find multiple subgroups of slow solar wind on the O-C frame that could be indicative of different coronal origins. In fact, both ACE/SWICS and Solar Orbiter/HIS measurements indicate that the slow solar wind consists of multiple sub-groups identified in the O-C frame, having very distinguishable proton and heavy ion properties. The coronal source regions of these wind sub-groups, obtained using the PFSS model, indicate that they are associated with different coronal structures. For example, after tracing the subset of slow speed solar wind located on the upper boundary of the data distribution in the O-C plot back to the Sun using PFSS model we found that this wind is more likely associated with quiet Sun regions. In this slow wind subset both the proton density and elemental abundances relative to protons, such as N/P, O/P, Ne/P, Mg/P, Si/P, S/P, Fe/P, He/P, and C/P are systematically depleted compared to the slow wind in the main-stream distribution in the O-C plot (the normal slow wind). Therefore, the dependences of the slow wind properties on the O^{7+}/O^{6+} and C^{6+}/C^{5+} ratios as revealed by their distributions on the O-C plot could be used as a "map" to indicate the coronal origins of the slow wind.

Unified Framework of Alfven Resonances and Forced Reconnection

Daniel Urbanski

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Most of the plasmas encountered in space and laboratory are weakly collisional or collisionless, in the sense that diffusion time scales at macroscopic spatial scales are too long to explain the fast energy release as well as heating observed during explosive events, such as flares, geomagnetic storms and disruptions in magnetic confinement devices. For this reason, understanding the dynamical formation of quasi-singular boundary layers is fundamental to understanding explosive energy release as well as plasma heating and control. Alfven wave resonance and forced reconnection are two processes by which such boundary layers can be generated in inhomogeneous plasmas. In this project, we investigate the driven, time dependent solution of the inhomogeneous, linear MHD equations. We approach this problem by adopting a unified theoretical and numerical framework. We show that Alfven wave resonance can transition to forced reconnection in the limit of zero-frequency driver. In future work, we will explore this transition in the visco-resistive and nonlinear regimes.

Rapid succession of SEP events associated with a series of EUV jets: Solar Orbiter, STEREO-A and near-Earth spacecraft observations

David Lario

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A series of near-relativistic solar electron events was observed on November 9 to 15, 2022 by STEREO-A at 0.96 au, by near-Earth spacecraft such as ACE, Wind and SOHO at $\sim$0.99 au, and by Solar Orbiter at heliocentric distances ranging from 0.59 to 0.66 au. At least 22 electron intensity enhancements at energies >10 keV were clearly distinguishable in the particle data collected by the Energetic Particle Detector (EPD) suite of instruments on board Solar Orbiter, with 12 of these events occurring on 11 November 2022. Several of these electron events were accompanied by <10 MeV proton and $<\sim$2 MeV/n heavy ion intensity enhancements. The origin of this rapid succession of particle events is a series of jet-like eruptions detected in extreme ultraviolet (EUV) observations from the vicinity of active region AR 13141 that were closely associated with type III bursts in the decametric-hectometric range. We find a close association between the EUV jets, type III radio bursts and the release of near relativistic electrons. The events on 9 November and late on 14 November are particularly interesting in that they were just evident at electron energies below $\sim$30 keV, were rich in heavy ions with energies below $\sim$1 MeV/n, associated with type III radio bursts at frequencies below $\sim$1.0 MHz, and originated at EUV solar eruptions lacking a clear jet. By combining remote and in-situ data from the three viewpoints (Solar Orbiter and STEREO-A were $\sim$20 degrees and $\sim$15 degrees east of Earth, respectively), we analyze the origin of this sequence of events, determine the interplanetary context where they were observed, and investigate the interplanetary transport of electrons to the different spacecraft.

Undercount Corrections and Novel Dust Dynamics Observations: First Results from the Parker Solar Probe Dust Detection Database

David Malaspina

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When micrometeoroids collide with a spacecraft, they produce highly transient plasma clouds which perturb the electric, and sometimes magnetic, environment near that spacecraft. These perturbations can be detected by electric and magnetic field instruments on spacecraft.

The Parker Solar Probe (PSP) spacecraft detects micrometeoroid impacts via impact plasma clouds. With its unique orbit, PSP is able to observe the inner heliosphere, where the interplanetary dust cloud is most dense and the evolution of micrometeoroid populations is most dynamic. These observations provide in-situ observations that can be used to constrain the mechanisms and rates by which the Sun processes the Zodical dust cloud.

This talk describes the creation and validation of a database of in-situ dust impact detections made by the Parker Solar Probe spacecraft. The database is created to facilitate future studies of interplanetary dust dynamics in the inner heliosphere, and to enabling more direct comparisons between different dust studies by establishing a standardized dust detection methodology. The database includes individual impact detections and derived dust impact rates. Impact rates are corrected for effects related to high amplitude plasma waves and under-counting due to finite detection window duration. These corrections suggest that: (i) most (but not all) dust impacts on Parker Solar Probe are randomly distributed in time and space, (ii) the true dust impact rate may be $\sim$50% greater than the impact rate determined using uncorrected data, especially near perihelion. A specific population of dust detections is found not to be randomly distributed in time and space, suggesting a novel aspect of near-Sun dust dynamics is newly visible in the Parker Solar Probe in-situ data.

Solar Wind Interactions at the Edge of the Heliosphere: From IBEX to IMAP

David McComas

David McComas, Princeton University - On behalf of the entire IBEX & IMAP Science Teams

This talk provides a brief summary of what we have learned about the interaction of the distant and highly pickup ion-loaded solar wind at the boundaries of our heliosphere. In contrast to the two trajectories that have been sampled by the Voyager spacecraft, the Interstellar Boundary Explorer (IBEX) has provided the initial global observations and derived an understanding of the distant heliosphere and its three-dimensional interstellar interactions. IBEX observes both direct interstellar neutrals drifting into the heliosphere from the interstellar medium and a globally distributed flux of Energetic Neutral Atoms (ENAs) produced by charge exchange between the solar wind and pickup ions largely in the heliosheath, the region between the termination shock and heliopause. The ENA-bright IBEX Ribbon is further likely produced by triple charge exchange that recycles neutralized solar wind and heliosheath ions in the nearby interstellar medium beyond the heliopause and provides a further remote sampling of this important region. The journey has just begun as the Interstellar Mapping and Acceleration Probe (IMAP) is slated for launch in early 2025. IMAP comprises ten instruments (three with dual heads and one on a pivot platform), which greatly increase the measurement capabilities of ENAs and interstellar neutrals beyond IBEX, directly measure interstellar dust transiting the solar system, and observe the solar wind both directly and remotely, interplanetary magnetic field, and pickup ions and energetic particles. Together these measurements allow IMAP to investigate simultaneously two of the most important and intimately coupled research areas in Heliophysics today: 1) the acceleration of energetic particles and 2) the interaction of the solar wind with the local interstellar medium. For a description of IMAP at the time it was selected, see McComas, D.J. et al., Interstellar mapping and acceleration Probe (IMAP): A New NASA Mission, Space Science Review, 214:116, doi:10.1007/s11214-018-0550-1, 2018. Open Access: https://link.springer.com/article/10.1007%2Fs11214-018-0550-1

Subion Scale Turbulence Driven by Magnetic Reconnection

Davide Manzini

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The interplay between plasma turbulence and magnetic reconnection remains an unsettled question in astrophysical and laboratory plasmas. Here we report the first observational evidence that magnetic reconnection drives sub-ion scale turbulence by transferring energy to small scales. We employ a spatial coarse-grained model of Hall magnetohydrodynamics, enabling us to measure the nonlinear energy transfer rate across scale l at position x. Its application to Magnetospheric Multiscale mission data shows that magnetic reconnection drives intense energy transfer to sub-ion scales. This observational evidence is remarkably supported by the results from Hybrid Vlasov-Maxwell simulations of turbulence to which the coarse-grained model is also applied. These results can potentially answer some open questions on plasma turbulence in planetary environments and open new pathways to investigate the interplay between turbulence, reconnection and energy dissipation in collisionless magnetized plasmas.

Magnetohydrodynamic Modeling of the 2018 August 20 Slow Coronal Mass Ejection and Solar Wind Interaction

Dinesha Hegde

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A coronal mass ejection (CME) that erupted from the Sun on August 20, 2018 caused the third-strongest geomagnetic storm of solar cycle 24, which occurred on August 26, 2018 during the cycle declining phase. It is of interest that this particular event was driven by a slower and smaller CME, which is unusual because geomagnetic storms are typically triggered by fast and large CMEs. The earlier studies have suggested that the flux rope associated with this CME experienced a complex rotation in the interplanetary medium before it reached Earth, and the magnetic cloud at Earth had a high-density structure. In this study, we employ a constant-turn flux rope-based magnetohydrodynamic model to simulate the propagation of this CME through the time-dependent, data-driven ambient solar wind. By fitting the coronagraphic observations of this CME, including the data from the Heliospheric Imager (HI) on STEREO-A, with the parameters of a graduated cylindrical shell model, we constrain the properties of the corresponding flux rope. To investigate the rotation of this CME in the inner heliosphere, we characterize the simulated CME using the Marubashi force-free flux-rope fitting. Our research highlights the significance of modeling CME propagation to better understand the dynamics of these events and their impact on the Earth's space environment.

The Parker Spiral Model Revisited: Role of the Radially Evolving Solar Wind Turbulence on the Geometry of the Interplanetary Magnetic Field Lines

Du Toit Strauss

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Solar wind turbulence can be considered locally homogeneous and stationary although its properties evolve on global heliospheric scales. The dominant component of the magnetic fluctuations is polarized transversely to the direction of the guiding magnetic field. As pointed out originally by Jokipii and Parker, the presence of these fluctuations results in cross-field dispersion of the magnetic field lines, and hence, cross-field transport of the high-energy particles. In this work, we consider the role of the radially evolving solar wind turbulence on the geometrical structure of the heliospheric magnetic field (HMF), and in particular on the magnetic field lines connecting the Sun to the spacecraft. Using observationally-constrained turbulence levels in the field line random walk (FLRW) limit of 2D turbulence, we find that the addition of turbulence can alter the average HMF geometry. For the turbulence parameters used in the model, this yields an underwound magnetic field at the Earth (the spiral angle is 5 degrees smaller) and offset from the standard Parker spiral by up to 10 degrees. Such deviations from a standard Parker HMF geometry have important consequences for energetic particle transport that are also discussed.

The Effect of Perpendicular Diffusion on Solar Energetic Particle Electron and Proton Onset Times

Du Toit Strauss

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In a turbulent magnetic field with transversal complexity, energetic particles will be scattered along (through pitch-angle diffusion) and perpendicular (through cross-field diffusion) to the mean magnetic field. For the sake of simplicity, the perpendicular diffusion process is often incorrectly ignored when studying solar energetic particle (SEP) transport between the Sun and Earth. In this work we present simulations of MeV SEP proton and electron onset times that illustrate the importance of including perpendicular diffusion in transport models. A good comparison between simulations and ensemble observations is obtained, indicating that the observed electron and proton distributions are consistent with a single acceleration source close to the Sun. Additionally, to account for the large inter-event variation noticed in the observed SEP events, we apply an ensemble modeling approach where the numerical SEP transport model is initiated with slightly different input parameters. We show that this can account for much of the observed variability and might be a viable method to implement in real-time physics-based predictive models.

Anisotropies in He+ Pickup Ion Pitch angle distributions: Traces of fresh PUIs or tracers for transport effects?

Duncan Keilbach

Duncan Keilbach, Verena Heidrich-Meisner, Lars Berger, Robert F. Wimmer Schweingruber; Institut für Experimentelle und Angewandte Physik, CAU Kiel

Interstellar pickup ions (PUIs) originate from neutral particles that flow into the heliosphere and are embedded into the solar wind (SW). The initial velocity distribution function of PUIs is anisotropic, hence a narrow banded pitch angle distribution (PAD) is expected. The initial pitch angle of PUIs is a function of the orientation of the magnetic field relative to the SW velocity and the neutrals' velocity. Yet scattering and acceleration processes broaden the distribution considerably during transport. Thus, transport effects play an important role in the determination of the initial properties of interstellar neutrals from PUI observations.

Following our work presented at the 2022 AGU Fall Meeting, we investigate He+ PUI PADs as a function of the orientation of the local magnetic field's orientation and the PUI velocity relative to the SW proton bulk velocity. To mitigate projection effects, the particles' pitch angles are derived from three dimensional vectorial velocities which were observed with the PLAsma and SupraThermal Ion Composition (PLASTIC) instrument on board of the Solar TErestrial RElations Observatory Ahead (STEREO A).

Since for fresh PUIs a certain velocity relative to the SW proton bulk is expected, the velocity dependent behavior of the PADs is described in three velocity tiers: (i.) fresh PUIs, (ii.) decelerated PUIs and (iii.) accellerated PUIs. (i.) The PADs as a function of magnetic field azimuthal angle show distinct lines of increased denstiy. For in-ecliptic magnetic field configurations these most prominently include a pitch angle of 90° for magnetic field angles of +/-90°. These lines fit the initial pitch angle expected for injection at the observed magnetic field orientation not only for in-ecliptic magnetic field configurations, but also for tilted magnetic field vectors. (ii.) For PUIs which, based on their velocity, have undergone deceleration, and therefore are likely are older than PUIs in tier (i.), the trend vanishes. This is to be expected since the magnetic field orientation during creation differs from the orientation during observation. However, the anisotropic patterns observed might indicate that they have undergone pitch angle scattering. (iii.) For PUIs which, based on their velocity, have undergone acceleration, the trend observed for tier (i.) also vanishes. Here, low numbers of events hinder a clear observation of the distribution.

In addition, the velocity and magnetic field orientation dependent PADs are observed for different orbital positions and different SW velocities and it is discussed, whether and under which conditions common features of these or the absence of common features can be employed as indicators for transport effects and the time scales of pitch angle scattering.

Voyager 1 and 2 observations within interplanetary space of upstream suprathermal < 6 keV electrons during times when magnetically connected to Jupiter's Bow Shock

Edmond C. Roelof

Edmond C. Roelof, Ralph L. McNutt, and Peter Kohlmann

The Voyager-1 magnetometer (VGR1/MAG) recently observed a train of 6 quasi-periodic oscillations (30 days) in the magnetic field intensity (B) at a helioradius of 155AU during days 40-200 of 2021 [Burlaga et al., ApJ, 932:59, 2022]. We have searched for a solar source (26-day rotation period) of these oscillations by examining the archive of NSO/GONG potential-field source-surface (PFSS) coronal models for the global coronal magnetic field lines (available at gong.nso.edu). The integral Carrington longitude plots are useful in identifying the location of coronal holes, which are known to be sources of the high-speed solar wind streams that produce CIRs and SIRs over a range of heliolatitudes. These stream/stream interactions can persist out to the solar wind termination shock and then can propagate as supra-thermal pressure pulses through the heliosheath and thence across the heliopause into the VLISM as modified magneto- sonic waves. We estimate that the solar disturbance should have commenced no earlier than 5.5 years earlier, i.e., at year Aug-Sep 2015, corresponding to Carrington rotation CR2167. From the GONG plots, we found severe distortions of the heliospheric current sheet (HCS) beginning with CR2170, actually forming an unusual double HCS, one of which circumscribed a strong, isolated coronal hole at the middle latitudes (MLCH) of VGR1 (N35deg). This timing is confirmed by ecliptic observations at 38 AU from New Horizons/PEPSSI of a sequence of 6 unusual CIR-associated intensity variations of 16 keV He+ heated interstellar pickup ions Nov 2015 – Apr 2016 [Kohlmann et al., 876:46, 2019] This MLCH lasted no more than 6 rotations, terminating abruptly after CR2176 with the re-establishment of the usual (single) HCS. We suggest that the emergence (and disappearance) of this mid-latitude coronal hole was the solar source of the train of the six 30-day oscillations in (B) observed 5.5 years later by VGR1/MAG at 155 AU.

Voyager 1 and 2 observations within interplanetary space of upstream suprathermal < 6 keV electrons during times when magnetically connected to Jupiter's Bow Shock

Edward C Sittler Jr

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We present for the first time the Voyager 1 and 2 plasma instrument observations within the interplanetary space of upstream suprathermal $E < 6$ keV electrons during times when magnetically connected to Jupiter's bow shock. These measurements are a biproduct of our recovery of the Voyager Jupiter flyby measurements of the plasma electrons made by the Plasma Science Experiment (PLS) (Bridge et al., 1977). The initial ion and electron plasma observations were first reported by Bridge et al. (1979a, b). The periods chosen follow those reported by Zwickl et al. (1981) using energetic particle data with $E \geq 30$ keV from the Low Energy Charged Particle (LECP) instrument (Krimigis et al., 1977). For this study we also use Voyager magnetic field data (Ness et al., 1979a, b) which are critical for this study. Basically, whenever the interplanetary magnetic field is nearly radially aligned relative to the spacecraft sun line, connection to the Jovian bow shock is occurring and that's when we see evidence of suprathermal electron enhancements and will report on our present progress. Whenever the magnetic field is radial the plasma instrument's D cup or side sensor, which makes the electron observations (10 eV $\leq E \leq$ 6 keV), is viewing ~ 90 degree pitch angle electrons but evidently its wide field-of-view (FOV) allows it to see these hot electrons which we assume to be field aligned. So, we will be looking into FOV alignment issues relative to the local magnetic field vector and any evidence for pitch angle scattering by plasma waves (see Scarf et al., 1981) that might broaden their width in pitch angle and allow their detection.

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Parker Solar Probe observations of waves during an interplanetary shock at 15 Rs

Elizabeth (Lily) Hanson

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During Encounter 13, Parker Solar Probe (PSP) was enveloped by a coronal mass ejection, with an interplanetary (IP) shock at ∼.075 au. The FIELDS instrument obtained a waveform capture (WFC) of ∼7s duration which covered the complete ramp, as well as parts of the upstream and downstream regions. This is the first case where a WFC was obtained over this broad IP shock region so close to the Sun. This WFC covers the frequency range ∼0.2Hz to ∼75kHz (<0.1fci to ∼4fce). In addition, 34 higher frequency, shorter duration Time Domain Sampler (TDS) bursts were recorded during the 7s WFC, providing frequency coverage from ∼60Hz to 960 kHz (<flh to <2fpe).

Earlier studies using the STEREO 2s WFC (Cohen et al, 2020), the ARTEMIS 10s WFC (Davis et al., 2021) and the Wind 17ms and 1000ms WFC (Wilson et al., 2007; 2020) demonstrated that waves occurring in association with IP shocks at 1au show variability both in wave amplitudes and in wave modes, including ion acoustic waves, electron cyclotron drift instability, solitary waves, Langmuir waves and whistler-mode waves. Several ARTEMIS WFC covered the complete ramp and portions of the adjacent upstream and downstream regions.

For the IP shock that occurred during PSP's Encounter 13, we will discuss the wave modes observed, their association with ions and electrons, and their potential role in shock dissipation and particle energization. We will also compare the moments and distributions measured for ions and electrons. Finally, we will compare the PSP results to those obtained at 1 au to assess the impact of waves between the ion cyclotron and electron plasma frequencies on shock evolution.

Coronal mass ejections and their journey through the solar wind: Current status and paths forwards

Erika Palmerio

Erika Palmerio, Predictive Science Inc., USA

scene-setting talk

SOLAR WIND 16

Evolution of the Heliospheric Current Sheet during a PSP-SolO radial alignment

Etienne Berriot

Etienne Berriot (1), Olga Alexandrova (1), Pascal Démoulin (1), Arnaud Zaslavsky (1), Milan Maksimovic (1), Georgios Nicolaou (2)

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Helios 1 & 2 opened a new era as they allowed for synergistic observations of the solar wind. In particular, there have been studies about the radial evolution of what can be considered the same solar wind parcel passing through both spacecraft when they were radially aligned during so called “plasma line-ups”. The recently launched Parker Solar Probe (PSP) and Solar Orbiter (SolO) are great new opportunities for such studies. Results of plasma line-ups studies are however strongly dependent on the considered time intervals. We propose here a new solar wind propagation method allowing to identify what we believe to be the same plasma passing through PSP (∼0.075 au) & SolO (∼0.9 au) during a radial alignment. We show the matching of two density structures (with radial lengths of ∼ 10ˆ7 km), corresponding to crossings of the Heliospheric Current Sheet on both spacecraft. Data also indicate the development of Stream Interaction Region during the plasma propagation. The unperturbed slow wind observed at PSP has indeed been caught up by a faster wind, creating a propagating shock and trailing compression region, eventually engulfing the Heliospheric Current Sheet.

Evolution of the Heliospheric Current Sheet during a PSP-SolO radial alignment.

Etienne Berriot

Etienne Berriot (1), Olga Alexandrova (1), Pascal Démoulin (1), Arnaud Zaslavsky (1), Milan Maksimovic (1), Georgios Nicolaou (2)

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Modeling the Interaction between the Solar Wind and the Local Interstellar Medium: The Role of Electrons and Helium Ions and Atoms

Federico Fraternale

Federico Fraternale, University of Alabama in Huntsville, USA; Nikolai V. Pogorelov, University of Alabama in Huntsville, USA; Ratan K. Bera, University of Alabama in Huntsville, USA

Numerical modeling is crucial for understanding the global, three-dimensional features of the heliosphere and interpreting in situ measurements from in the outer heliosphere by Voyager and New Horizons (NH), as well as improving neutral atom imaging from remote observations by the IBEX and the upcoming IMAP. This study presents a novel 3-D MHD-plasma/kinetic-neutrals model of the interaction between the solar wind (SW) and the local interstellar medium (LISM) that treats both hydrogen and helium atoms and ions self-consistently, including includes electrons as a distinct fluid co-moving with the plasma mixture. The model also incorporates the effect of Coulomb collisions between electrons, He+ ions, and protons. The properties of electrons in the distant SW and in the LISM are mostly unknown due to the lack of in situ measurements. Nonetheless, electrons are critically important, and we explore the effects of using different models for the electron pressure and validate our findings with NH observations. In single-ion global models, a typical assumption is that electrons have the same pressure as all ions, resulting in hot electrons the distant solar wind since pickup ions carry most of the thermal energy. In contrast, our new model predicts that electrons in the SW are colder, with temperatures comparable to those of core protons. This outcome results in a better agreement with the supersonic SW observations made by NH. In the VLISM, our findings show that Coulomb collisions between ions and electrons can lead to almost thermal equilibrium with temperatures ranging from 30,000 K to 40,000 K in proximity of the heliopause. Notable differences between models are observed in the plasma mixture properties of the inner heliosheath. Colder electrons in the new model result in an enhanced probability of charge exchange (H-H+), which leads to increased cooling of the plasma mixture. As a result, the heliosheath becomes thinner by approximately 5 AU along the upstream direction and up to 60 AU in the downwind region. Additionally, the filtration of interstellar H and He atoms is discussed. At 1 AU, the model with separate electrons shows an increase in H density by approximately 2%. However, the fraction of pristine H atoms becomes lower by about 12%, while the fraction of atoms born in the IHS increases by up to 35%. While the density of He atoms in the SW remains essentially unchanged, the contribution from the warm breeze, i.e. the secondary He born in the VLSIM, becomes higher by about 3%. Remarkably, the inclusion of helium ions in the model suggests that the density of LISM protons may need to be revised to values around 0.65-0.75 cm-3.

Observations of Plasma and Magnetic Field Turbulence in the Heliosheath and VLISM

Federico Fraternale

Federico Fraternale, University of Alabama in Huntsville, USA; Nikolai V. Pogorelov, University of Alabama in Huntsville, USA; John D. Richardson, Massachusetts Institute of Technology, USA; Daniela Tordella, Politecnico di Torino, Italy.

The inner and outer heliosheath offer unique opportunities to study compressible turbulence in distinct plasma environments. The inner heliosheath (IHS) is characterized by the weakly collisional solar wind, which is energetically dominated by pickup ions. The heliopause separates the solar plasma from the collisional, partially ionized very local interstellar medium (VLISM) in the outer heliosheath, a region which is strongly influenced by the presence of the heliosphere and by its dynamics up to hundreds of AU from the Sun. Voyager spacecraft observations have revealed that compressible turbulence exists in both regions, along with large-scale waves or quasi-periodic structures. Although the previous studies have examined magnetic turbulence spectra in the inner heliosheath (IHS), there has been a lack of turbulence analysis focused on plasma density and velocity fluctuations. In this study, we aim to address this gap by extending our previous work to analyze both plasma and magnetic field fluctuations in the IHS, specifically at the energy-injection and inertial scales where fluctuations are above the noise level of V2/PLS data. Our analysis is conditioned on two factors: the spacecraft's location inside or outside of the sector region, and the proximity of the heliospheric current sheet crossings. By considering these factors, we aim to gain a more detailed understanding of the properties of turbulence and their effect on the large-scale flow in the heliosheath. An estimate is provided for the turbulent energy cascade rate along the V2 trajectory using PLS data at the 1 day resolution. Additionally, we perform a time-frequency analysis of the most recent high-resolution magnetic field data from Voyager 1 and 2 in the VLISM, covering distances of up to 153 and 127 au from the Sun, respectively. We discuss the radial evolution of magnetic field fluctuations and compare the turbulence properties observed by the two spacecraft.

Can (fluid) 3rd order laws capture some kinetic physics?

Fouad Sahraoui

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The popular 3rd order law formalism has been used extensively in numerical experiments and spacecraft data to identify the inertial range in turbulent flows and to estimate the related turbulent energy cascade (heating) rate. In recent years the derived theoretical models have grown in complexity by incorporating new ingredients such as density fluctuations and/or small scale effects (e.g., Hall, electron inertia, . . .). Here I will discuss recent progress on the subject with a particular focus on two new questions: to what extent the heating rate estimated from the (fluid) 3rd order laws in spacecraft data can reflect "true" heating due to kinetic effects (e.g., Landau damping)? How the presence of plasma instabilities (as those emerging from the Hall-CGL closure) can impact the energy cascade process.

Non-universality of the turbulent spectra at sub-ion scales in the solar wind: dispersive effects vs. the Doppler shift

Fouad Sahraoui

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Large surveys of power spectral density of the magnetic fluctuations in the solar wind have reported different slopes distributions at MHD, sub-ion and sub-electron scales, the smaller the scale the broader the distribution. Several explanations of the broadening of the slopes at sub-ion scales have been proposed in the literature. Here, we present a new one that has been overlooked in the literature. It is based on the relative importance of the dispersive effects w.r.t. the Doppler shift due to the mean flow speed. We build a toy model based on a dispersion relation of a linear mode that matches at high frequency ($\omega \gtrsim \omega_{ci}$) the Alfvén (resp. whistler) mode at high oblique (resp. quasi-parallel) propagation angles θ **kB**. Starting with a double power-law spectrum of turbulence $k\perp^{-1.66}$ in the inertial range and $k\perp^{-2.8}$ at the sub-ion scales, the transformed spectrum (in frequency f) as it would be measured in the spacecraft reference frame shows a broad range of slopes at the sub-ion scales that depend both on the angle θ **kB** and the flow speed V. Varying θ **kB** in the range $4° - 106°$ and V in the range $400 - 800$ km/s, the resulting distribution of slopes at the sub-ion scales reproduces quite well the observed one in the solar wind. Fluctuations in the solar wind speed and the wave vector anisotropy of the turbulence may explain (or at least contribute to) the variability of the spectral slopes reported from spacecraft observations in the solar wind.

Three-dimensional energy transfer in space plasma turbulence from multipoint measurement

Francesco Pecora

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A novel multispacecraft technique applied to Magnetospheric Multiscale (MMS) mission data collected in the Earth's magnetosheath enables evaluation of the energy cascade rate solving the full Yaglom's equation in a turbulent space plasma. The method differs from existing approaches in that (i) it is inherently three-dimensional; (ii) it provides a statistically significant number of estimates from a single data stream; and (iii) it allows for a direct visualization of energy flux in turbulent plasmas. This new technique will ultimately provide a realistic, comprehensive picture of the turbulence process in plasmas.

Path Lengths of Stochastic Parker Field Lines

Gang Li

Gang Li and Nic Bian
University of Alabama in Huntsville

In the 1960's, Leighton developed a diffusion model for the transfer of magnetic flux on the photosphere, and hence, for the turbulent motions of magnetic footpoints on the solar wind source surface. The Leighton's model is the basis of the stochastic solar wind magnetic field line model put forth by Jokipii and Parker. They assume a Brownian diffusion on the source surface yielding an infinite path length of the boundary-driven magnetic field lines. Here, we extend these models by describing the magnetic footpoint motions by a spherical Ornstein–Uhlenbeck process with a drift due to the Sun's rotation. The boundary-driven interplanetary magnetic field (IMF) lines become smooth differentiable curves with finite path lengths. The model is parameterized by two measurable quantities, the Lagrangian integral timescale and the root-mean-square footpoint velocity. It reduces to Leighton's model in the singular Markov limit when the Lagrangian integral timescale tends to zero while keeping the footpoint diffusivity finite. The joint velocity and position of the magnetic footpoints on the source surface are the solutions of a set of stochastic differential equations which are solved numerically. The path-lengths of the IMF lines and their probability distributions at 1au are computed numerically and their dependency with respect to the two controlling parameters is determined.

Linear Mode-Decomposition in Magnetohydrodynamics Revisited

Gary Zank

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Small amplitude fluctuations in the magnetized solar wind are measured typically by a single spacecraft. In the magnetohydrodynamics (MHD) description, fluctuations are typically expressed in terms of the fundamental modes admitted by the system. An important question is how to resolve an observed set of fluctuations, typically plasma moments such as the density, velocity, pressure and magnetic field fluctuations, into their constituent fundamental MHD modal components. Despite its importance in understanding the basic elements of waves and turbulence in the solar wind, this problem has not yet been fully resolved. Here, we present a new method that identifies between wave modes and advected structures such as magnetic islands or entropy modes and computes the phase information associated with the eligible MHD modes. Our mode-decomposition method identifies the admissible modes in an MHD plasma from a set of plasma and magnetic field fluctuations measured by a single spacecraft at a specific frequency and an inferred wave number. We present data from three typical intervals measured by the WIND and Solar Orbiter spacecraft at ∼1 au and show how the new method allows for the identification of both propagating (wave) and non-propagating (structures) modes, including entropy and magnetic island modes. This allows us to identify and characterize the separate MHD modes in an observed plasma parcel and to derive wave number spectra of entropic density, fast and slow magnetosonic, Alfvenic, and magnetic island fluctuations for the first time. We discuss briefly how these results help in identifying the fundamental building blocks of turbulence in the magnetized solar wind.

What Have we Learned About 3He-rich Solar Energetic Particle Events so far on Solar Orbiter?

George Ho

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Ever since the first 3He-enhanced solar energetic particle (SEP) event was reported in the literature in 1970, the exact mechanism by which the isotope is enhanced orders of magnitude higher than its solar wind value remains unknown. Observations with ACE and Wind in the last decade showed evidences that these 3He-rich SEP events are often accompanied by energetic electrons (10s-100s of keV), type III radio emission, and enhancements of heavy ions. Some events also appear to be associated with solar jets and have ion dropouts at 1 au. The number of observed 3He-rich events is generally correlated with the solar activity. However, no correlation has been found between the enrichment of 3He with other accompanying observations.

Solar Orbiter that was launched in February 2020, is designed to study the Sun and inner heliosphere in greater detail than ever before. The Energetic Particle Detector (EPD) investigation on Solar Orbiter is a suite of four different sensors that measure the energetic particles from slightly above solar wind energies to hundreds of MeV/nucleon. During the first two years in orbit, the Supathermal Ion Spectrograph (SIS) on EPD observed numerous 3He-rich SEP events inside of 1 au in greater temporal and spectral resolutions than ever before. Many of the findings such as the correlation with energetic electrons, type III bursts, and/or solar jets are similar to prior observations near 1 au. In this work, we will report some of the new/old features that we have identified with two years of Solar Orbiter data.

Understanding the Kinetic Physics of Particle Energization at Quasiperpendicular Collisionless Shocks Using the Field-Particle Correlation Technique

Gregory G. Howes

Gregory G. Howes (U Iowa), James Juno (PPPL), Collin R. Brown (U Iowa), Colby C. Haggerty (U Hawaii), Sage Constantinou (U Hawaii), Jason M. TenBarge (Princeton U), Damiano Caprioli (U Chicago), Anatoly Spitkovsky (Princeton U), Lynn B. Wilson III (NASA Goddard)

Collisionless shocks play an important role in the conversion of supersonic flow energy to thermal energy at important boundaries in the heliosphere, such as at planetary bow shocks, the termination shock in the outer heliosphere, and interplanetary shocks propagating through the solar wind. In addition, collisionless shocks can lead to the acceleration of a small fraction of particles to high energy. Many of these energization mechanisms remain poorly understood, but kinetic simulations and spacecraft observations present valuable opportunities to improve our understanding of the fundamental kinetic physics. The recently developed field-particle correlation technique was devised to identify and characterize the mechanisms that energize particles in the six-dimensional (3D-3V) phase space of kinetic plasmas—such mechanisms underlie the fundamental plasma processes of kinetic turbulence, collisionless magnetic reconnection, collisionless shocks, and kinetic instabilities. Here we present an overview of how the field-particle correlation method can be applied to gain deeper insight into the kinetic plasma processes that govern how particles are energized at collisionless shocks. Requiring only single-point measurements in space, the technique can be used to identify well-known acceleration mechanisms, such as shock drift acceleration, using either kinetic numerical simulations or spacecraft observations. In addition, it shows promise to be able to separate the energization mediated by micro-instabilities arising in the shock transition from that due to the macroscopic shock fields.

Identifying the Physical Mechanisms Governing the Damping of Turbulence in the Solar Wind and Quantifying the Rate of Particle Energization

Gregory G. Howes

Gregory G. Howes, University of Iowa

In weakly collisional space plasmas, such as the solar wind, the particle velocity distribution functions contain a wealth of information about the plasma dynamics and transport of energy. Fundamental plasma processes—such as kinetic plasma turbulence, collisionless magnetic reconnection, collisionless shocks, and kinetic instabilities—govern the transport of energy across scales and the consequent energization of the plasma, through either the heating of the plasma species or the acceleration of a small fraction of particles to high energy. All of these mechanisms generate a signature in velocity space, but a detailed application of kinetic plasma theory is essential to interpret these signatures. Here I will present the application of the field-particle correlation technique, which employs single-point measurements of particle velocity distributions and electromagnetic fields, to understand how turbulence is dissipated in the weakly collisional solar wind plasma, yielding a unique velocity-space signature for each physical mechanism involved. The unique velocity-space signatures of these different processes can be compiled to generate a "Rosetta stone" for the definitive identification of different particle energization mechanisms in space and astrophysical plasmas. Application of the technique to large statistical samples of spacecraft data holds the promise to create predictive models of energy transport and plasma heating in turbulence, reconnection, shocks, and instabilities as a function of the plasma and system parameters.

Study of Small Scale Magnetic Reconnection and Energy Release in the Source Regions of Solar Wind

Haimin Wang

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We aim to understand the transport of small-scale ejections/eruptions from the low atmosphere to the corona for possible origins of the dynamic solar wind structures observed by the Parker Solar Probe (PSP). We used state-of-the art magnetic field and photospheric/chromospheric imaging observations from the 1.6-m Goode Solar Telescope (GST) at Big Bear Solar Observatory (BBSO) along with PSP and other NASA HSO data. The major findings are: (1) The time sequence of unprecedented high resolution and high sensitivity GST magnetogram observations disclose that magnetic reconnections in small scale provide sufficient energy and mass for coronal heating and solar wind acceleration; (2) Recent studies suggest that the magnetic switchbacks (SBs) detected by the PSP carry information on the scales of solar supergranulation (large scale) and granulation (medium scale). We tested this claim using high-resolution Hα images obtained with the visible spectropolarimeters of GST. We found that the medium scale of SBs can be understood as an equilibrium distance resulting from a random walk within each diverging magnetic field funnel connected to the chromospheric networks; (3) Using full-disk extreme ultraviolet images from SDO/AIA, we identify small-scale ejections in CH regions during PSP Encounters 5, 7, and 8, and study their statistical properties. These ejections belong to two categories: standard jets and below-out jets. With nearly 30,000 ejections identified in 24 days (about 2/3 of them are blow-out jets), we updated the expected frequency for PSP to detect their counterparts in the heliospace. The ejections we identified are comparable to the frequency of PSP-detected SMFRs, but they are insufficient to serve as the only producer of SBs or SB patches. Smaller events such as jetlets may fill the gap.

MMS and STEREO observations of ion cyclotron waves in the solar wind: indications of wave instabilities and source ions

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Electromagnetic waves, with nearly circular polarizations and field-aligned propagations and near the proton cyclotron frequency, are frequently observed in the solar wind at multiple heliocentric distances. They are often called ion-scale cyclotron waves and could play important roles in transferring energies and mediating the level of temperature anisotropy of ions. The Magnetospheric Multiscale (MMS) spacecraft orbits in "pristine" solar wind near apogee which provides high-resolution plasma and fields measurements to advance our understanding of the wave properties and the wave-particle interactions at the ion kinetic scale. Using multi-spacecraft observations, we can calculate the wave vector and better determine the wave mode in the solar wind plasma frame. The plasma observations indicate ion beams exist at or near the wave intervals and allow us to investigate the wave generation instabilities and possible wave-particle interactions. However, due to MMS being near Earth orbit, we cannot exclude the bow shock being the ultimate source of these ion beams. While STEREO observes similar waves in the solar wind near no celestial objects, we can compare the wave behaviors in MMS data and STEREO data to better understand the wave modes and their energy sources.

Collisional Transport of Solar Wind Plasma During its Journey from the Sun to the Earth

Isabella Dieguez

Isabella Dieguez, UC Berkeley

Parker Solar Probe (PSP) is the first spacecraft to dive deep into the solar corona, making the first-ever direct measurements of the plasma within the corona and offering unprecedented observations of solar wind plasma in its nascent form. In their journey outward from the Sun, the streams that make up solar wind plasmas interact, expand, and evolve in a number of different ways. Previous theoretical work has shown that coulomb collisions are one of the many factors that dictate the thermodynamic properties that distinguish different kinds of solar wind. Plasma instruments onboard the PSP spacecraft, making up the Solar Wind Electrons, Alphas, and Protons (SWEAP) suite, provide an opportunity to further test and investigate this well-known collisional hypothesis by identifying solar wind plasma streams that are also measured by other spacecraft such as Solar Orbiter and Wind during suitable conjunctions. These multi-point observations will be compared to collisional predictions to evaluate the evolution of plasma distributions as they travel through the inner heliosphere. This work examines the degree to which collisional transport can explain the radial evolution of plasma parameters within 1 au.

Magnetic field connection from the photosphere to Parker Solar Probe

Iulia Chifu

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The solar wind plasma and magnetic field properties have their sources in the solar corona and underlying chromosphere and photosphere. During their evolution into interplanetary space, the solar phenomena change due to different physical processes. The variability of the photospheric magnetic fields plays a crucial role in a variety of spatial and time scales. There are indications that switchbacks occurrence is modulated by the supergranular network. Magnetic field activity, i.e. the phase of the solar cycle, determines the topology of the overlying coronal field and the shape of different structures, e.g. heliospheric current sheet (HCS), coronal streamers, etc. To understand better the in-situ solar wind properties, we therefore need to investigate the photospheric and coronal structures and the variation of the magnetic field in the higher layers of the solar atmosphere during the solar cycle. The proximity of PSP to the Sun offers unique opportunities to connect solar and space observations. For this purpose, we select to study those orbits when simultaneous ground and space-based observations exist. For completing the global picture, we will use the white-light images provided by WISPR telescopes to find the correspondence between the structures observed by WISPR and the underlying solar magnetic field topology.

Processes underlying the variation of the magnetic field spectral index in the inner solar wind

Jack McIntyre

J R McIntyre, Queen Mary University of London; C H K Chen, Queen Mary University of London

The solar wind is known to contain a turbulent cascade and it is proposed it plays a role in its heating and acceleration. An indicator of the nature of this turbulence is the magnetic field spectral index; using data from the Parker Solar Probe (PSP) mission we are able to measure it across an unprecedented range of heliocentric distances. Common predictions for the spectral index in incompressible magnetohydrodynamic (MHD) turbulence theory are -5/3, as predicted by models including the 1995 Goldreich-Sridhar anisotropic turbulence model, and -3/2, as predicted by models including the 2006 Boldyrev scale-dependent alignment model. At distances above $\sim$0.4au we find it to be consistent with -5/3 but find it to increase with decreasing radial distance to be consistent with -3/2 below $\sim$0.2au, indicating unexpected changes in the turbulence close to the Sun. By measuring also the normalised cross helicity and residual energy of the intervals used, properties of the solar wind known to vary with heliocentric distance, we separate this variation with distance from variation with these parameters to present new insights into the physical mechanism responsible for this transition. This analysis was repeated with further parameters including the turbulence age, as the turbulence plausibly evolves with the number of nonlinear times that have past; sampling angle, as the turbulence is known to be anisotropic; and the magnitude of the magnetic fluctuations. Of all parameters considered the cross helicity was found to be the strongest candidate for the underlying parameter responsible for the transition - the implications of this for our understanding of solar wind turbulence will be discussed.

The Effects of Non-Equilibrium Velocity Distributions on Alfv\'en Ion-Cyclotron Waves in the Solar Wind

Jada Walters

Jada Walters (University of Arizona), Kristopher Klein (University of Arizona), Emily Lichko (University of Chicago), Michael Stevens (Smithsonian Astrophysical Observatory), Daniel Verscharen (Mullard Space Science Laboratory, University College London), and Benjamin Chandran (University of New Hampshire)

In this work, we investigate how the complex structure found in solar wind proton velocity distribution functions (VDFs), rather than the commonly assumed two-component bi-Maxwellian structure, affects the onset and evolution of parallel-propagating microinstabilities. We use the Arbitrary Linear Plasma Solver (ALPS), a numerical dispersion solver, to find the real frequencies and growth/dampingrates of the Alfvén modes using proton VDFs extracted from Wind spacecraft observations in the solar wind. We compare this wave behavior to that obtained by applying the same procedure to core-and-beam bi-Maxwellian fits of the Wind proton VDFs. We find several significant differences in the plasma waves obtained for the data and bi-Maxwellian fits, including a strong dependence of the growth/damping rate on the shape of the VDF. By application of the quasilinear diffusion operator to these VDFs, we pinpoint resonantly interacting regions in velocity space where differences in VDF structure significantly affect the predictions of wave growth and damping rates. This demonstration of the sensitive dependence of Alfvén mode behavior on VDF structure could explain why the Alfvén ion-cyclotron instability thresholds predicted by linear theory for bi-Maxwellian models of solar wind proton background VDFs do not entirely constrain spacecraft observations of solar wind proton VDFs, such as those made by the Wind spacecraft.

Interchange magnetic reconnection within coronal holes drives a structured, turbulent solar wind

James Drake

J. F. Drake (University of Maryland), S. D. Bale (UC Berkeley), M. Swisdak (University of Maryland) and the PSP Science Team

The Parker Solar Probe (PSP) data close to the sun has revealed a bursty solar wind with a periodicity that matches the spatial periodicity of the magnetic field at the surface of the sun. This points to reconnection between open and closed magnetic flux in coronal holes (interchange reconnection) as the driver of the fast wind. We use the PSP data along with the basic characteristics of reconnection to deduce the local properties of interchange reconnection near the solar surface, including the characteristic strength of the reconnecting magnetic, the ambient density, the rate of reconnection and associated rate of energy release. The large-scale structure of the wind based on the reconnection drive mechanism has been calculated and the minimum condition for wind generation based on reconnection driven outflow and heating have been derived. A minimum reconnection Alfven speed of 350-400km/s is required for wind generation. The resulting global wind radial profiles are presented and benchmarked with PSP observations at 12 solar radii. Because reconnection in the coronal environment is bursty, the wind is predicted to be highly structured rather than quasi-uniform as in conventional Alfven wave drive models. The consequence is the development of super-Alfvenic sheared flows close to the sun that drive strong turbulence that is the likely the source of the ubiquitous switchbacks documented in the wind environment close to the sun. PIC simulations of the development of this strong shear-driven turbulence have been carried out and will be presented.

Simulating Alfvén Wave Collapse and Wave-Particle Interactions in the Solar Wind Using an Expanding Box Model

Jarrod Santo Bianco

Jarrod Santo Bianco; University of Texas at Austin Anna Tenerani; University of Texas at Austin Carlos Gonzalez; University of Texas at Austin

Field aligned proton beams drifting with respect to the core proton population at the local Alfvén speed have been commonly observed in the Alfvénic solar wind at distances from the sun, R>0.3 AU. Interestingly, observations by Parker Solar Probe have shown that proton beams are far more common than previously thought. Closer to the sun, beams can also achieve drift speeds exceeding the Alfvén speed, possibly triggering kinetic instabilities. Understanding the origin, evolution and stability of proton beams in the solar wind, and how they interact with waves and fields, is fundamental in understanding solar wind dynamics and heating. In this work, wave-particle interactions mediated by the collapse of an Alfvén wave are investigated by making use of a hybrid Particle in Cell code that can mimic dynamical effects introduced by the solar wind radial expansion. Starting with an amplitude-modulated Alfvén wave, we show that the Alfvén wave undergoes a local collapse leading to the formation of a field-aligned beam drifting at the Alfvén speed. We discuss the initial wave collapse and the proton beam formation, by focusing on the effects of the radial expansion on the system and on long-term wave-particle interactions. We provide a comparison between simulations with and without expansion, as well as a comparison between simulations with different initial plasma beta and discuss the role of expansion in the evolution of the proton beam.

Quantifying the Energy Budget for Solar Wind Acceleration with Parker Solar Probe

Jasper Halekas

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A variety of energy sources, ranging from dynamic processes like magnetic reconnection to quasi-steady terms like the plasma pressure gradient and the associated ambipolar electric field, may contribute to the acceleration of the solar wind. Fluctuations and waves, while inherently dynamic, can act as an effective additional pressure gradient term. The heat flux carried by the charged particle distributions may also play a role. We utilize a combination of plasma and magnetic field data from the SWEAP and FIELDS experiments on the Parker Solar Probe (PSP) to attempt to quantify the contribution of the ambipolar electric field, the ion pressure gradient, the wave pressure gradient, and the electron heat flux to the wind acceleration observed by PSP between ∼13 and ∼100 solar radii. In agreement with previous work, we find that the ambipolar potential can fully explain the acceleration of the slowest wind streams. Meanwhile, a combination of the ion thermal and wave pressure gradients appears sufficient to explain the continuing acceleration of the faster wind streams outside of the PSP perihelion.

As Seen by Parker Solar Probe: Multi-Scale Wave-Particle Interactions Near the Heliospheric Current Sheet

Jaye Verniero

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Parker Solar Probe (PSP) is sampling regions of the inner heliosphere never seen before to address where and why energy flows between the Sun and earth. The onset of proton beams are observed often coincident with ion-scale, near-circularly polarized waves, which appear both left (ion-cyclotron, ICW) and right-handed (fast/magnetosonic, FM) in the spacecraft frame. Recent observations reveal the presence of electrostatic waves in concert with these lower frequency electromagnetic fluctuations, coupled with variations in the properties of the electron strahl population. These intervals are associated with the proximity to the Heliospheric Current Sheet (HCS), which has been recently shown to comprise dynamic features in the near-Sun region and is potentially an understudied source of free energy for particle energization. Although their intrinsic handedness is sign-ambiguous, the ICW/FM waves may be mediating cross-scale energy transfer between large-scale perturbations (such as oscillation of the HCS) and kinetic-scale particle acceleration. We present an overview of these wave-particle interaction observations and hypothesize on their role in plasma energization and subsequent solar wind heating.

Statistical magnetic connectivity study from in-situ measurements of Solar Orbiter extrapolated sunward the Solar Corona.

Jean-Baptiste DAKEYO

J-B .Dakeyo (IRAP, LESIA), A. Rouillard (IRAP), P. Démoulin (LESIA), V. Réville (IRAP), M. Maksimovic (LESIA), P. Louarn (IRAP)

We trace back the trajectory and solar origin of plasma parcels measured in-situ in the solar wind by exploiting simple numerical models of the coronal and interplanetary magnetic field. Past studies using such approaches have shown that the solar wind speed measured in situ near 1AU is anti-correlated with the expansion factor of the coronal magnetic flux tube channeling estimated to channel the measured wind (Wang & Sheeley 1990). In this study we estimate the solar origin of Solar Orbiter measurements made between 0.3 AU to 1 AU and classify the measured wind properties according to the types of magnetic structures (streamers, pseudo-streamers, coronal holes) encountered in the estimated source regions using Potential Field Source Surface (PFSS) reconstructions. To better approximate the departure time and location of the plasma at the Sun, we constrain the trajectory of the solar wind and the time travel using the iso-poly speed profile of Dakeyo et al. 2022, modeling the bulk speed from the probe location sunward the source surface Rss. In addition, we take into account the radial dependence of corotating effect on the Parker spiral (Koukras 2022). We aim to follow the classification of Maksimovic et al. 2020 and Dakeyo et al. 2022, to extrapolate sunward the coronal parameters of the different wind speed populations observed by Solar Orbiter. This statistical analysis shows that the correlations are not globally conserved for all types of sources, which means that a value of the expansion factor at Rss alone does not determine the outflowing wind speed. We present an analysis of other important effects such as varying heating rates at the coronal hole base or the refocusing of flux tube expansion factors.

Exploring the effect of turbulent fluctuations on the onset of reconnection

Jeffersson Agudelo

Jeffersson Agudelo Rueda, (Department of Physics and Astronomy, Dartmouth College, Hanover, NH, USA), Yi-Hsin Liu (Department of Physics and Astronomy, Dartmouth College, Hanover, NH, USA), Kai Germaschewski (Space Science Center, University of New Hampshire, Durham NH 03824, USA)

In space plasmas, explosive and energetic events are routinely observed. Many of these events are associated with magnetic reconnection. Moreover, turbulence is undeniably present in a wide range of plasmas, e.g., solar wind, solar corona, accretion disks, etc. Magnetic reconnection and turbulence are important energy-transport and energy-transfer processes which not only transport energy across a broad range of scales but also facilitate the energy transfer between fields and particles. From in-situ observations in the Earth's magnetosheath and numerical simulations, it is well known that turbulence can lead to reconnection events. Likewise, from observations in the Earth's magnetotail, as well as simulations, turbulence might be present in almost any region of a reconnection event. Despite decades of research, there are still many open questions about turbulence and reconnection. By means of 2D PIC simulations, we explore the effect of driving turbulent fluctuations on a current sheet and study how these fluctuations can modify the onset of reconnection and its dynamics. Our results cast some doubt on the role of turbulent fluctuations as triggers of reconnection events in current sheets.

Measurement of the rate of change of the electron heat flux with Solar Orbiter observations

Jesse Coburn

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Xiangrong Fu, New Mexico Consortium, Los Alamos, NM , USA (& Los Alamos National Laboratory, Los Alamos, NM , USA).

Non-Maxwellian features of coronal electrons are important for some models of solar wind acceleration processes. Remnants of these features are detectable in spacecraft observations, in particular in the form of a field-aligned beam (strahl) and sunward deficit in the electron velocity distribution function (VDF), both of which contribute to the total electron heat flux. These features are shaped by large-scale fields, collisions, turbulence, and instabilities. Therefore, determining how these processes alter the VDF provides a better understanding of how the solar wind is accelerated and of the total thermal energy budget of the solar wind. In particular, the strahl and deficit can destabilise the plasma causing wave emission at the expense of particle energy, softening these unstable features. The work presented here examines an interval observed by Solar Orbiter during which narrow-bandwidth whistler waves were measured by the Radio and Plasma Waves instrument and the Solar Wind Analyser measured an electron strahl and deficit. A Hermite-Laguerre spectral method is applied to the VDF to obtain a low-pass filtered velocity space gradient. The combined observations provide a measurement of the rate of change of electron moments, in particular the heat flux, in accordance with quasilinear theory. Quantification of the rate of change of the moments allows direct comparison of the efficiency of the various processes. Finally, the potential of the technique to better understand the role of wave-particle interactions in the evolution of the solar wind is demonstrated.

The Structure and Origin of Switchbacks: Parker Solar Probe Observations

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Switchbacks are rapid magnetic field reversals that last from seconds to hours. Current Parker Solar Probe (PSP) observations pose many open questions in regard to the nature of switchbacks. For example, are they stable as they propagate through the inner heliosphere, and how are they formed? In this work, we aim to investigate the structure and origin of switchbacks. In order to study the stability of switchbacks, we suppose the small scale current sheets therein are generated by magnetic braiding, and they should work to stabilize the switchbacks. With more than one thousand switchbacks identified with PSP observations in seven encounters, we find many more current sheets inside than outside switchbacks, indicating that these micro-structures should work to stabilize the S-shape structures of switchbacks. Additionally, we study the helium variations to trace the switchbacks to their origins. We find both helium-rich and helium-poor populations in switchbacks, implying the switchbacks could originate from both closed and open magnetic field regions in the Sun. Moreover, we observe that the alpha-proton differential speeds also show complex variations as compared to the local Alfvén speed. The joint distributions of both parameters show that low helium abundance together with low differential speed is the dominant state in switchbacks. The presence of small scale current sheets in switchbacks along with the helium features are in line with the hypothesis that switchbacks could originate from the Sun via interchange reconnection process. However, other formation mechanisms are not excluded.

Upstream Solar Wind Prediction up to Mars by an Operational Solar Wind Prediction System

Jingjing Wang

Jingjing Wang, National space science center, Chinese academy of science

Combining the upstream solar wind observations measured by Mars Atmosphere and Volatile Evolution (MAVEN), Advanced Composition Explorer(ACE) and Deep Space Climate Observatory (DSCOVR) from October 2014 to April 2021, we investigate the statistical properties of the background solar wind at Mars and Earth. By applying an operational solar wind prediction system (Wang et al., 2018) in Space Weather Prediction Center (SEPC), we simulate the solar wind conditions and carry out a comparative analysis with observations to study our model performance. We find that our model is able to simulate the solar wind conditions upstream of Earth and Mars, corresponding to the different heliocentric distances and different levels of solar activity. Furthermore, we apply an event-based evaluation by analyzing the high speed enhancements (HSEs), and find that the hit rate of HSEs is 70.38% and 66.37% for Earth and Mars, respectively. By predicting the HSEs at Earth (Mars), our model reaches a Mean Absolute Error (MAE) of 83.93 km/s (65.91 km/s) and 22.98 hr (21.65 hr) for maximum speed and arrival time prediction error, respectively. We also conduct a three-month case study, from November 2020 to January 2021, analyzing solar wind conditions upstream of Earth, Mars, and measured by Tianwen-1 (China's first Mars mission), for which our model is capable to predict the upstream solar wind conditions up to Mars.

The Role of Shocks in Producing Suprathermal Particles

Joe Giacalone
Joe Giacalone, University of Arizona

Suprathermal particles have received considerable attention in the study of the solar wind. We seldom, if ever, observe purely thermal distributions in space – they nearly always have a high-energy, non-thermal tail. The charged particles in this tail have presumably have been accelerated, but pinpointing the process (or processes) involved is made difficult by the fact the particles are very mobile and do not necessarily directly relate to the local magnetic field and plasma. However, shocks provide an excellent laboratory for the study of suprathermal particles and provide a good example of the local production of suprthermal particles. It is widely accepted that shocks naturally produce high-energy tails in the heated downstream distribution and is often observed locally as the shock crosses the spacecraft. Fast CME-related shocks have the highest intensity of suprathermal particles that we observe – often by a few orders of magnitude about the background. Parker Solar Probe, which has ventured closer to the Sun than any prior spacecraft, has observed a number of CME-related events, even relatively weak ones, each of which have been associated with very large increases in suprathermal particles. It is certainly reasonable that shocks are by far the dominant contributor to the production of suprathermal particles. In this talk, I will discuss the implications of this, including the basic physics involved and will present several observational examples.

Voyager Observations of the Interstellar Medium

John Richardson

John Richardson MIT The Voyager Team (William Kurth, Iowa; Alan Cummings, Caltech; Adam Szabo, GSFC, Len Burlaga, GSFC, Tom Krimigis, Athens; Rob Decker, APL, Jamie Rankin, Princeton; Linda Spilker, JPL;, Suzy Dodd, JPL)

The Voyager spacecraft are both making observations in the very local interstellar medium (VLISM). This paper summarizes recent results. Highlights are a magnetic field direction that did not change at the heliopause and still remains in roughly the Parker field direction over 30 AU beyond the heliopause at Voyagr 1, continuing observations of solar transients propagating into the VLISM producing shocks and pressure fronts with density and magnet field increases, and continued regions with anisotropic galactic cosmic ray distributions. We discuss these observations and their implications.

Trends in and Interpretations of Routine IBias Sweep Results on PSP Fields - Encounters 1 through Now

John William Bonnell

John W. Bonnell, Millan Diaz-Aguado, Space Sciences Laboratory, UC Berkeley.

Routine sensor bias current and offset voltage sweeps are a key part of the operation of the double-probe E-field sensor suite on PSP Fields. These sweeps (aka. sensor diagnostic tests) cycle through a programmable set of sensor bias settings while recording the sensor potentials, allowing one to see how the sweeping sensors, fixed sensors, and spacecraft respond to the changing current balance conditions, and from those data infer the electrical properties of the plasma sheaths surrounding the PSP spacecraft and sensors.

Here, we present summary data regarding trends in the observed sweep properties through the first five years of the PSP mission, both over the mission and over radial distance from the Sun, detailed exploration of the electrical properties one can derive from the sweep data, as well as some of the unexpected behaviors observed during the mission. We'll discuss those results in the context of existing plasma sheath and current balance theory, and describe plans for sweep operations through the end of the nominal mission.

Radial evolution of imbalance and differential heating of the solar wind

Jonathan Squire

Jonathan Squire (University of Otago), Romain Meyrand (University of Otago), Matthew W Kunz (Princeton University)

Low-frequency Alfvénic turbulence is a leading candidate to explain the heating of the solar corona and launching of the solar wind. A sufficiently energetic source of such motions is observed near the coronal base, and in-situ measurements reveal that the solar wind is filled with Alfvénic fluctuations. However, a persistent difficulty has been understanding the detailed thermodynamics – how do we explain the different ion and proton temperatures in fast- and slow-wind streams? why is the heating usually perpendicular to the magnetic field? and what explains the enormous temperatures of minor-ion species? Such questions can be relevant to both local in-situ observations and the solar wind's global structure and acceleration. In this work, we explore the promise of the recently discovered "helicity barrier" mechanism for answering such questions. When the turbulence is imbalanced (dominated by outwards-propagating fluctuations) the mechanism stops the turbulent flux of energy to small scales. This implies the thermodynamics is controlled by imbalance, which is in turn controlled by magnetic geometry, heliocentric distance, and wind speed. We present new hybrid-kinetic simulations of plasma turbulence with an imbalance that slowly decreases in time, used as a mock up of what should occur as the plasma flies away from the Sun. We show that the helicity barrier controls the partition between proton and electron heating, with ion-cyclotron-mediated proton heating at high imbalance giving over to electron heating at low imbalance. As this occurs, the steep transition range in the magnetic spectrum disappears and the turbulence amplitude drops significantly, in good agreement with in-situ observations. We will discuss the potential impacts and observational signatures of this physics on the heating of the solar wind at increasing heliocentric radii.

Proton and electron heating near reconnection sites: pressure strain analysis

Joshua Goodwill

Joshua Goodwill: University of Delaware, Yan Yang: University of Delaware, Sohom Roy: University of Delaware, Fan Guo: Los Alamos National Lab, William Matthaeus: University of Delaware

Magnetic Reconnection occurs when opposing magnetic fields collide and convert magnetic energy into kinetic and thermal energy. In a turbulent environment, magnetic reconnection modifies the cascade of energy of the system, meaning that there must be a connection between the two processes. In previous studies the pressure strain interaction has been shown to have a characteristic conversion between internal energy and fluid energy of the plasma at reconnection sites (Bandyopadhyay 2021). In particular, electrons are shown to be heated more at these sites, suggesting that there is little coupling to ions due to the small length scales associated with turbulence (Adhikari 2022). A 2.5D VPIC (Vector Particle-in-Cell) simulation with solar-wind like variables has been produced where the reconnection sites are found. Performing a statistical analysis of the pressure strain interaction around reconnection sites will provide a deeper understanding of couplings during reconnection onset. Although the only current spacecraft that can measure pressure strain at present is MMS in the magnetosheath, the present study may help inform expectations for heating in the solar wind. Future missions such as HelioSwarm, are expected to routinely measure pressure strain in the solar wind.

Scaling properties of Elsasser increment probability distribution functions (PDF) in solar wind and MHD simulations.

Juan Carlos Palacios

Juan Carlos Palacios (Florida Institute of Technology), Jean Carlos Perez (Florida Institute of Technology), Sofiane Bourouaine (Florida Institute of Technology)

In this work we investigate the scaling properties of probability distribution functions (PDFs) of Elsasser increments in magnetohydrodynamic (MHD) turbulence using large sets of spacecraft data from the WIND mission and high-resolution numerical simulations of Reduced MHD turbulence. The scale-dependent PDFs of Elsasser increments are measured over 23 years of WIND data near 1 AU, from 1995 to 2017, as well as from high-resolution numerical simulations of steadily driven, homogeneous Reduced MHD turbulence on a 2048^3 rectangular mesh. The PDF obtained from observations and numerical simulations are then fitted to analytical functions that capture the core and tail of the PDF in terms of a few adjustable parameters, which are then used to identify possible universal scaling laws and their role in the scaling of structure functions in observations and simulations.

Theoretical prediction of ion scale waves observed in the inner heliosphere

Jungjoon Seough

Jungjoon Seough1, Peter H. Yoon2, and Yasuhiro Nariyuki3 1Korea Astronomy and Space Science Institute, Daejeon, South Korea 2IPST, University of Maryland, College Park, Maryland, USA 3Faculty of Human Development, University of Toyama, Toyama, Japan

The coherent electromagnetic waves at ion scales have been frequently observed in the inner heliosphere. It is expected that ion-scale waves, propagating preferentially quasi-parallel to the mean magnetic field, are locally driven by the ion micro-instabilities that are dynamically associated with turbulent heating and thermodynamic processes in the expanding solar wind. In order to discuss the underlying physical processes of how the ion-scale waves are generated in the inner heliosphere, we here present a recently developed expanding box model based upon the velocity moment-based quasilinear kinetic analysis. This model incorporates the kinetic physics, such as plasma heating driven by Alfven-wave turbulence and micro-instabilities calculated by a self-consistent manner, into the large-scale fluid description. The theoretical results may help us understand the observational features, not only the presence of abundant ion-scale waves but also the thermodynamic evolution of solar wind protons.

Ion-scale waves in the inner heliosphere: Expanding Box Quasilinear Model

Jungjoon Seough

Jungjoon Seough (Korea Astronomy and Space Science Institute, South Korea), Peter H. Yoon(Univ. Maryland, College Park, USA), and Yasuhiro Nariyuki (University of Toyama, Japan)

The coherent electromagnetic waves at ion scales have been frequently observed in the inner heliosphere. It is expected that ion-scale waves, propagating preferentially quasi-parallel to the mean magnetic field, are locally driven by the ion micro-instabilities that are dynamically associated with turbulent heating and thermodynamic processes in the expanding solar wind. In order to discuss the underlying physical processes of how the ion-scale waves are generated in the inner heliosphere, we here present a recently developed expanding box model based upon the velocity moment-based quasilinear kinetic analysis. This model incorporates the kinetic physics, such as plasma heating driven by Alfven-wave turbulence and micro-instabilities calculated by a self-consistent manner, into the large-scale fluid description. The theoretical results may help us understand the observational features, not only the presence of abundant ion-scale waves but also the thermodynamic evolution of solar wind protons.

HelioSwarm: Characterizing Space Plasma Turbulence with a Multi-Point, Multi-Scale Observatory

Kris Klein

Kristopher Klein, University of Arizona; Harlan Spence, University of New Hampshire; the HelioSwarm Science and Engineering Teams

Characterizing the nature of turbulent fluctuations and the associated transport of mass, momentum, and energy requires simultaneous measurements at multiple points spanning characteristic length scales. The HelioSwarm Observatory, a NASA mission currently in Phase B-prep, has been designed to make such measurements in the solar wind, magnetosheath, and magnetosphere, revealing the three-dimensional, dynamic mechanisms controlling the physics of turbulence in near-Earth plasmas. These measurements will allow us to address two overarching science goals: 1) Reveal the 3D spatial structure and dynamics of turbulence in weakly collisional plasmas and 2) Ascertain the mutual impact of turbulence near boundaries and large-scale structures.

Addressing these goals is achieved using a first-ever “swarm” of nine spacecraft, consisting of a “Hub” spacecraft and eight “Node” spacecraft, designed to operate as a single Observatory. Flight dynamics design and on-board propulsion produce ideal inter-spacecraft separations ranging from fluid scales (1000’s of km) to sub-ion kinetic scales (10’s of km) in the necessary geometries to enable the application of a variety of established multi-point techniques that distinguish between proposed models of turbulence.

In this presentation, we discuss the Observatory design and the application to synthetic data of several multipoint analysis methods that will be enabled by HelioSwarm.

A series of small-scale flux ropes originating from the same longitudinal and latitudinal source region close to the Sun as identified from the fifth Parker Solar Probe encounter

Kyung-Eun Choi

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Small-scale magnetic flux ropes (SMFRs) in the solar wind have a similar magnetic topology to large-scale interplanetary flux ropes such as magnetic clouds, while their origins are yet to be understood. Since the Parker Solar Probe (PSP) operates the closest to the Sun, its in-situ observations allow one to seek the origin of SMFRs closest to the Sun ever. In this work, we investigate SMFRs identified from the fifth PSP encounter observations on the verge of the neutral sheet as inferred from the potential field source surface (PFSS) map. We find a series of low plasma beta SMFRs ($\sim$10 events) which were successfully modelled by force-free fitting technique. From the corotating frame of the Sun, they were found during $\sim$30 hrs over several solar radii range (between $\sim$0.165 AU to 0.195 AU) within a very narrow longitudinal and latitudinal zone ($<$ a few degrees). We presume that they were generated repetitively from the same source region inside the PSP location near the heliospheric current sheet or they may be a bunch of flux ropes separated by a short radial distance across some (undetermined) radial distance range, which were transported outward at a slow speed ($<$ 300 km/s). Further we determine whether they are mixed with or distinguished from Alfven waves based on cross helicity and residual energy. Implications on this will be addressed in this presentation.

Parker Solar Probe Langmuir Wave Observations in the Venusian Electron Foreshock

L. Claire Gasque

L. C. Gasque[1], T. A. Bowen[1], S. D. Bale[1], O. M. Romeo[1], C. S. Salem[1], M. P. Pulupa[1]

[1]Space Sciences Lab, UC Berkeley

On its mission to descend lower into the Sun's atmosphere, Parker Solar Probe (PSP) has so far completed five Venus gravity assists, flying within a single planetary radius of the surface each time. These Venus encounters present a unique opportunity to study plasma processes near Venus, including in Venus's electron foreshock, where solar wind electrons energized in Venus's bowshock stream back along magnetic field lines. These beams of energetic electrons create a bump in the tail of the electron distribution function, which can exchange energy with the ambient electric field and excite resonant Langmuir waves. This work uses data from the FIELDS and SWEAP instrument suites on PSP, which measure in situ electric and magnetic fields and charged particle distributions, respectively. The FIELDS Time Domain Sampler (TDS) captures high-resolution bursts at 1.92 MSa/s in including four electric field channels and the high-frequency winding of the search coil magnetometer, allowing us to examine Langmuir waveforms in Venus's electron foreshock in more detail than was previously possible. In this work, we present both a statistical view of where PSP views Langmuir mode waves, indicating when the spacecraft is magnetically connected to the bowshock, along with case studies of individual bursts. For the case studies, we observe some Langmuir waves with clear harmonic structure, sometimes coincident with lower-frequency plasma waves. We will discuss the implications of this work for fundamental physical processes in Venus's bowshock and electron foreshock.

Investigation of the Ion-Scale Cyclotron Waves in the Inner Heliosphere

Lan Jian

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Since the launch in August 2018, Parker Solar Probe (PSP) has explored the regions as close to the Sun as 13.3 solar radii, occasionally below the Alfven surface. Using the high-cadence magnetic field data from PSP, we have surveyed the circularly-polarized electromagnetic waves near the proton cyclotron frequency during October 2018 – December 2021 and covering PSP's first 10 elliptical orbits around the Sun. In this PSP database including thousands of wave events, the left-hand (LH) polarized waves are detected slightly more often than the right-hand (RH) polarized waves. By comparing with the STEREO wave survey covering the same time period at 1 AU, we investigate the radial evolution of the wave properties from 0.1 to 1 AU statistically, including the wave duration, occurrence rate, wave frequency, wave power, etc. We compare the distributions of ion temperature anisotropy vs. parallel beta for LH wave, RH wave, and no-wave solar wind intervals at 0.1, 0.2, and 0.3 AU. We also assess the Doppler shifts in super- vs. sub-Alfvenic solar wind. For a few selected events in which LH and RH polarized waves occur closely in time or simultaneously, we analyze their plasma conditions including temperature anisotropies of solar wind protons and alpha particles, secondary populations of protons and alpha particles as well as their relative drifts from the core protons. Our investigation produces statistical relationships between plasma parameters and wave properties, and provides observational constraints and validations for simulations of the interactions between solar wind ions and ion-scale waves.

Science Investigations Enabled with the Faraday Effect Tracker of Coronal and Heliospheric Structures (FETCH) Instrument

Lan Jian

E. A. Jensen (1), N. Gopalswamy (2), L. K. Jian (2), S. F. Fung (2), J. E. Kooi (3), W. Manchester (4), T. Nieves-Chinchilla (2), D. Wexler (5), L. B. Wilson (2), A. A. Pevtsov (6), B. E. Wood (3), A. Kumari (2), L. Li (2), M. Deshpande (2), M. Shelton (2), J. Lazio (7), S. Bale (8), M. Kenny (9), G. Voellmer (2), L. Purves (2)

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As one of the ten instruments on the proposed Multiview Observatory for Solar Terrestrial Science (MOST) mission concept submitted to the 2024 Heliophysics Decadal Survey, FETCH introduces the new capability to remotely investigate magnetic field structures in the heliospheric space from the Sun to the Earth.

FETCH consists of radio transceiver antennas on the four MOST spacecraft arrayed on either side of the Earth-Sun (E-S) line, enabling four radio signal lines of sight (LOS) (i.e., transmitting from one side of the E-S line and receiving at the other). With this array configuration, we have begun analyzing the strengths and limitations in the potential measurements with these LOS's intersecting the E-S line at 0.14 AU (30 Rs), 0.25 AU, and 0.5 AU.

We first use a MHD model (with and without a CME) to generate synthetic in-situ observations at various locations of the inner heliosphere, and then derive the magnetic field, velocity and other quantities from the Faraday Rotation (FR) and Total Electron Content (TEC) measurements based on the simulated density distribution. From preliminary work, we have found, for example, that the average magnetic field component parallel to the LOS from the quotient of FR and TEC could be accurate within a factor of two; however, this FR/TEC approximation becomes less accurate when the intervening plasma density along the LOS becomes more irregular. We have also found that CME velocities can be analyzed in detail by tracking the evolution of different structural elements of the CME using the FR and TEC profiles. A Corotating Interaction Region (CIR) investigation has found the magnetic field parallel to the LOS and TEC distribution can be observed and analyzed via modeling between L4, Earth, and L5, upstream of 0.5 AU as it evolves. The limitation with the FR/TEC measurement is the typical deconvolving challenge with integrated remote-sensing observations.

The CME structure presents a challenge in a more realistic heliosphere with a CIR complicating the identification of the trailing edge of the magnetic flux rope. Unique identification of the leading and trailing edges of a CME is important to properly fit a magnetic flux rope model. Comparison with synthetic in-situ observations shows that while in-situ data can be offset from the CME nose, impacting the estimate of its crossing time, the FR/TEC measurement through multiple LOS's unmistakably identifies the start of the crossing. In contrast with the synthetic data from the MHD model, the magnetic field can be weaker and the flux rope orientation fitted based on FR/TEC measurement can be more tilted towards the ecliptic. Coarse tomographic analysis for electron density is being conducted to investigate how it can improve these results.

Understanding the Relations between CME Origins and Its Interplanetary Properties

Lan Jian

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As one of the major space weather drivers, CMEs originate from active regions or quiescent regions of the Sun. The interesting properties of their solar source regions are the association with flare and/or filament eruptions, post-eruption arcade, ribbon, coronal dimming, and others, while the CMEs near the Sun are characterized by their speed, angular size and other geometric parameters. Using the quadrature configuration between STEREO A/B and Earth in July 2012 – December 2013, we investigate about 45 CMEs encountered by ACE/Wind at L1 in depth and determine their progenitor CMEs and the sources near the solar surface. We study the statistical relations between their solar origins and interplanetary properties including magnetic field increase and rotation, velocity expansion, bidirectional suprathermal electron (BDE) strahls, plasma beta, and heavy ion charge state, etc. Through this comprehensive investigation, we improve our understanding of CME origin and evolution, which will ultimately help improve space weather prediction.

Theory and Transport of Nearly Incompressible Magnetohydrodynamic Turbulence: High Plasma Beta Regime

Laxman Adhikari

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Nearly incompressible magnetohydrodynamic (NI MHD) theory for $\beta \sim 1$ (or $\beta << 1$) plasma has been developed and applied to the study of solar wind turbulence. The leading order term in $\beta \sim 1$ or $\beta << 1$ plasma describes majority 2D turbulence, while the higher-order term describes a minority slab turbulence. Here, we develop new NI MHD turbulence transport model equations in the high plasma beta regime. The leading order term in a $\beta >> 1$ plasma is fully incompressible and admits both structures (flux ropes or magnetic islands) and slab (Alfvén waves) fluctuations. This paper couples the NI MHD turbulence transport equations with a three fluid (proton, electron and pickup ion) equations, and solves the 1D steady-state equations from 1 au to 75 au. The model is tested against 27 years of Voyager 2 data, and Ulysses and NH SWAP data. The results agree remarkably well, with some scatter, about the theoretical predictions.

Observations and Modeling of Unstable Proton and Alpha Particle Velocity Distributions in Sub-Alfvénic Solar Wind at PSP Perihelia

Leon Ofman

Leon Ofman (1, 2), Scott A Boardsen (3, 2), Lan K Jian (2), Parisa Mostafavi (4), Davin Larson (5), Roberto Livi (5), Michael McManus (5), Ali Rahmati (5), Michael L Stevens (6), Jaye L Verniero (2)

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The solar wind (SW) accelerates mostly in the inner heliosphere until it reaches the local Alfvén speed at typical distances of 10–20 Rs (solar radii). The sub-Alfvénic zone is where solar wind acceleration occurs, according to past models and observations. Recently, Parker Solar Probe (PSP) traveled through sub-Alfvénic solar wind regions near perihelia in encounters E8–E12 and later, and it became clear that the SW measured properties differ greatly from the super-Alfvénic wind. Examples include changes in relative abundances and drift of alpha particles with regard to protons, as well as variations in magnetic fluctuations and switchbacks. We use 2.5D and 3D hybrid models of proton-alpha SW plasma using the data of the magnetic field that is currently available from the FIELDS instrument and the ion velocity distribution functions (VDFs) from the sub-Alfvénic areas that are constructed using data from the Solar Probe Analyzer Ions (SPAN-I). The nonlinear hybrid models allow investigating the evolution and saturation of the kinetic instabilities, expanding significantly the linear Vlasov stability analysis. In a number of case studies, we examine the nonlinear evolution of the ion kinetic instabilities associated with the observational VDFs and evaluate the energy exchanged between protons, alpha particles, and kinetic waves. The models provide the complete 3D structure of the proton and alpha particles VDFs at the various stages of the instability progression in the SW frame, not limited by the data constraint of the single point spacecraft frame and the instrumental line-of-sight limits brought on by the PSP heat shield. We investigate the heating and accelerating processes of the SW plasma and identify the exchange of energy on kinetic scales between ion-scale waves and particles in the sub-Alfvénic SW regions using the observationally constrained modeling results.

The Solar Wind Interaction with Planetary Magnetospheres

Lina Hadid

Laboratory of Plasma Physics (LPP), CNRS, École Polytechnique, Sorbonne Université

TBD

The in situ shock acceleration of solar wind suprathermal electrons at 1 AU

Linghua Wang

Linghua Wang, Peking University; Zixuan Liu, Peking University; Liu Yang, University of Kiel; Robert F. Wimmer-Schweingruber, University of Kiel; Stuart D. Bale, University of California at Berkeley

The shock acceleration is an important particle acceleration mechanism in the interplanetary space, but the electron shock acceleration process is not fully understood yet. Here we summarize the observational properties of in situ shock acceleration of solar wind suprathermal electrons at 1 AU, using the Wind measurements and MMS measurements. For both the Earth' s bow shock and shocks driven by interplanetary coronal mass ejections (ICMEs), the observed power-law spectral index of shocked suprathermal electrons is significantly larger than the theoretical prediction of first-order Fermi acceleration, while the flux enhancement ratio between the downstream shocked and upstream unshocked suprathermal electrons peaks near 90° pitch angle. These observations favor the shock drift acceleration process. However, the shocked electron spectra appear to exhibit different behaviors for ICME-driven shocks and terrestrial bow shock. At ICME-driven shocks, the significantly shocked suprathermal electrons generally have a double-power-law spectrum bending upwards at a break near 2keV with a low-energy spectral index of ∼3.7 and high-energy spectral index of ∼2.5, similar to the upstream unshocked suprathermal electrons. At the terrestrial bow shock, the strongly shocked suprathermal electrons show a double-power-law spectrum bending downwards at a break near ∼ 65 keV with a low-energy spectral index of ∼3.1 and high-energy index of ∼7.6, different from the upstream unshocked suprathermal electrons. Furthermore, the observed break energy is comparable to a critical electron energy with its cross-shock gyrodiameter equal to the bow shock's ramp thickness. These results suggest that the shock drift acceleration process of suprathermal electrons could strongly depend on the electron trapping efficiency at the shock.

Pan-Spectrum Fitting Formula for Suprathermal Particles

Linghua Wang

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We propose a pan-spectrum fitting formula of suprathermal particles with five parameters: A is the amplitude coefficient, E0 represents the spectral transition energy, α (>0) describes the sharpness and width of spectral transition around E0, and the power-law index $\beta 1$ ($\beta 2$) gives the spectral shape before (after) the transition. This formula incorporates many commonly used spectral functions as special cases. When α goes to infinity (zero), this spectral formula becomes the classical double-power-law (logarithmic-parabola) function. When both $\beta 2$ and E0 approach infinity, this formula can be simplified to the Ellison-Ramaty-like function. Under some other specific parameter conditions, this formula can be transformed to the Kappa or Maxwellian distribution. Considering the uncertainties in both particle intensity and energy, we improve the fitting method and fit this pan-spectrum formula well to the representative energy spectra of various suprathermal particle phenomena including SEPs (electrons, protons, 3He, and heavier ions), ESPs, bow-shocked electrons, solar wind suprathermal electrons, anomalous cosmic rays, and hard X-rays. Therefore, this pan-spectrum fitting formula would help us comparatively examine the properties of energy spectrum of different suprathermal particle phenomena (typically with a single energy break).

Observations of Waves and Structures by Frequency–Wavenumber Spectrum in Solar Wind Turbulence

Lingling Zhao

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A well-known shortcoming of single-spacecraft spectral analysis is that only the 1D wavenumber spectrum can be observed, assuming the characteristic wave propagation speed is much smaller than the solar wind flow speed. This limitation has motivated an extended debate about whether fluctuations observed in the solar wind are waves or structures. Multispacecraft analysis techniques can be used to calculate the wavevector independent of the observed frequency, thus allowing one to study the frequency–wavenumber spectrum of turbulence directly. The dispersion relation for waves can be identified, which distinguishes them from non-propagating structures. We use magnetic field data from the four Magnetospheric Multiscale (MMS) spacecraft to measure the frequency–wavenumber spectrum of solar wind turbulence based on the k-filtering and phase differencing techniques. We conclude that the solar wind turbulence intervals observed by MMS show features of non-propagating structures that are associated with frequencies close to zero in the plasma rest frame. However, there is no clear evidence of propagating Alfvén waves that have a nonzero rest-frame frequency. The lack of waves may be due to instrument noise. Our results support the idea of turbulence dominated by quasi-2D structures.

Dr.

Liping Yang

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Energy Transfer of Imbalanced Alfvénic Turbulence in the Heliosphere

Liping Yang

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Imbalanced Alfvénic turbulence is a universal process playing a crucial role in energy transfer in space, astronomy, and laboratory plasmas. A fundamental and long-lasting question about the imbalanced Alfvénic turbulence is how and through which mechanism the energy transfers between scales. To solve this problem, we successfully decompose and trace the dynamics of interacting fluctuations and find that the energy transfer of imbalanced Alfvénic turbulence is completed by coherent interaction between Alfvén waves (Elsässer variable δZˆ+) and co-propagating anomalous fluctuations (Elsässer variable δZˆ-). These anomalous fluctuations are generated by nonlinear couplings instead of linear reflection. We also reveal that the energy transfer of the waves and the anomalous fluctuations is carried out mainly through local-scale and large-scale nonlinear interactions, respectively, responsible for their bifurcated power-law spectra. This work unveils the essential energy transfer physics of imbalanced Alfvénic turbulence, and advances the understanding of imbalanced Alfvénic turbulence observed by the Parker Solar Probe in the inner heliosphere.

The evolution of suprathermal protons in an ICME event

Liu Yang

Liu Yang, Verena Heidrich-Meisner, Lars Berger, Robert Wimmer-Schweingruber, IEAP, University of Kiel

We present a case study of the evolution of suprathermal protons during the 2021 November 3 ICME event with unprecedented high-resolution measurements by Energetic Particle Detector onboard the Solar Orbiter spacecraft. We first reconstruct the pitch-angle distributions (PADs) of suprathermal protons in the solar wind frame and then investigate the PAD, flux temporal profile, and velocity distribution function (VDF) of this proton population close to the shock, in the shock sheath, in the magnetic cloud and after the ICME event. We found that the suprathermal proton fluxes at ~1000-3600 km/s peak ~12 to ~24 seconds before the shock in the upstream region with velocity dispersion feature. Furthermore, the proton VDFs close to the shock and in the shock sheath fit a double power law at ~1000-10000 km/s, which bends down at ~1800 km/s. However, in the magnetic cloud, the proton VDF shows a double power law bending up at ~4000 km/s. After the ICME event, the proton VDF at ~1000-10000 km/s appears as a knee. As proton fluxes decrease, the proton VDF at ~1000-4000 km/s significantly flattens, while the spectral shape at >4000 km/s does not vary significantly. Moreover, we estimated the parallel and perpendicular mean free paths in different flux tubes based on the observed flux temporal profile. We correlated them with the solar wind magnetic turbulence.

Ion beams and differential streaming in the expanding solar wind: instabilities and plasma heating

Lorenzo Matteini

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PSP and Solar Orbiter observations in the inner heliosphere have shown that non-thermal features in solar wind ion distributions are particularly enhanced and dominant in the close-Sun environment. Proton beams and large differential flows of alpha particles are ubiquitously observed, also in slow, though Alfvénic, streams, qualitatively at odds with typical observations at 1AU, where non-Maxwellian features are usually less apparent in the slow solar wind. All this reinforces the idea, also supported by past Helios and Ulysses explorations, that preferential ion heating and acceleration take place already in the Corona and signatures of the kinetic processes involved are gradually relaxed during expansion. Moreover, beams and differential streaming between ion species are a source of free energy for plasma heating with distance.

To explore further properties of ion differential streaming during expansion, as well as associated kinetic instabilities and their possible role in plasma heating, we perform expanding box hybrid simulations of a multi-species solar wind composed by core-beam protons and alphas. We focus on the role of wave-particle interactions in shaping distribution functions and controlling relative drifts, and on the associated conversion of bulk kinetic energy into thermal energy for the different populations. Radial trends and typical distributions found in simulations are then compared with PSP and Solar Orbiter observations in the inner Heliosphere.

Structure of the coronal streamer belt by Solar Orbiter/Metis and EUI/FSI observations

Lucia Abbo

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Comprehensive solar observations from the disk to the corona are essential to understand the coronal processes that play a key role in driving the structured slow solar wind flowing in the streamer belt at solar minimum. In this perspective, Metis coronagraphic observations are crucial to address the open questions about the identification of the coronal sources of the solar wind, one of the Solar Orbiter mission science objectives. Even more important is the possibility offered by Solar Orbiter of combining data from different remote-sensing instruments, like Metis and the Extreme Ultraviolet Imager (EUI), which were also developed to have partially overlapping fields of view to exploit cospatial measurements. In particular, the Metis coronagraph provides for the first-time simultaneous observations of the outer solar corona in polarized visible-light and in the ultraviolet, imaging the electron-scattered K-corona and the neutral hydrogen Lyman-α line (121.6 nm) intensity. In this frame, we aim at deriving a set of physical parameters (i.e. electron density, electron temperature, outflow velocity of protons) of equatorial streamers and close-by regions, combining observations acquired at the same time by Metis and EUI in March 2021, close to the minimum of solar activity. In particular, we use the first images obtained with the Full Sun Imager (FSI) channel of EUI in coronagraphic mode, which allows stray-light free off-limb observations. The Metis field of view (FOV) during the observations covered the range from 4 to 7.4 solar radii, while the EUI FOV is, above the limb, up to 4.5 solar radii. We show how the coronal electron density derived from Metis polarized data can be used to reproduce FSI observations and, in particular, to infer an estimate of the electron temperature across the equatorial streamers in the region where Metis and FSI fields of view overlap (in the height range 4-4.5 solar radii). These results are useful to better characterize the physical structure and properties of the slow solar-wind sources and to constrain global coronal models.

Solar Wind observed from Solar Orbiter with Metis: overview of recent results

Lucia Abbo

Romoli M. (1) and the Metis team (presented by Abbo L.(2)) (1) Università di Firenze (2) INAF - OATo

In this overview, we will present recent results concerning the solar wind origin, acceleration and propagation obtained mainly from images acquired by Metis on Solar Orbiter and recently published or almost ready for publication. Using Metis first light images, the outer corona solar wind has been measured at the boundary of the equatorial streamer belt via the Doppler dimming technique, during the minimum phase of the solar cycle. Using data acquired by Metis during the Solar Orbiter cruise phase, the first estimate of the expansion rate of polar coronal flows out to 5.5 solar radii was obtained. A work based on more continuatively data is in preparation with full coronal maps of proton outflow velocity. Additional studies related to the link between the coronal solar wind acceleration regions observed by Metis and the heliospheric wind signature measured by Parker solar Probe were performed, analyzing data obtained from their mutual quadratures (i.e. extracting the magnetic connectivity between coronal and interplanetary plasma features), and including also the first detection of the formation of a magnetic switchback in the solar corona.

Status update from NASA HQ on Heliophysics Big Year and Science of Inner Heliospehric Domain

Madhulika Guhathakurta

Madhulika Guhathakurta, NASA HQ, Heliophysics Division

In this short information presentation I would like to brief the community on the concept of Inner Heliopsheric domain from an R&A perspective as well as national and international collaborations with upcoming missions like PUNCH, MUSE, IMAP, Aditya L1 and others as well as ground-based mission like DKIST. In addition I would provide input on the concept behind Heliophysics Big Year and how you can support it.

Inter-Patch Flow in the Solar Wind from Polar Coronal Holes

Marcia Neugebauer

Marcia Neugebauer, Lunar and Planetary Laboratory, University of Arizona

Data from Ulysses high-latitude passage at solar-activity minimum suggest that most of the flow from a coronal hole is accelerated by processes responsible for patches of switchbacks. This flow is occasionally interrupted by a source of wind that is cooler and has a slightly lower Fe/O ratio, but which can have either greater or smaller helium content than the rest of the coronal-hole wind.

Slow solar wind sources

Marco Velli

Velli, M., Panasenco, O., D'Amicis, R., Reville, V., Lionello, R., Downs, C., Chi, C.

UCLA, USA Advanced Heliosphysics INAF IRAP PSI

Solar wind streams are characterized by different plasma properties, from overall speed, to temperature and temperature anisotropies, composition, as well as different properties for the embedded turbulence. While it has been established that the source of fast solar wind streams at solar minimum are the polar coronal holes, the larger than expected filling factor of slow solar wind has been attributed to flows comine from coronal hole boundaries, i.e., regions with large expansion factors, or from the complex mapping of the magnetic field from the photosphere into the heliosphere, i.e. the S-Web, or squashing factor. The observation by Parker Solar Probe that much of rhe solar wind, independently of speed, is dominated by Alfvénic fluctuations, and the frequent observation of slow Alfvénic solar wind, previously observed relatively rarely in Helios and Wind data, provide evidence for a modified picture of slow wind origins. Here we argue that coronal holes, except for an extremely narrow boundary layer separating closed from open regions where expansion factor and squashing factor are high, generate Alfvénic wind, whose speed depends on the overall coronal expansion factor. The expansion in fact can not vary significantly across the coronal hole (boundary layer excepted). Alfvénicity is rapidly destroyed in boundary layers and in high-squashing factor regions, while it is preserved longer in fairly homogeneously even though rapidly expanding coronal holes. Thus, Alfvenic slow solar wind can be attributed to rapidly expanding coronal holes, and the decay of Alfvénicity depends on the subsequent interactions occurring as the wind evolves into the heliosphere. Thus, coronal holes provide the bulk of fast Alfvénic solar wind, rapidly expanding holes provide slow Alfvénic wind, while S-web and boundary layers provide slow non-Alfvénic wind, supplemented by the reconnection mediated erosion of closed fields at the complex boundary of coronal holes, helmet streamers and pseudo-streamers.

ASHI: The All Sky Heliospheric Imager: August 22-26, 2022, NASA Balloon Flight Image Data Reduction Analysis

Matthew Bracamontes

Matthew Bracamontes, Center for Astrophysics and Space Sciences, University of California, San Diego, USA; Bernard V. Jackson, Center for Astrophysics and Space Sciences, University of California, San Diego, USA; Stephen White, Air Force Research Laboratory, AFRL/RVBXD, Kirtland AFB, NM, USA; Mario M. Bisi, UK Research and Innovation – Science & Technology Facilities Council, RAL Space, Oxfordshire, UK; Andrew Buffington, Center for Astrophysics and Space Sciences, University of California, San Diego, USA; Stuart Volkow, Center for Astrophysics and Space Sciences, University of California, San Diego, USA; Ed Stephan, Stephan Design-Build, Haslet, TX, USA; Philippe Leblanc, Stephan Design-Build, Haslet, TX, USA; Ron Quillin, Stephan Design-Build, Haslet, TX, USA

We have conceived, designed, and evaluated components for an All-Sky Heliospheric Imager (ASHI), suitable for flight on future space missions. ASHI was tested last summer on a NASA-sponsored topside balloon flight; this presentation highlights the images taken and the current state of the image data reduction from this instrument's successful overnight flight. The data reduction involves the removal of atmospheric glows, starlight, and zodiacal light in order to ultimately provide measurements of the outward flow of heliospheric structures. ASHI is currently being promoted as a hosted payload on a DoD Space Test Program satellite. As a simple, light weight (∼6kg), and relatively inexpensive instrument, the ASHI system has the principal objective of providing a minute-by-minute and day-by-day near real time acquisition of precision Thomson-scattering photometric maps of the inner heliosphere. The instrument's unique optical system is designed to view a hemisphere of sky starting a few degrees from the Sun. A key photometric specification for the spacecraft ASHI is better than 0.05% differential photometry in one-degree sky bins at 90 degrees elongation that enables the three-dimensional (3-D) reconstruction of heliospheric density extending outward from the Sun. The ASHI system, unlike coronagraphs or other planned heliospheric imagers, will maximize the remotely-sensed analysis of heliospheric structures that pass the spacecraft.

Understanding the Complexity of Photospheric Flux Emergence with Machine Learning Techniques

Matthew Lennard

Matthew Lennard (University of Sheffield, United Kingdom), Suzana S. A. Silva (University of Sheffield, United Kingdom), Benoit Tremblay (High Altitude Observatory, University Corporation for Atmospheric Research), Andrés Asensio Ramos (Instituto de Astrofísica de Canarias, Spain), Hideyuki Hotta (ISEE, Nagoya University, Japan), Haruhisa Iijima (HEPL, Stanford University, USA), Sung-Hong Park (Stanford University, Stanford, California, USA) , Gary Verth (University of Sheffield, United Kingdom), Viktor Fedun (University of Sheffield, United Kingdom)

Advances in modelling magnetic flux inside the Sun's convective region (see, e.g. Hotta & Iijima, 2020; Chen et al., 2021) have provided high-resolution data, which allow the study of the influence of photospheric flows on emerging magnetic flux. In the literature, photospheric velocity fields have been inferred by employing optical feature tracking, e.g., local correlation tracking (LCT), which typically displays poor performance at smaller scales. Neural network approaches, such as DeepVel (DV, Asensio Ramos et al., 2017), have been developed for deriving transverse flows from time-consecutive images of the photosphere by learning from numerical simulations. DV works for photospheric observations at a wide range of spatial resolutions and cadences, only limited by the training data thereby averting the limitations of feature tracking. The combination of speed and accuracy of recovery from a trained version of DV provides opportunity to study structures in solar images, which have previously been inaccessible. These highly detailed velocity fields can be used to analyse the evolution of complex flow topology in the photosphere, hence giving insight to the constant restructuring of the magnetic field and subsurface flows e.g., with methodologies utilising the Finite-Time Lyapunov Exponent (FTLE) proposed by Chian et al., 2020. In this work, we have tested the ability of DV to recover velocities from a simulated emerging active region using the R2D2 code (Hotta and Iijima, 2020). We have found that the FTLE fields obtained from the velocity fields recovered by DV are able to better capture the complexity of photospheric flows before, during and after emergence in comparison to those obtained using recovery via FLCT. In particular, our results identify signatures in emerging active regions compared with quiet regions; i.e., before any visible indicators of strong flux emergence through the presence of pores or sunspots.

Phase mixed Alfven waves in partially ionised plasma

Max McMurdo

Max McMurdo, Istvan Ballai, Gary Verth, Viktor Fedun

The chromospheric heating problem is described as the rapid increase in temperature of the solar atmosphere from approximately 6000 Kelvin (K) to a few million K occurring over a few hundred kilometers.

Effective plasma heating requires short transversal scales. Phase mixing is one of the most promising mechanisms for explaining the heating of the upper solar atmosphere by producing small transversal scales in the presence of large transversal gradients in the Alfvén speed, here we take that to mean a gradient in the equilibrium plasma density profile. Such transversal gradients in the equilibrium plasma density are abundant in the solar atmosphere.

Using a single fluid approximation of a partially ionized chromospheric plasma we study the effectiveness of the damping of phase mixed shear Alfvén waves and investigate the effect of varying the ionization degree on the dissipation of waves.

Our results show that the dissipation length of shear Alfvén waves strongly depends on the ionization degree of the plasma, but more importantly, in a partially ionized plasma, the damping length of shear Alfvén waves is several orders of magnitude shorter than in the case of a fully ionized plasma, providing further evidence that phase mixing is a large contributor to heating the chromosphere. The effectiveness of phase mixing is investigated for various ionization degrees, ranging from fully neutral to fully ionized plasmas.

Coronal Loop Heating by Phenomenological and Reduced Magnetohydrodynamic Approaches: A Comparative Study

Mehmet Sarp Yalim

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The transport of waves and turbulence beyond the photosphere is central to the coronal heating problem. Turbulence in the quiet solar corona has been modeled on the basis of the nearly incompressible magnetohydrodynamic (NI MHD) theory to describe the transport of low-frequency turbulence in open magnetic field regions. It describes the evolution of the coupled majority quasi-2D and minority slab component, driven by the magnetic carpet and advected by a subsonic, sub-Alfvénic flow from the lower corona. In this study, we couple the NI MHD turbulence transport model with an MHD model of the solar corona to study the heating problem in a coronal loop. In a realistic benchmark coronal loop problem, we find that a loop can be heated to $\sim$1.5 million K by transport and dissipation of MHD turbulence described by the NI MHD model. We also find that the majority 2D component is as important as the minority slab component in the heating of the coronal loop. We compare our coupled MHD corona/NI MHD turbulence transport model results with a reduced MHD (RMHD) model. An important distinction between these models is that RMHD solves for small-scale velocity and magnetic field fluctuations and obtains the actual viscous/resistive dissipation associated with their evolution whereas NI MHD evolves scalar moments of the fluctuating velocity and magnetic fields and approximates dissipation using an MHD turbulence phenomenology. Despite the basic differences between the models, their simulation results match remarkably well, yielding almost identical heating rates inside the corona.

Solar Wind at Large Distances and its Interaction with the Interstellar Medium

Merav Opher

Boston University

TBD: solicited talk

Reflection-driven turbulence in the super-Alfvénic solar wind

Meyrand Romain

Meyrand Romain, Otago University Squire Jonathan, Otago University Alfred Mallet, University of California, Berkeley Benjamin D. G. Chandran, University of New Hampshire, Durham

An important paradigm for the heating of the solar corona and solar wind is that of reflection-driven turbulence. The idea is that outwardly propagating waves are reflected by background gradients, setting up a turbulent cascade, then dissipating to heat the plasma. Here, we study such turbulence in its simplest form the so called expanding box model. Using theoretical arguments supported by direct numerical experiments, we will explain how the turbulent growth of wave action anastrophy causes the energy to decay while rushing toward larger and larger scales through a split cascade, whereby energy is forced to flow to both small and large scales simultaneously. This split cascade generates a 1/k spectrum which strongly resembles those observed in the solar wind. We will discuss why this situation is transitory and how it leads inexorably to high negative residual states that materialize in the form of large scales isolated Alfven vortices.

Some Implications of a Non-Spherical Source Surface for Global Modeling of the Heliosphere

Michael Schulz

Michael Schulz (Lockheed Martin Retiree)

Certain pitfalls inherent in the traditional source-surface model based on a sphere of radius 2.5 solar radii can be overcome by making the source surface non-spherical so as to reflect the underlying geometry of the Sun's main magnetic field. Most notably, the usual spherical source surface leads not to a thin heliospheric current sheet but rather (for the test case of a solar dipole field) to a current-density distribution that attains half its equatorial maximum at plus or minus 60 deg heliomagnetic latitude. My present formulation involves a non-spherical source surface that is somewhat rounded (via an adjustable "shape" parameter) relative to an isogauss of the Sun's main magnetic field, but which contains the same volume as a sphere of radius 2.5 solar radii. Magnetic field lines extend normally outward from this non-spherical source surface, across which continuity is adequately satisfied by minimizing the mean-square tangential component of B for the interior solution with respect to a family of adjustable harmonic expansion coefficients. For the test case of a solar dipolar main field, the maximum (equatorward) latitudinal deflection of B from radial at the source surface in this construction occurs at heliomagnetic latitudes plus or minus 26.565 deg and amounts to about 13.2 deg there for a source-surface shape that is rounded only slightly relative to a main-field isogauss and leads asymptotically to a nearly latitude-independent radial component of B in either hemisphere (northern or southern) outside the consequently thin heliospheric current sheet. Corresponding conical magnetic surfaces map from heliospheric latitudes lambda = 26.565 deg (north or south) at the source surface to lambda = 16.4 deg at distance rho = 10 solar radii from Sun's magnetic dipole axis, to lambda = 14.9 deg at rho = 20, to lambda = 14.4 deg at rho = 30, and asymptotically to lambda = 13.4 deg as rho goes to infinity. Associated ratios between latitudinal and radial components of B vary from 0.234 = tan(13.2 deg) at the source surface, to 0.053 = tan(3.0 deg) at rho = 10, to 0.027 = tan(1.5 deg) at rho = 20, and to 0.018 = tan(1.0 deg) at rho = 30 solar radii. Parenthesized arguments of tangent function indicate expected angle between meridional component of B and the radial direction at various distances rho from Sun's dipole axis. Such systematic equatorward deflections of B could perhaps be detected by Parker Solar Probe near future perihelia, especially since dipole tilt angle relative to Sun's rotation axis should increase during approach toward solar maximum. The non-spherical source surface also implies inner-heliospheric deviations from the widely invoked inverse-square variation of the radial component of B with heliocentric distance.

Ion-Driven Instabilities in the Inner Heliosphere: Multi-Dimensional Characterization and Mapping

Mihailo Martinović

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Linear theory is a well developed framework for characterizing instabilities in the weakly collisional plasmas of the solar wind. In this work, we analyzed $\sim$1.5M proton and alpha particle Velocity Distribution Functions (VDFs) observed by Helios I & II to determine the statistical properties of the standard instability parameters such as the growth rate, frequency, the direction of wave propagation, and the power emitted or absorbed by each component, as well as to characterize their behavior with respect to the distance from the Sun and collisional processing. We use this voluminous set of calculations to train Stability Analysis Vitalizing Instability Classification (SAVIC) Machine Learning algorithm capable to accurately: 1) predict if an interval is unstable from observed VDF parameters; 2) predict the instability properties for a given unstable VDF; and 3) classify the type of the unstable mode into physically meaningful groups that correspond to different unstable modes. These methods enable us to map the instability properties in multi-dimensional phase space. We find that the parallel-propagating, proton-core-induced Ion Cyclotron (IC) mode dominates the young solar wind. Only when the core component of the VDF is isotropized by collisions, the proton beam and alpha populations start dominating the wave energy dynamics. We also demonstrate that the oblique Fast Magnetosonic mode regulates the proton beam drift in the collisionally old plasma. SAVIC code used here is publicly available for the community.

Suprathermal Ion Observations Associated with the Heliospheric Current Sheet Crossings by Parker Solar Probe During Encounters 7-15.

Mihir Desai

M. I. Desai, D. G. Mitchell, D. J. McComas, J. F. Drake, T. Phan, J. R. Szalay, E. C. Roelof, J. Giacalone, M. E. Hill, E. R. Christian, N. A. Schwadron, R. L. McNutt Jr., M. E. Wiedenbeck, C. Joyce, C. M. S. Cohen, A. J. Davis, S. M. Krimigis, R. A. Leske, W. H. Matthaeus, O. Malandraki, R. A. Mewaldt, A. Labrador, E. C. Stone, S. D. Bale, J. Verniero, A. Rahmati, P. Whittlesey, R. Livi, D. Larson, M. Pulupa, R. J. MacDowall, J. T. Niehof, J. C. Kasper, and T. S. Horbury

We report observations of $<$100 keV/nucleon suprathermal (ST) H, He, O, and Fe ions in association with three separate crossings of the heliospheric current sheet that occurred near perhelia during PSP encounters 7-15. In particular, we compare and contrast the ST ion time-intensity profiles, velocity dispersion, pitch-angle distributions, spectral forms, and maximum energies during the 8 separate HCS crossings. We find that these unique ST observations are remarkably different in each case, with those during E07 posing the most serious challenges for existing models of ST ion production in the inner heliosphere. In contrast, the ISOIS observations during the remaining 7 HCS crossings during E08-15 appear to be consistent with a scenario in which ST ions escape out of the reconnection exhausts into the separatrix layers after getting accelerated up to $\sim$50-100 keV/nucleon by HCS-associated magnetic reconnection-driven processes. We discuss these new observations in terms of local versus remote acceleration sources as well as in terms of expectations of existing ST ion production and propagation, including reconnection-driven and diffusive acceleration in the inner heliosphere.

The baseline solar wind

Milan Maksimovic

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Recent studies have revealed the existence of a baseline solar wind which represents the wind with the lowest speed that can be observed at a given radial distance. On top of this baseline wind is added a more patchy wind constituted of distinct streams that are organized on angular scales comparable to that of solar supergranulation convection scales at the surface of the Sun. In this study we analyse solar wind data from Parker Solar Probe, Helios, Ulysses and Voyager 1&2, from a minimum radial distance of 15 solar radii (PSP) to 75 astronomical units (Voyager 2) and show that the baseline solar wind extends to very large distances and reaches a terminal speed of about 350 km/s. As already suggested by Halekas (2022), we show that this baseline solar wind is compatible with an exospheric model, for which the electric ambipolar potential is very close to the electron pressure gradient observed by the Parker Solar Probe, Helios and Ulysses electron analysers.

An investigation of heliosheath evolution as measured by IBEX: A new look at the energetics of the 2014 pressure enhancement

Nehpreet Walia

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The intensity of energetic neutral atom (ENA) flux generated from the interaction of solar wind ions with cold interstellar neutral atoms varies strongly with changes in the dynamic pressure of the solar wind. Thus, a rapid and strong enhancement in the solar wind dynamic pressure in 2014 caused a significant intensification in the ENA flux measured by the Interstellar Boundary Explorer (IBEX), first in late 2016 and continuing through at least 2021. The rate and the directions in which this flux enhancement propagates can provide us with important information regarding the shape, size, and energetics of the heliosphere plasma. Since ENAs formed in the heliosheath have different energies, the changes in the flux from the pressure enhancement are time-dispersed, first seen at higher energies and gradually at lower energies, leading to an evolving energy spectrum. A similar trend in spectral evolution can be measured in different directions as the pressure enhancement reaches first the upwind heliosheath below the nose, then the poles and flanks, and finally the heliotail. The changes in spectral shape not only reflect time dispersion, but also an intrinsic heating of the plasma, on account of the persistent hardening of the spectral index. Studying the detailed energetics of this event can lead to new insights into the roles of shocks, turbulence, and wave-particle interactions in pickup ion heating.

To help discern more accurately local changes arising in the ENA enhancement, this study makes use of a new statistical imaging technique to construct higher resolution and more statistically robust maps with improved background removal. Also, because the observed location of the pressure enhancement overlaps with the IBEX ribbon at many locations, a new statistical masking technique with a variable ribbon profile is used to separate the ribbon flux (which is believed to originate beyond the heliopause) from the inner heliosheath ENA flux to more accurately estimate the temporal and spatial evolution of energy spectra as the pressure enhancement propagates throughout the heliosheath.

A Lagrangian Perspective on Alfvenic Turbulence in the Solar Wind

Nic Bian

Nic Bian (University of Alabama in Huntsville, USA), Gang Li (UAH, USA), Du Toit Strauss (Center for Space Research, North-West University, South Africa). Eugene Engelbrecht (North-West University, South Africa)

From a Lagrangian viewpoint, the average rate “epsilon” of turbulent energy dissipation, which determines the turbulent heating rate in the solar wind, is also the velocity-space diffusivity of the solar wind fluid particles. It stands for the amount of kinetic energy per unit mass the solar wind fluid particles gain, on average, per unit time in the inertial range of the stationary turbulence. As pointed out originally by Landau, this rather general and perhaps paradoxical statement, follows simply from that, under the Kolmogorov’s assumptions, the fluid particle velocity increments grow diffusively as a function of the time-lag at a rate uniquely determined by the average cascading rate “epsilon”. Surprisingly enough, the Lagrangian perspective on turbulence in the solar wind is scarcely adopted. Yet, we will show it can provide crucial insights. In this presentation at the Solar Wind 16 meeting, a Lagrangian perspective on strong anisotropic Alfvenic turbulence is adopted and the connections between the Eulerian and the Lagrangian properties of the turbulence are analysed. We also present related zeroth order and first-order Lagrangian stochastic models describing the transport of fluid particles and the dispersion of magnetic field lines resulting from Alfvénic turbulence in the solar wind. The kind of question that motivated this work is “where is a solar wind fluid particle that left the Sun 4 days earlier?”. Transverse diffusive acceleration produces cross-field transport of the fluid particles and, due to the frozen-in condition for the magnetic field, it yields cross-field dispersion of the magnetic field lines. Solar wind measurements show that the Eulerian velocity and magnetic field increments grow diffusively with the time-lag provided they are evaluated in the local scale-dependent magnetic field direction. The first-order Lagrangian stochastic models presented here are consistent with these properties. Each transport model can be parameterized by two independent measurable quantities: the average rate of energy dissipation ”epsilon” and the root mean square of the fluctuating fields. The magnetic field line diffusivity is given by the fluid particle diffusivity divided by the Alfvén speed when the field fluctuations are in equipartition.

PSP/WISPR Observations of High Frequency Periodic Density Structures

Nicholeen Viall

Angelos Vourlidas, JHU/APL, Russ Howard, JHU/APL, Mark Linton, NRL, Larry Kepko, NASA/GSFC, Simone DiMateo, and Aleida Higginson, NASA/GSFC

Decades of in situ density measurements made in and around L1 show that the solar wind is often comprised of periodic density structures on scales of 0.2 mHz ($\sim$90 minutes) up to 5 mHz ($\sim$ a few minutes). Periodic density structures are important drivers of Geospace. They are periodic dynamic pressure structures, and thus directly drive oscillations in Earth's magnetosphere as a forced-breathing, wherein each density structure engulfs the magnetosphere, squeezing it as it passes. Additionally, periodic density structures are important diagnostics of solar wind formation. Studies of composition during these periodic density structures demonstrates that they are created at the Sun as the solar wind is formed. White light imaging data of the young solar wind taken by STEREO/COR2 and STEREO/HI1 have shown that the source of the longest/largest of these trains of periodic density structures is streamers. However, even with the highest cadence data available, it was not previously possible to image the higher frequency periodic density structures at their solar formation. Now for the first time we demonstrate with Wide-field Imager for Parker Solar PRobe (WISPR) high cadence data the presence of periodic density structures on the minutes time scales immediately after solar wind formation. We speculate that a possible source of these higher frequencies periodic density structures is periodically driven interchange reconnection.

Improving Space Weather Predictions with a New Sequence of Data-driven Models of the Solar Atmosphere and Inner Heliosphere

Nikolai Pogorelov

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To address Objective II of the National Space Weather Strategy and Action Plan 'Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts' and US Congress PROSWIFT Act 116–181, our team is developing a new set of open-source software that would ensure substantial improvements of Space Weather (SWx) predictions. On the one hand, the focus is on the development of data-driven models. On the other hand, we ensure that each individual component of our software has higher accuracy with a dramatically improved performance over existing software used in operations. The application of new computational technologies and enhanced data sources paves ways for improved SWx predictions and makes it possible to forecast hazardous SWx effects on the space-borne and ground-based technological systems, and on human health. Our models involve (1) a new, open-source solar magnetic flux model (OFT), which evolves information to the back side of the Sun and its poles, and updates the model flux with new observations using data assimilation methods; (2) a new potential field solver (POT3D) associated with the Wang-Sheeley-Arge coronal model, and (3) a new adaptive, 4-th order of accuracy solver (HelioCubed) for the Reynolds-averaged MHD equations implemented on mapped multiblock grids (cubed spheres). We describe the simulation results obtained with our codes. We also demonstrate that the application of machine learning to modeling coronal mass ejections (CMEs) , with training based on STEREO data, makes it possible to substantially improve their arrival time forecasts.

Incorporating Kinetic Behavior of Pickup Ions at the Heliospheric Termination Shock into the Global Model of the Solar Wind Interaction with the Local Interstellar Medium

Nikolai Pogorelov

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The Sun moves with respect to the local interstellar medium (LISM) and modifies its properties to heliocentric distances as large as 1 pc. The solar wind (SW) is affected by penetration of the LISM neutral particles, especially H and He atoms. Charge exchange between the LISM atoms and SW ions creates nonthermal, pickup ions (PUIs) and secondary neutral atoms that can propagate deep into the LISM. Neutral atoms measured at 1 au can provide us with valuable information on the properties of pristine LISM. Voyager 1 and 2 spacecraft perform in situ measurements of the LISM perturbed by the presence of the heliosphere and relate them to the unperturbed region. We discuss observational data and numerical simulations that shed light onto the mutual influence of the SW and LISM. Special attention is paid to the behavior of PUIs at collisionless shocks, such as the heliospheric termination shock (TS), which experience preferential heating and acceleration. For this reason, the description of the PUI crossing the TS with fluid (MHD) models is highly inaccurate. Substantial improvements in modeling of the SW-LISM interaction can be made if special, kinetically-derived boundary conditions are specified at the TS. Spacecraft observations, as well as a plethora of kinetic simulations, demonstrate that such boundary conditions should be specified on the MHD scale, where the ion distribution function becomes nearly isotropic. We have derived such boundary conditions with an extensive, multi-parametric, hybrid simulations and, after a proper calibration, used them to describe the distributions of PUIs and neutral atoms throughout the heliosphere. To ensure correct description of discontinuities, the mixture of electrons and all ion populations is modeled in the conservation-law form. The results of the new, fully self-consistent model have been validated with the New Horizons and Voyager data. They have been compared with the major currently existing approaches and demonstrated substantially better agreement with in situ data and IBEX remote observations.

Higher-Order Analysis of Three-Dimensional Anisotropy in Alfvenic Turbulence

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Our understanding of 3D Magnetohydrodynamic (MHD) turbulence is based on phenomenological models grounded in the principles of critical balance and scale-dependent dynamical alignment of velocity-magnetic or Elsasser fields. Parker Solar Probe's (PSP) recent measurements near solar wind sources provide a unique opportunity to test the predictions and conjectures of these turbulence theories through in-situ observations. In this study, we analyze the statistical properties of 3D anisotropic higher-order moments and assess the extent to which the conjectures made by these models align with observations. We find that although the scaling exponents of the structure functions in the perpendicular and displacement directions are consistent with the models proposed by Chandran et al. (2015) and Mallet and Schekochihin (2017), the parallel scaling significantly deviates from predictions. Furthermore, the increasing alignment of the fields at smaller scales, which forms the foundation of these models, is at best questionable.

Magnetic field spectral evolution in the inner heliosphere

Nikos Sioulas

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Leveraging data from the Parker Solar Probe and Solar Orbiter missions, we examine the radial evolution, and underlying plasma parameter dependence of power and spectral-index anisotropy, in the wavevector space of solar wind turbulence, spanning heliocentric distances $0.06 \lesssim R \lesssim 220\ R_{\odot}$.

Our observations reveal that near the Sun, the inertial range , is constrained to a narrow range of scales, displaying a power-law exponent of $\alpha_B = -3/2$, independent of plasma parameters. Turbulence spectra associated with large magnetic energy excesses and low Alfvénic content steepen considerably with distance, unlike highly Alfvénic intervals that preserve their near-Sun scaling. As the distance increases, the inertial range extends to larger spatial scales progressively steepening, on average, towards a $\alpha_B = -5/3$ scaling.

Our study also uncovers distinct radial evolutions of anisotropic turbulence signatures in fast ($V_{sw} \geq\ 400\ km\ s^{-1}$) and slow ($V_{sw} \leq\ 400\ km\ s^{-1}$) wind streams. Slow wind streams at Earth orbit exhibit a "critically balanced" cascade, with anisotropy decreasing with diminishing heliocentric distance. In contrast, fast streams retain their near-Sun anisotropic properties, more closely reflecting a "dynamically aligned" cascade.

Using Parker Solar Probe to estimate proton and electron turbulent dissipation rates via Landau and Cyclotron damping

Niranjana Shankarappa

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Characterizing solar wind heating is a long-standing problem in space plasma physics, with the dissipation of turbulence a likely source of this heating. In our initial work, we applied a simple 1D wavevector-anisotropic, low-frequency Alfvenic, critically balanced cascade model that dissipates via Landau damping to the Parker Solar Probe (PSP) observations of solar wind thermal plasma and electromagnetic fields. We find that 39.4 percent of intervals in PSP Encounters 1 and 2 are well described by the model, a result consistent with turbulent dissipation via Landau damping driving parallel heating of solar wind with order unity plasma beta. From these same intervals, waves with frequencies comparable to the ion cyclotron frequency- consistent with parallel propagating Ion Cyclotron Waves (ICWs) and/or Fast Magnetosonic waves (FMs)- are observed 41 percent of the time. As cyclotron damping of ICWs onto protons is expected to be a significant source of anisotropic heating of protons that enhances closer to the Sun (e.g. Hollweg & Isenberg 2002), we extend our previous work to account for the dissipation of the ion-scale wave. This is done by comparing the observed wave frequency in the spacecraft frame to doppler shifted dispersion relations for the ICWs and FMs calculated using the PLUME hot plasma dispersion solver, which allows the distinguishing between the two kinds of parallel ion-scale waves. This enables a subsequent estimate of the proton heating rates via cyclotron damping, which can be compared to the rates calculated from the cascade models.

Solar wind data analysis aided by synthetic modeling: a better understanding of plasma-frame variations from temporal data

Norbert Magyar

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In-situ measurements of the solar wind, a turbulent and anisotropic plasma flow originating at the Sun, are mostly carried out by single spacecraft, resulting in one-dimensional time series. The conversion of these measurements to the spatial frame of the plasma is a great challenge, but required for direct comparison of the measurements with MHD turbulence theories. Here we present a toolkit, based on the synthetic modeling of solar wind fluctuations as two-dimensional noise maps with adjustable spectral and power anisotropy, that can help with the temporal-spatial conversion of real data. Specifically, by following the spacecraft trajectory through a noise map (relative velocity and angle relative to some mean magnetic field) with properties tuned to mimic those of the solar wind, the likelihood that the temporal data fluctuations represent parallel or perpendicular fluctuations in the plasma frame can be quantified by correlating structure functions of the noise map. Synthetic temporal data can also be generated, which can provide a testing ground for analysis applied to the solar wind data. We demonstrate this tool by investigating Parker Solar Probe's E7 trajectory and data, and showcase several possible ways in which it can be used. We find that whether temporal variations in the spacecraft frame come from parallel or perpendicular variations in the plasma frame strongly depends on the spectral and power anisotropy of the measured wind. Data analysis assisted by such underlying synthetic models as presented here could open up new ways to interpret measurements in the future, specifically in the more reliable determination of plasma frame quantities from temporal measurements.

The Firefly Constellation: A Holistic View of the Sun and its Environment

Nour E. Raouafi

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Firefly is an innovative mission concept study for the Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033 to fill long-standing knowledge gaps in Heliophysics. A constellation of spacecraft will provide both remote sensing and in situ observations of the Sun and heliosphere from a whole 4π-steradian field of view. The concept implements a holistic observational philosophy that extends from the Sun's interior, to the photosphere, through the corona, and into the solar wind simultaneously with multiple spacecraft at multiple vantage points optimized for continual global coverage over much of a solar cycle. The mission constellation includes two spacecraft in the ecliptic and two flying as high as $\sim 70^{\mathrm{o}}$ solar latitude. The ecliptic spacecraft will orbit the Sun at fixed angular distances of $\pm 120^{\mathrm{o}}$ from the Earth. Firefly will provide new insights into the fundamental processes that shape the whole heliosphere. The overarching goals of the Firefly concept are to understand the global structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona as it creates the heliosphere. We will provide an overview of the Firefly mission science and architecture and how it will revolutionize our understanding of long-standing heliospheric phenomena such as the solar dynamo, solar cycle, magnetic fields, solar activity, space weather, the solar wind, and energetic particles.

Exploring the Near-Solar Environment: Parker Solar Probe Status, Discoveries, and Future Prospects

Nour E. Raouafi

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Launched on 12 August 2018, NASA's Parker Solar Probe has completed 16 of its scheduled 24 orbits around the Sun. The mission's primary science goal is to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what processes accelerate energetic particles. Parker Solar Probe returned a treasure trove of science data far exceeding quality, significance, and expectations, leading to many discoveries. Starting with Orbit 8 (i.e., 28 April 2021), Parker flew through the magnetically dominated corona, one of the mission's primary objectives. Among the significant advances driven by Parker Solar Probe is our renewed and deep understanding of the physical processes that drive the solar wind. With the rise of the solar cycle toward the activity maximum, Parker Solar Probe encountered several events of different sizes, revealing aspects of solar activity that were poorly understood or unknown. We present an overview of the status, science advances, and the prospects of the mission.

Magnetic Reconnection as the Driver of the Solar Wind

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We present EUV solar observations showing evidence for omnipresent jetting activity driven by small-scale magnetic reconnection at the base of the solar corona. We argue that the physical mechanism that heats and drives the solar wind at its source is ubiquitous magnetic reconnection in the form of small-scale jetting activity (a.k.a. jetlets). This jetting activity, like the solar wind and the heating of the coronal plasma, is ubiquitous regardless of the solar cycle phase. Each event arises from small-scale reconnection of opposite-polarity magnetic fields producing a short-lived jet of hot plasma and Alfvén waves into the corona. The discrete nature of these jetlet events leads to intermittent outflows from the corona, which homogenize as they propagate away from the Sun and form the solar wind. This discovery establishes the importance of small-scale magnetic reconnection in solar and stellar atmospheres in understanding ubiquitous phenomena such as coronal heating and solar wind acceleration. Based on previous analyses linking the switchbacks to the magnetic network, we also argue that these new observations might provide the link between the magnetic activity at the base of the corona and the switchback solar wind phenomenon. These new observations need to be put in the bigger picture of the role of magnetic reconnection and the diverse form of jetting in the solar atmosphere.

Advancing Solar Wind Electron Density Estimations with Parker Solar Probe Quasi-Thermal Noise Data

Oksana Kruparova

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We present a comprehensive analysis of the electron density in the solar wind, obtained from quasi-thermal noise (QTN) spectroscopy applied to data from the first 15 encounters of the Parker Solar Probe mission. This novel dataset covers radial distances from the Sun between 13 R_{Sun} and 100 R_{Sun}. Our analysis demonstrates that the electron density can be robustly described by a power-law relation, $n_e(r) = (343466 \pm 19921) \times r^{(-1.87 \pm 0.11)}$, which improves the accuracy of density estimations for the considered range of distances compared to previous models. The derived electron density model has important implications for localizing interplanetary solar radio bursts, such as type II and III bursts. The complete dataset of electron density measurements is made available to the scientific community and can be utilized for further studies in the solar wind.

Photospheric and coronal sources of different types of solar wind and transients observed by Parker Solar Probe and Solar Orbiter

Olga Panasenco

Advanced Heliophysics Inc.

Initial Parker Solar Probe results have shown that slow Alfvénic solar wind intervals appear to be a frequent, if not standard, component of the nascent solar wind inside 0.5 AU. In addition to the strong presence of Alfvénic fluctuations propagating away from the Sun, such intervals also display the oscillations known as switchbacks, where the Alfvénic fluctuation is accompanied by a fold in the radial magnetic field and a corresponding forward propagating radial jet. Switchbacks often come in patches, separated by short intervals depleted with fluctuations, and periods without switchbacks may also show a striking quiescence, with the magnetic field remaining mostly radial and very small amplitude velocity and magnetic field fluctuations. These observations pose a series of questions on the origins of the solar wind and the role of coronal structure, as well as of the evolution of fluctuations within the solar wind.

This paper explores the origins of different solar wind streams, from the fastest, Alfvénic streams, to slow Alfvénic wind, to the extremely slow sub-Alfvénic and barely supersonic winds seen inside 15 Rs by Parker Solar Probe.

Looking through solar coronal holes

Olga Panasenco

Olga Panasenco (Advanced Heliophysics Inc.) and Shadia Habbal (Institute for Astronomy, University of Hawaii)

The solar dynamo and plasma convection produce three main observed structures extending from the solar surface into the corona: active regions, solar filaments (prominences when observed at the limb) and coronal holes. Each of these three key features is interlinked with the other two in its evolution and dynamics.

In this paper we investigate the solar corona dominated by the open magnetic fields with the help of solar eclipse spectroscopic observations and discuss the energization of the solar corona at different temporal and spatial scales. We compare observations of the extended solar corona observed during total solar eclipses and corresponding PFSS modeling of the coronal magnetic field to resolve a mystery of temperature boundaries between large-scale coronal structures.

Determining the Anatomy of a CME by Relating Remote Sensing and in-situ Observations within 13 Rs

Orlando Romeo

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During encounter 13 of Parker Solar Probe's (PSP) mission, the spacecraft traveled through a topologically complex Interplanetary Coronal Mass Ejection (ICME) event beginning on September 5th, 2022, which has been modeled as the result of an eruption of two CMEs. The Solar Probe ANalyzer (SPAN) detectors were the only instrument able to collect in-situ measurements of the thermal plasma. We present these observations, focusing on electron, proton and alpha plasma parameters such as density, velocity, and temperature. Interesting features of this event include a fast-forward shock, bidirectional electrons, possible evidence of magnetic clouds, a magnetic reconnection exhaust region, current sheet crossings, and multiple sub-Alfvenic regions. We compare these in-situ measurements with observations from WISPR onboard PSP and SECCHI on the STEREO mission, as well as forward modeling of two CMEs.

The effect of Coulomb Collisions on Thermalizing solar wind

Parisa Mostafavi

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Previous observations have revealed that solar wind ions exhibit distinct kinetic non-thermal features, such as the preferential acceleration and heating of alpha particles (He2+) compared to protons (the predominant component of the solar wind). Additionally, Coulomb collisions in the solar wind act to reduce the ion non-thermal features and drive the solar wind towards thermal equilibrium. Wind spacecraft data at 1 au showed that solar wind properties are strongly organized by collisionality. In this work, we present an analysis of the Parker Solar Probe observations and the effect of Coulomb collisions on non-thermal features of the plasma (alpha-proton differential flow and alpha-to-proton temperature ratio). Furthermore, we demonstrate how the alpha-to-proton temperature ratio correlates with solar wind properties.

Nonthermal Energetic Pickup Ions in the Outer Heliosphere: New Horizons' Observations

Parisa Mostafavi

Parisa Mostafavi, Matthew Hill, Gary Zank, Peter Kollmann, Pontus Brandt, Ralph McNutt, David McComas, Merav Opher, Alan Stern, Bishwas Shrestha, Fran Bagenal, Kelsi Singer, Anne Verbiscer4, and John Spencer

Nonthermal energetic pickup ions (PUIs) are created in the heliosphere through charge exchange between solar wind ions and interstellar neutral atoms, and they play an essential role in understanding solar wind evolution in the outer heliosphere as well as the structure and dynamics of the global heliosphere. The New Horizons spacecraft, launched in 2006 and currently located at about 55 AU from the Sun, is exploring the outer heliosphere and is the only spacecraft equipped with proper instruments to measure nonthermal energetic PUIs in this region. Its observations have shown that energetic PUIs dominate the internal pressure of the outer heliosphere, with PUI pressures larger than the thermal solar wind and magnetic pressures beyond ~ 20 AU. At these distances, PUIs contribute substantially to the heating and slowing down of the solar wind. Moreover, New Horizons observations have shown that PUIs mediate shock waves in the outer heliosphere. In this work, we provide an overview of the energetic particles in the outer heliosphere and their effects on shocks, and we present in situ observations of hydrogen and helium PUIs made by New Horizons' SWAP and PEPSSI instruments.

Heating and Acceleration of the Solar Wind by Ion Acoustic Waves

Paul Kellogg

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Ion acoustic waves are very commonly observed in the solar wind though their study has been eclipsed by the study of the less damped modes and their Kolmolgorov distributions. They disappear quickly because their frequency has a large imaginary part, meaning rapid damping. The heating due to the absorption of the energy of observed ion acoustic waves is calculated in this work, using essentially the same method used in Kellogg 2020. The result is that the absorbed energy of these observed ion acoustic waves is not only sufficient to account for the observed heating but is large enough to provide much if not all of the solar wind acceleration.

Modeling the source temperature of slow and fast solar winds using a 16 moments multi-species fluid model

Paul Lomazzi

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In this study, we exploit the newly developed Irap Solar Atmospheric Model (ISAM) to study the ionisation level of heavy ions transported in the fast and slow solar winds. ISAM is a high-order moment multi-species model that couples self-consistently the transport equations of both neutral and ionized particles (H, p, e, He, O and Mg) from the chromosphere to the solar wind. The charge state of heavy ions is set in the collisional part of the solar corona and is strongly dependent on the local electron temperature. This charge state gives us therefore important information on the coronal conditions at the source of the solar wind, in particular the source electron temperature. This region of the corona is strongly coupled to the transition region through downward heat conduction. Solving first for H, p and e, we retrieve past modeling results showing that variations in the source temperature change the transition region pressure which in turn modulates the mass flux of the solar wind. Using a simple heating function with a scale-height made inversely dependent on the expansion factor of magnetic field lines channeling the solar wind, we first retrieve the general properties of the fast and slow solar wind as well as the well-known observation that the source temperature of the slow wind is higher than for fast wind. We then solve explicitly for the ionization processes and coupled transport of heavy ions (including all relevant ionisation levels of O and Mg) with the majority species (H, p, e) to isolate the different processes that contribute to the ionisation level of heavy ions. We compare our modeling results with both spectroscopic and in situ data.

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Structure of the Plasma of the Heliospheric Current Sheet as seen by WISPR/Parker Solar Probe from Inside the Streamer Belt

Paulett Liewer

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Parker Solar Probe (PSP) crossed the Heliospheric Current Sheet (HCS) near perihelion on Encounters E8 and E11, enabling the Wide-field Imager for Solar Probe (WISPR) to image the streamer belt plasma in high resolution while flying through it. With perihelia of 16 $R_\odot$ and 13 $R_\odot$ for E8 and E11, respectively, WISPR images enable investigation of the structure of the plasma encasing the HCS at much higher resolution than reported previously. As PSP flies closer to the Sun, fine-scale structure is resolved within the coronal rays of the streamer belt. Near the HCS, WISPR observes a fan of rays of varying size and brightness, indicating large density variations in the HCS plasma sheet transverse to the radial direction. Near perihelion, when PSP's speed exceeds the solar corotation speed, some rays exhibit large changes in apparent latitude as the HCS is encountered and the rays pass over and under the spacecraft. The multiple viewpoints of the fine-scale rays provided during the HCS crossing enable us to extract the coordinates of a few rays in a heliocentric frame. For all ray coordinates determined to date, the rays lie near the HCS predicted by a PFSS model. We also compare their locations to the location of the streamers as seen in synoptic maps from the Large Angle and Spectrometric COronagraph (LASCO), and find that the rays generally fall within the bright/high density regions seen in these maps, which confirms that they are features of the streamer belt plasma. The locations of the rays were traced from the source surface down to 1.2 $R_\odot$ using a PFSS model. We found that they originate near the boundaries of polar coronal holes or their extension. We speculate that the large density variations observed in the plasma sheet of the HCS result from continuous interchange reconnection along the coronal hole boundaries that separate regions of open and closed magnetic field lines. This is consistent with EUV and X-ray observations of reconnection associated with bright points along coronal hole boundaries by Madjarska & Wiegelmann (2009) and Subramanian et al. (2010), respectively.This is also consistent with the concept that continuous interchange reconnection of minority polarity inclusions plays a dominant role in providing the energy to heat and accelerate the solar wind (Wang, 2020; Raouafi et al, 2023).

Collisional Relaxation of Solar Wind Protons, Core and Halo Electrons

Peter H. Yoon

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It is well known that the solar wind 1 AU is characterized by anisotropic temperatures associated with the protons, electrons (both core and halo components), as well as minor ions. The collection of data for these charged particles are customarily plotted as a two-dimensional histogram in parameter space with one axis corresponding to the beta value and the other axis being the temperature ratio for each charged particle species. While the charged particles are broadly distributed around the order-unity beta value and the temperature ratio roughly equal to unity, a small number of data points are scattered away into outer fringes that form an overall rhombic shape in the beta versus temperature ratio space. While it is also well established that the outer boundaries on the right-hand side are satisfactorily explained by various temperature anisotropy-driven instability threshold conditions, the boundaries to the left are largely unexplained. In this paper we report that the collisional relaxation process can satisfactorily account for the outer fringes of the data distribution to the left. Of course, the combined instability and collisional processes form the foundational mechanisms that explain the outer boundaries of the 1AU solar wind proton and electron data distributions, but additional effects such as the radial expansion in the spiraling (Parker) magnetic field and turbulence-induced heating processes further modify the dynamics of the solar wind.

Source and Evolution of Kinetic Alfvén Waves in the Near-Sun Solar Wind

Peter Tatum

Peter Tatum (LASP), David Malaspina (LASP)

The solar wind has been observed to heat internally as it expands outward from the Sun, but the nature of this heating has not yet been fully characterized. One primary mechanism for heating comes from turbulent fluctuations that can carry energy from large scales to kinetic scales. Recent solar wind observations at 1AU show the presence of KAWs below inertial range scales, suggesting that they play a role in energy dissipation. Understanding how KAWs are generated and evolve closer to the Sun can help elucidate their role in the radial evolution of solar wind. We present observations of KAWs in the near-sun environment (0.074 AU) using Parker Solar Probe. We show that KAW wave power is spatially correlated with intermittent large-scale Alfvénic fluctuations (including Switchbacks) that may be acting as source regions for KAWs. We take advantage of this spatial inhomogeneity to estimate the decay rate of the KAW fluctuations as they propagate away from their source. We track these relationships with radial distance from the Sun and investigate how KAWs relate to switchback evolution and solar wind heating.

Ion-scale transition of plasma turbulence: Pressure-strain effect

Petr Hellinger

P. Hellinger, A. Verdini, S. Landi, L. Franci, E. Papini, L. Matteini, and V. Montagud-Camps

We investigate properties of solar wind-like plasma turbulence using direct numerical simulations. We analyze the transition from large, magneto-hydrodynamic (MHD) scales to the ion characteristic ones using two-dimensional hybrid (fluid electrons, kinetic ions) simulations. To capture and quantify turbulence properties, we apply the spectral transfer (ST) and Karman-Howarth-Monin (KHM) equations to the numerical results. The ST and KHM analyses exhibit equivalent and complementary behaviours and indicate that the transition from MHD to ion scales results from a combination of an onset of Hall physics and of an effective dissipation owing to the pressure-strain energy-exchange channel and resistivity.

Kinetic Model of Fast Solar Wind Generation and Heating by Kinetic Alfvén Wave Turbulence

Phil Isenberg

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We present preliminary results from our kinetic guiding-center model for coronal hole protons heated by cyclotron and Landau damping of a critically-balanced turbulent spectrum of kinetic Alfvén waves (KAWs). The model follows the collisionless proton distribution function as it advects out from 2 solar radii along a radial flux tube, evolving under the combined action of gravity, ambipolar E-field, mirror force, and energization by the KAW turbulence. The turbulent dissipative heating is represented by velocity-space diffusion using coefficients calculated from the fluid dispersion relation for KAWs (Isenberg & Vasquez, 2019) and a radial intensity profile from Cranmer & van Ballegooijen (2005). We obtain a plausible fast solar wind flow, reasonable perpendicular anisotropies, and an emerging secondary proton beam from the Landau interaction. We compare results of heating from a balanced KAW spectrum with those from a 9:1 intensity imbalance, and find little qualitative difference from this change alone. We will discuss the implications of these results and outline the next steps we will take to incorporate the effects of kinetic dispersion and the proposed helicity barrier.

ESCAPADE: Unraveling Mars' Hybrid Magnetosphere and Solar Wind Interaction with a Dual-Spacecraft Mission

Phyllis Whittlesey

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ESCAPADE (Exploration of Solar Wind-Mars Plasma Interactions and Dynamics) is a mission employing a twin-spacecraft concept to revolutionize our understanding of Mars' magnetosphere and its complex interactions with the solar wind. ESCAPADE aims to unravel the mechanisms driving atmospheric ion and sputtering escape, which have shaped Mars' climate evolution over our solar system's history. Two small spacecraft, each with a dry mass of ¡125 kg, will be deployed via ballistic Hohmann transfers to reach Mars in Fall 2024. Operating from elliptical orbits (160 km x 7000 km), ESCAPADE will measure magnetic field strength and topology, light and heavy ion plasma distributions, as well as electron and ion densities via the mission's plasma detectors, miniaturized langmuir probes, and a scientific fluxgate magnetometer. The mission's year-long, two-part scientific campaign will involve multipoint measurements separated in both space and time across Mars' local and varied plasma environment. By characterizing the cause-and-effect relationship between solar wind dynamics and atmospheric escape, ESCAPADE will offer unprecedented insights into Mars' dynamic magnetosphere, with applications to plasma physics and planetary atmospheres across the solar system.

New instrumental models for quasi-thermal noise spectroscopy and mutual impedance experiments in magnetized space plasma

Pietro Dazzi

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Quasi-thermal noise spectroscopy and mutual impedance experiments are two in situ plasma diagnostic techniques. They measure the electron properties of space plasmas, including the total density and temperature. To perform these measurements, both techniques rely on electric antennas. Quasi-thermal noise is a passive technique, which measures the antenna voltage power spectrum. This spectrum is generated by the plasma thermal motion, and is related to its electron properties. In contrast, mutual impedance is an active technique in the sense that the plasma is excited by one electric antenna, and the propagation characteristics of this excitation are used to retrieve the plasma properties. Both techniques are included in the scientific payload of past, current, and future NASA, ESA, and JAXA space missions, such as Ulysses, WIND, Rosetta, Parker Solar Probe, Solar Orbiter, BepiColombo, JUICE, and Comet Interceptor. Instrumental models for both quasi-thermal noise spectroscopy and mutual impedance experiments provide are needed to transform the instrumental output into measurements of the electron properties. The modelling current state-of-the-art is mainly focused on the limit of an unmagnetized and isotropic plasma (in this context, a plasma for which the electron cyclotron frequency is much smaller than the plasma frequency). For both techniques, the geometry of antennas used have a significant impact on the measurement. Regarding quasi-thermal noise, the two geometries that are currently mainly considered in instrumental models are the double wire and the double sphere antenna. The magnetized plasma regime is of interest for space missions aimed at the study of the interaction of the solar wind with magnetized bodies of our solar system, such as Mercury (BepiColombo), Jupiter and Ganymede (JUICE), and Earth. In this context, we provide for the first time a complete diagnostic, in magnetized and anisotropic plasmas, for the plasma electron density and temperature, as well as for the magnetic field magnitude and direction, based on mutual impedance experiments and quasi-thermal noise spectroscopy. For this purpose, we developed numerical models for both quasi-thermal noise spectroscopy and mutual impedance experiments in a magnetized and anisotropic plasma. From the main features of these two numerical calculations, a diagnostic is derived for the plasma density, the electron temperature, as well as for the magnetic field magnitude and direction. A comparison with the quasi-thermal noise measurements obtained by the WIND mission is presented. Also, the effect of a separation between the two wires is investigated in the unmagnetized regime, with particular attention to the possible application to the Parker Solar Probe/FIELDS antenna.

Large-scale Magnetic Flux Ropes in the Solar Wind

Qiang Hu

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Magnetic flux rope, a type of magnetic field structure in space plasmas, has been studied for decades through both observational and theoretical means. We provide a brief report on our recent modeling study of its magnetic field configuration based on in-situ spacecraft measurements from the flagship missions including PSP and Solar Orbiter, focusing on those made for large-scale flux ropes in the interplanetary space. We illustrate the complexity in its field-line topology by presenting event studies employing a unique analysis method. In particular, we demonstrate the feasibility and challenges for the approach to use two or more in-situ spacecraft datasets. We discuss the implications of our results for the origination of these structures on the Sun.

Transverse dimensions associated with Alfvenic turbulence at the base of solar corona

Rahul Sharma

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In the last decade, Alfvénic fluctuations remained a major focus of research on coronal heating and the origin of solar wind. Theoretical studies postulated that predominantly outward propagating waves carry a significant fraction of energy and momentum from the lower solar atmosphere and dissipate in corona via MHD turbulence, thereby heating the plasma and accelerating the solar wind. Perpendicular correlation length(s) is a key parameter of such Alfvénic turbulence driven models which can strongly influence energy dissipation below and above the sonic point, while affecting the solar wind acceleration profiles in the solar corona and beyond. Previous attempts of correlation length estimations from in-situ solar wind measurements remained restricted to radial distances beyond the Alfven critical zone, which were far from the coronal base where Alfvenic wave energy is injected. We present recent work where the magnitudes of the correlation lengths are estimated, for the first time, from observed transverse waves in the solar corona using Coronal Multi-Channel Polarimeter (CoMP) data. We further compare these estimates with perpendicular correlation length magnitudes obtained from in-situ measurements and numerical models highlighting possible contradictions due to inhomogeneous nature of lower and middle corona. Our results provide a critical insight into the MHD turbulent energy injection scales associated with Alfvenic waves in the solar atmosphere and a clear constraint for future numerical Alfvén wave turbulence studies.

Continuing Observations of the Distant Solar Wind by New Horizons

Ralph McNutt

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The New Horizons spacecraft, launched in 2006, continues to return unprecedented charged particle data from the heliosphere. The Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) and Solar Wind Around Pluto (SWAP) instruments had the prime purpose of probing the interaction of the solar wind with Pluto, which they did at the Pluto flyby in July 2015. However, they have also, and continue to, provide ground breaking discoveries throughout the heliosphere, beginning with detailed investigation of Jupiter's magnetotail following the Jupiter gravity assist in early 2007, and now continuing with measurements of the distant solar wind, on a near-continuous basis since 2014. Originally targeted to measure ions (with compositional information) and electrons from 10 s of keV to ∼1 MeV in a 160° x 12° fan-shaped beam in six sectors for 1.5 kg and ∼2.5 W, PEPSSI measurements now include time-of-flight measurements below ∼15 keV of mostly pickup He+ (inaccessible to the Voyager LECP instrument) and sampling of galactic cosmic rays (GCRs). Similarly, SWAP, targeted to measure the thermal proton and alpha components of the solar with an energy-per-charge scan of 35 eV to 7.7 keV for 3.3 kg and ∼2.8 W, has sufficient sensitivity to measure directly pickup ions in the solar wind, which have not been accessible in the far solar wind to the Voyager PLS instrument. With newly uploaded software improvements, New Horizons continues to return unprecedented measurements of the solar wind near the plane of the ecliptic, a region of space not sampled by the Voyagers past the orbit of Neptune. With other new approaches to power savings on board, New Horizons should be able to continue these operations through the termination shock, into the heliosheath, and perhaps to ∼130 au (in 2050), beyond the heliopause. These heliophysics measurements, coupled with ongoing observations of distant Kuiper Belt Objects (KBOs – at phases at phase angles not possible from any other operating spacecraft) can also provide new insights into the nature and evolution of this "third zone" of our solar system. Such a synergy of planetary science and heliophysics was not possible with the Voyager cameras and its other instruments, but with a fully-funded, continuing extended mission bodes well for unprecedented new insights into our home in the galaxy.

Interstellar Probe: A Unifying Mission Pushing the Frontier of Solar & Space Physics

Ralph McNutt

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Our solar system was formed in a journey around the galaxy from the protosolar nebula plowing through interstellar space filled with gas, dust, plasma and cosmic rays. After only a few ten million years, the Sun formed and has helped shape our home ever since. On this 4.6-billion-year journey our protective magnetic bubble has been exposed to dramatically different interstellar environments and supernovae, leaving the entire solar system exposed to the interstellar medium amplifying the central role of an astrosphere in the evolution of habitable systems. After traversing the Local Interstellar Cloud (LIC) for the past 60,000 years, the Sun is now about to enter the unknown environment of the neighboring G-Cloud that will continue to shape the evolution of our home. Our current knowledge lacks the direct measurements necessary to understand how our star upholds its vast heliosphere and its potentially game-changing role in the evolution of our galactic home. Using conventional, chemical propulsion and a Jupiter Gravity Assist, Interstellar Probe would launch 2036-2042 on a trajectory through the forward hemisphere of the heliosphere at a speed of about 7 au/year and a 50-year design life. From this trajectory it would return complete space plasma observations from the orbit of Earth transecting the entire heliosphere over more than a solar cycle. Following the evolving solar wind on an outward trajectory enables comprehensive investigations of hundreds of propagating disturbances, particle acceleration, turbulence, and reconnection processes required to build a unified description of the heliosphere from 1 au to beyond its boundary, complemented by the detailed picture inside of 1 au that Parker Solar Probe (PSP) is giving us. Beyond the heliopause it would directly sample the VLISM to understand the heliospheric interaction, and to shed light on the history of the LIC and the new environment the Sun is about to enter. Interstellar Probe therefore presents an opportunity for heliophysics to make a leap beyond our historical Sun-Earth system bringing expanding research opportunities across multiple sub-disciplines for generations. It would act as a moving pillar of the Heliophysics System Observatory (HSO), eventually becoming humanity's farthest outpost, far beyond where the Voyager and New Horizons missions will reach. In this presentation we provide an overview of the 4-year Mission Concept Study of a Pragmatic Interstellar Probe that is now under consideration by the Solar & Space Physics Decadal Survey, including the compelling discoveries that await, and the example science payload ensuring a historic data return that would push the boundaries of space exploration to understand where we came from and where we are going.

Heavy Ion Solar Energetic Particle Observations from EPI-Hi on Parker Solar Probe During the 5 September 2022 Event

Richard Leske

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The EPI-Hi instrument in the Integrated Science Investigation of the Sun (IS⊙IS) suite on Parker Solar Probe measures the time profiles, anisotropies, spectra, and composition of energetic ions from H to Ni at energies ranging from ∼1 MeV/nucleon to above 100 MeV/nucleon. During large solar energetic particle (SEP) events, EPI-Hi autonomously eliminates its sensitivity to H, He, and electrons in certain energy intervals by disabling high gains on parts of the instrument in a process known as ”dynamic thresholds”, which complicates the analysis, but sensitivity to heavy ions is much less impacted. Combining data from the three EPI-Hi telescopes, we present heavy ion observations throughout the large SEP event observed on 5 September 2022 at a distance of 0.07 au from the Sun, including periods around the shock, inside the coronal mass ejection, and near the heliospheric current sheet crossing.

DENSITY FLOW IMPLICATIONS UNLOCK SOURCE AND ACCELERATION OF THE AMBIENT SOLAR WIND

Richard Woo

Richard Woo, Jet Propulsion Laboratory, California Institute of Technology

Despite six decades of solar wind exploration, from where on the Sun the wind originates remains unknown. Lack of coronal measurements of velocity and magnetic field impedes. Since white-light and radio occultation investigations of coronal density began prior to discovering the solar wind, it is the most thoroughly observed solar wind parameter. When Ulysses radio and white-light density measurements found the polar fast wind expanded radially from the Sun rather than superradially from polar coronal holes, it sparked questions about density. What is its relevance to and role in exploring the solar wind? Why does expansion defined by density measurements differ from that inferred from images of density?

Discovering the solar wind meant the white-light corona represented its source region. Determining what it tells us about the solar wind is challenging, because this natural phenomenon is unusual and unique. With brightness proportional to density, mutually exclusive disciplines share the same measurements. Brightness is relevant to seeing and imaging the corona, whereas density is relevant to the solar wind. Measured density distribution is true, and so is radial expansion. Measured brightness is also true, but because seeing and imaging brightness are limited by dynamic range, they are not an alternative to seeing and imaging density, and superradial expansion is not true. This paper, therefore, uses only measured density distributions to explore the corona.

Radial expansion of fast wind demonstrates large-scale density distributions carry and convey flow information. This is groundbreaking for density, because it unifies white-light and radio occultation density measurements spanning a wide range of temporal and spatial variations. Density and its variations are fossil structures that originate at the base of the corona and are advected as passive scalars with the ambient wind. This explains why: (1) small-scale temporal density fluctuations of turbulence yield indirect velocity measurements, (2) small-scale spatial density variations identify coronal filamentary structures, (3) delta n/n is constant, (4) density spectra are independent of delta n/n, and (5) large-scale density and velocity are anticorrelated throughout the solar wind.

Flow implications of density distributions here show all of the ambient wind expands radially from the Sun, identifying their sources and defining their acceleration. Flow along the heliospheric current sheet is not part of the ambient wind, explaining why it does not appear in Ulysses velocity maps of the streamer belt. Measured isophotes — representing contours of constant brightness hence density — convey sources and acceleration. Superposing them on images of diverging polar coronal holes and tapering streamers, therefore, reveals their flow implications while providing a tool for connecting Parker Solar Probe and Solar Orbiter measurements to their source region within 2 Ro.

Unusually long path length for a nearly scatter-free solar particle event observed by Solar Orbiter at 0.43 au

Robert F. Wimmer-Schweingruber

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After their acceleration and release at the Sun, solar energetic particles (SEPs) are injected into the interplanetary medium and are bound to the interplanetary magnetic (IMF) field by the Lorentz force. The expansion of the IMF close to the Sun focuses the particle pitch-angle distribution, scattering counteracts this focusing. Solar Orbiter observed an unusual solar particle event (SPE) on 9 April 2022 when it was at 0.43 astronomical units (au) from the Sun. We use velocity dispersion analysis (VDA) and pitch-angle information to infer the spiral length along which the electrons and ions traveled and infer their solar release times and arrival direction. The path length inferred from VDA is approximately three times longer than the nominal Parker spiral. Nevertheless, the pitch-angle distribution of the particles of this event is highly anisotropic and the electrons and ions appear to be streaming along the same IMF structures. The angular width of the streaming population is estimated to be approximately 30 degrees. The highly anisotropic ion beam was observed for more than 12 hours which may be due to the low level of fluctuations in the IMF. The latter is very probably due to this event being inside an Interplanetary Coronal Mass Ejection (ICME), the slow rotation

in the IMF suggests a flux-rope structure. Small flux dropouts are associated with very small changes in pitch angle which may be explained by different flux tubes connecting to different locations in the flare region. However, it is remarkable that these small directional changes in the IMF are also seen in the ICME observed here and that these are much smaller than previously reported. The unusually long path length along which the electrons and ions have propagated virtually scatter-free together with the short-term flux dropouts offer excellent opportunities to study the transport of solar energetic particles within interplanetary structures. The 9 April 2022 solar particle event offers an especially rich number of unique observations that can be used to limit solar energetic particle transport models.

Main results obtained by EPD during Solar Orbiter first science orbit

Robert F. Wimmer-Schweingruber

Robert F. Wimmer-Schweingruber1, Javier Rodriguez-Pacheco2, George Ho3, and the Solar Orbiter EPD team

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Solar Orbiter is an ESA mission in collaboration with NASA that was launched in February 2020 to answer the question how the Sun creates and controls the Heliosphere. For that purpose, the spacecraft will reach an orbit with a perihelion within 0.3 au from the Sun and carries onboard a comprehensive scientific payload of ten instruments. Among them, the Energetic Particle Detector (EPD) is aimed to answer the question of how the Sun produces energetic particles that eventually fill the entire heliosphere. EPD is a suite of multiple sensors (STEP, SIS, EPT, HET), which measure particle intensities over a wide range of energies (from suprathermal up to relativistic energies) and for different species (e-, protons, and heavy ions) in different directions. Last December, Solar Orbiter initiated the nominal science phase with an orbit that carried the spacecraft to a close encounter with the Sun (0.32 au) in March 26th 2022. In this talk we will present the main EPD results obtained during this orbit and particularly at distances below 0.4 au from the Sun.

Time-Dependent Evolution of the Solar Wind Driven by Realistic Photospheric Flux Evolution

Roberto Lionello

Roberto Lionello, Pete Riley, Cooper Downs, Jon A. Linker, Emily Mason / Predictive Science Inc.

There is a general consensus that photospheric motions provide the energy source of the solar wind and that the magnetic field must play a fundamental role. However, the properties of the solar wind, as measured by orbiting spacecraft, have never been conclusively linked with the physical processes occurring in the corona. In this study, we calculate the response of the solar wind to realistic time-dependent evolution of the photosphere, using coupled 3D full MHD numerical models of the corona and heliosphere.The boundary conditions of the coronal model are provided through a sequence of magnetic maps that are smoothly interpolated and corrected to minimize spurious currents. From the output of the coronal model, we drive a heliospheric model with an outer boundary set to 1 au. For comparison, we also develop a steady state solution, obtained by stopping the photospheric changes and allowing the system to reach a dynamic steady-state equilibrium. We evaluate the plasma and magnetic field properties of the solar wind (including power spectra and Alfvenicity) of both models at different locations in the inner heliosphere and compare their statistical properties with in situ measurements.

Simulation of Thermal Nonequilibrium Cycles in the Solar Wind

Roger Scott

Roger Scott (NRL), Jeff Reep (NRL), Mark Linton (NRL), Steve Bradshaw (Rice U.)

Thermal nonequilibrium (TNE) is a condition of the plasma in the solar corona in which energy loss due to radiation increases to a point that it cannot be sustained by the various heating terms, precluding the existence of a steady-state solution. TNE can manifest as a temporary condition, as may be the case after large flare-driven heating events, or as an enduring condition when the heating is steady in time, in which case the plasma falls into a limit cycle of condensation and evaporation that proceeds ad infinitum or until interupted by some other external process. TNE-induced limit cycles have been studied carefully in the context of closed magnetic flux domains where the flow speed is typically much less than the thermal speed, so that the field-aligned enthalpy flux is negligible, and have also been observed along open field lines in 2D and 3D numerical simulations; however, a careful study of TNE conditions in the solar wind has not been performed until now. Here we demonstrate that for suitable combinations of local and global heating rates it is possible for the plasma to exhibit a nonequilibrium condition in the presence of an outward-flowing solar wind solution with a appreciable outward mass and energy (enthalpy) fluxes. This finding has implications for the interpretation of coronal rain observations near complex magnetic structures and along coronal hole boundaries. Moreover, because of the emergent nature of TNE condensation cycles, this result may help to explain some of the variability in the solar wind, even in cases where the driving conditions at the at the base of the corona are slowly varying in time.

Anisotropic Magnetic Turbulence in the Inner Heliosphere—Radial Evolution of Distributions Observed by Parker Solar Probe

Rohit Chhiber

Rohit Chhiber, NASA GSFC & University of Delaware

Observations from Parker Solar Probe's first five orbits are used to investigate the helioradial evolution of probability density functions (pdfs) of fluctuations of magnetic-field components between ∼28 and 200 solar radii. Transformation of the magnetic-field vector to a local mean-field coordinate system permits examination of anisotropy relative to the mean magnetic-field direction. Attention is given to effects of averaging-interval size. It is found that pdfs of the perpendicular fluctuations are well approximated by a Gaussian function, with the parallel fluctuations less so: kurtoses of the latter are generally larger than 10, and their pdfs indicate increasing skewness with decreasing distance r from the Sun. The behavior of the skewness of parallel fluctuations may be explained by the increasing Alfvénicity of the fluctuations. The ratio of perpendicular to parallel variances is greater than unity; this variance anisotropy becomes stronger with decreasing r. The ratio of the total rms fluctuation strength to the mean-field magnitude decreases with decreasing r, with a value ∼0.8 near 1 au and ∼0.5 at 0.14 au; the ratio is well approximated by an r^(1/4) power law. A moderate degree of axisymmetry is maintained in the plane perpendicular to the mean magnetic field. These findings improve our understanding of the radial evolution of turbulence in the solar wind, and have implications for related phenomena such as energetic-particle transport in the inner heliosphere.

The Influence of Eddy Viscosity and Turbulent Electric Field on Global Solar Wind Modeling

Rohit Chhiber

Rohit Chhiber (NASA GSFC & University of Delaware), Arcadi Usmanov (NASA GSFC & University of Delaware), William Matthaeus (University of Delaware), Melvyn Goldstein (Space Science Institute)

Global models of the solar atmosphere and the solar wind successfully describe numerous large-scale features of the heliosphere, and have proven to be very useful in providing important context for in-situ and remote sensing observations. Computational constraints on numerical resolution imply that turbulent fluctuations remain unresolved in such models, and their interaction with the large scales must therefore be represented by means of so-called subgrid-scale turbulence modeling. In a magnetohydrodynamic (MHD) description of the solar wind, two important terms that arise in the context of turbulence modeling are the eddy viscosity and the turbulent electric field. Using a well-tested global solar wind model that includes turbulence transport [1], we have initiated a parameter study to examine the effect of these two terms on our model's results. This study provides insight on how to improve the representation of turbulence in global solar wind models, and on the role of shear interactions and turbulent EMF (amplification and/or diffusion of magnetic field) in solar wind dynamics.

[1] Usmanov et al., ApJ, 865:25, 2018

Solar wind sources, coronal rotation and wind shear across the solar activity cycle

Rui Pinto

Rui F. Pinto, Alexis Rouillard, Adam Finley; IRAP, OMP/CNRS, U. Toulouse & LDE3, CEA Saclay

The solar wind is an uninterrupted flow of highly ionised plasma that streams from compact sources at or near the Sun, accelerates across the low solar corona, and expands into the whole interplanetary space. The physical properties of any wind streams thus reflect the characteristics of their source regions and those of the extended zones of the corona they cross, and are affected by the time-varying strength and geometry of the global background magnetic field. The rotational state of the solar corona also plays a fundamental role in a wide range of solar wind phenomena, but is much less well-known than that of the photosphere. In addition, surface dynamics and magnetic field evolution drive perturbations to the corona and wind that can either be transient or long-lasting. We investigate the geometry and spatial distribution of solar wind sources by means of an extended time series of data-driven 3D simulations that cover nearly 2 activity cycles. We furthermore examine the corresponding solar wind acceleration profiles (radial trends) as a function of source latitude and time, and highlight consequences for the interpretation of Parker Solar Probe (PSP) and Solar Orbiter (SolO) in-situ measurements (especially as the latter moves away from the ecliptic plane). We also highlight impacts on the rotation profile of the solar corona and on the occurrence of regions of enhanced poloidal and toroidal flow shear that can drive plasma instabilities.

CMEs – How we got here and where are we going?

Russell Howard

Russell Howard, Johns Hopkins University Applied Physics Lab

The observation of a large chunk of solar mass leaving Sun was unexpectedly observed in December 1971 from the Orbiting Solar Observatory #7, which had been launched 3 months earlier to study the large scale evolution of the solar corona. Such phenomena, now called coronal mass ejections (CMEs) with its interplanetary counterpart, ICMEs, have spawned new subdisciplines in Solar and Heliospheric Physics. A lot of progress in understanding the CME process has been made in the last 25 years, there is still a long way to go. This presentation will briefly review the history of CME observations, summarizing what is known and some issues that are not.

Driving the SEPCaster Model with an Automated Solar Active Region Identification and Characterization Module

Sailee M. Sawant

1. Sailee M. Sawant (University of Alabama in Huntsville) 2. Gang Li (University of Alabama in Huntsville, Huntsville) 3. Meng Jin (Lockheed Martin Solar and Astrophysics Laboratory)

Solar flares and coronal mass ejections (CMEs) can cause disruptive space weather phenomena, including geomagnetic storms and solar energetic particle (SEP) events, which can severely damage ground- and space-based technological systems and affect our daily lives. Therefore, we require state-of-the-art forecasting models to accurately predict space weather conditions. This research aims to develop a physics-based operational SEP forecast model, SEPCaster, for the energetic particle radiation environment in the inner Solar System and Earth's magnetosphere.

SEPCaster is based on two advanced research models: the Alfv\'en Wave Solar Model (AWSoM) and the improved Particle Acceleration and Transport (iPATH) model. The AWSoM model is incorporated to generate the background solar wind and CMEs, and the iPATH model is employed to track the acceleration and transportation of SEPs. SEPCaster operates in two distinct modes: an automatic forecasting mode and a user-interactive mode. In the automated mode, SEPCaster runs with minimal human interaction, while in the interactive mode, users can modify the inputs and analyze specific events in greater detail.

This presentation focuses on a new Python-based automated module for identifying and characterizing solar active regions (ARs). We start by using real-time National Solar Observatory/Global Oscillation Network Group (NSO/GONG) magnetograms as our raw inputs and apply an image segmentation technique to detect regions of interest (ROIs) with positive and negative polarities. Next, we implement and refine a hierarchical clustering algorithm to identify potential ARs from the detected ROIs. We then calculate a set of parameters to characterize these ARs, including our newly defined boundary- and area-based AR complexity indices. Based on these parameters, we also compute potential CME eruption speeds, which are then incorporated into SEPCaster.

Measuring solar wind speeds with WISPR via the stationary point

Sam Van Kooten

Sam Van Kooten Southwest Research Institute
Craig DeForest Southwest Research Institute
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The WISPR camera on Parker Solar Probe offers the first up-close view of the young solar wind, with a rapidly-changing field of view caused by the high velocity of the spacecraft and its close proximity to the structures being imaged. This unique vantage enables new types of analysis. We are developing a new technique, using the relative motion of the wind as a tool to measure its speed near the spacecraft at heliocentric distances comparable to PSP's own position, with the goal of using WISPR's wide field of view to make speed measurements at lattitudes outside the orbital plane. Amid the outflowing plasma visible in WISPR image sequences, we detect the "stationary point," a position in the field of view where plasma features do not move in the image plane. This indicates plasma which will collide with or pass near the spacecraft, as that plasma is on an inward trajectory in the spacecraft frame. The angular position of this stationary point is a function of the known spacecraft velocity and the unknown plasma velocity, allowing the plasma velocity to be determined in neighborhoods of varying size near the spacecraft, complementary to in situ measurements at the spacecraft itself. This will help answer open questions regarding the nature and early evolution of the young solar wind. In this presentation, we will discuss the development of our technique and necessary background-removal steps, and show current progress.

Characterizing the in situ observed solar wind at L1 from differing source regions

Samantha Wallace

Samantha Wallace (NPP, NASA/GSFC), Nicholeen Viall (NASA/GSFC), Nick Arge (NASA/GSFC)

A fundamental aspect of solar wind formation is where the plasma originates from on the Sun. The solar wind originates from 3 types of coronal magnetic field – the continuously open fields that form coronal holes (CHs), or from either active region (AR) or quiet Sun (QS) at the magnetic open-closed boundary. Relating in situ solar wind observations to their source at the Sun is a critical step to understanding how the solar wind is formed, because the source determines the plasma temperature, its elemental composition, and the possible mechanisms involved in its release and acceleration. Recent missions enable more direct measurements of the pristine solar wind closer to its solar origin, however, the use of a model is required to bridge in situ solar wind observations to their precise source region observed remotely. In this work we use the Wang-Sheeley-Arge (WSA) model driven by Air Force Data Assimilative Photospheric Flux Transport (ADAPT) time-dependent photospheric field maps to connect the in situ observed solar wind at ACE, with its source region at 1 Rs. We classify the ACE-observed solar wind based on source region (CH, QS, or AR) using model parameters derived for the magnetic field lines connected to each source (e.g. spacecraft separation from the HCS and S-web arc, source region distance from magnetic open-closed boundary), and the corresponding photospheric field measurements at the source. We characterize the in situ properties of the solar wind observed at ACE (e.g. speed, proton density, nA/nP, Fe/O, carbon and oxygen charge state ratios) that originate from each source, in order to investigate whether the source region as defined here ultimately determines the plasma properties observed in situ. We use this methodology to investigate two Carrington rotations, one near solar maximum and one near solar minimum. We find a strong relationship between source region and charge state ratio observed in situ, and consistently low FIP in solar wind from coronal holes with widely varying FIP measurements from solar wind originating from the magnetic open-closed boundary. We discuss these results and other findings in the context of how the source region determines or influences the solar wind properties observed in situ. We conclude with future plans to expand this work to a larger statistical analysis over a solar cycle, and to statistically quantify the solar conditions that produce geoeffective ambient solar wind.

Dispersive Suprathermal Ion Events Observed by the Parker Solar Probe Mission

Samer Alnussirat

Samer Alnussirat (UC Berkeley, Space Sciences Lab), On behalf of the SWEAP, FIELDS, and EPI-Lo teams

During Encounter 11, Parker Solar Probe (PSP) observed a new type of Low Energy Dispersive Ions (LED-Ions) event of solar origin. The event was observed in the SPAN-I and EPI-Lo sensors. The event started at a few MeV energy in the EPI-Lo sensor and progressed down in energy over the whole SPAN-I energy range (20 keV to 20 eV). This event is substantially different from typical Solar Energetic Particles (SEPs) because the energetic population shows a distinct peak in the energy spectrum that descends in energy (not a power law tail). Additionally, the angular distribution of protons shows a narrow beam compared to solar flare and Coronal Mass Ejection-related SEPs. In this work, we explore this event's nature, origin, and characteristics.

Ring Current Local Time Dependence using Dst index proxies

Santiago Pinzón-Cortés

Santiago Pinzón-Cortés, Universidad Nacional de Colombia; Natalia Gómez-Pérez, British Geological Survey; Santiago Vargas Domínguez, Universidad Nacional de Colombia, Observatorio Astronómico Nacional

Interaction between strong Solar Wind and the Geodynamo generates perturbations over the geomagnetic field that lead to geomagnetic storms. Intense storms can cause damage to infrastructure, GPS failures, electrical power black, and destabilization of satellites' orbits.

During a geomagnetic storm, the Ring Current (RC) enhances which leads to a decrease in the horizontal (H) component of the geomagnetic field at the equator. We measure the decrease of the H component with the Disturbance Index (Dst). Also, this index is an indirect measure of the RC. The Dst index is calculated using the H component from 4 observatories near the magnetic equator: Kakioka (KAK), Japan; Hermanus (HER), South Africa; Honolulu (HON), Hawaii; and San Juan (SJG), Puerto Rico.

In this study, we calculate several Dst index proxies to observe the RC local time dependence Initially, we calculate Dst proxies using data from low latitude observatories during varying geomagnetic intensities (from Quiet to Severe Storms). We found a strong correlation between the proxies and the Dst index (>0.8) during active periods (moderate to severe storms), and a more modest correlation (0.5 to 0.7) during quiet time. Also, we observe intensity differences that may be related to local time. Our results indicate that Dst index proxies using single observatories can be effectively used to study strong to great storms.

Then, we established 4 pairs of observatories distributed at different local times: 1) Honolulu - Isla de Pascua (UTC −8.5); 2) San Juan - Fuquene (UTC −4.5); 3) Hermanus - Tamanrasset (UTC +1.5); and 4) Kakioka - Learmonth (UTC +8.5). The results show a relation between storm intensity and local time: storms are more intense at dusk-midnight, and weaker at dawn-noon. Our results exhibit that geomagnetic storms have a greater impact in areas located at the dawn-midnight side. Additionally, this result will help to understand the RC behavior and improve RC models.

To be submitted

Saumitra Mukherjee
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To be submitted

Transport of MHD turbulence in the Solar Wind: Analytic Solutions

Sean Oughton

Sean Oughton (University of Waikato, Hamilton, New Zealand) and Mark A. Bishop (Victoria University of Wellington, New Zealand)

The evolution of MHD-scale fluctuations in the inhomogeneous solar wind is a topic of long-standing interest, in part due to its relevance to the scattering of cosmic rays.

Transport equations for energy-containing scale turbulent fluctuations, given a background solar wind, are well known and include various (often nonlinear) models for the nonlinear decay of fluctuation energy [eg, Matthaeus et al 1994, 1996, Smith et al 2001, Breech et al 2008, Oughton et al 2011, Zank et al 2012]. Quantities followed include the Elsasser energies (or their equivalents), the energy difference, and associated lengthscales.

We present new analytic solutions for the radial evolution of the fluctuations in a prescribed steady-state large-scale solar wind that embodies a radial uniform spherical flow and a Parker spiral magnetic field. The fluctuations are assumed to have a specific symmetry, namely either 3D isotropic, axisymmetric with respect to the Parker spiral, or slab with respect to the Parker spiral.

The obtained solutions are more general than those previously presented in the literature, and, in particular, they hold for (inner) boundary conditions of arbitrary cross helicity. The evolution and solutions also account for a nonlinear von Karman-Howarth energy decay model [eg, Dobrowolny et al 1980, Hossain et al 1995, Wan et al 2012]. At large heliocentric distances (r) the solutions are often powerlaws in r. The analytic forms support elucidation of the time and length scales associated with the fluctuation evolution, and are also useful in the testing and validating of numerical transport equation solvers.

Magnetic Reconnection at Thick Current Sheets: Insights from Solar Wind Observations

Senbei Du

Senbei Du, Los Alamos National Laboratory

Parker Solar Probe (PSP) reported frequent magnetic reconnection at the heliospheric current sheet (HCS), despite its thickness exceeding the ion inertial length by orders of magnitude. On the other hand, reconnection is relatively rare when HCS is observed near 1 au. We propose an explanation based on magnetohydrodynamic instabilities. Supporting evidence from PSP and ACE spacecraft is presented.

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Three-dimensional Reconstruction Of Transients In The Outer Corona By The CORAR Technique Based On Multi-view Observations From STEREO

Shaoyu Lyu

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Based on the simultaneous white-light observations of STEREO twin spacecraft, we proposed the CORrelation-Aided Reconstruction (CORAR) technique to locate and reconstruct the three-dimensional (3D) structures of solar wind transients in the interplanetary space. For the study of transients in the outer corona, we apply the CORAR method on synthetic and real images of COR-2 onboard STEREO. By comparing the reconstruction quality and precision of synthetic transient blobs under various conditions, we find that transients are generally reconstructed well when the separation angle between two spacecraft (θ_Sun) is between $120\circ$ and $150\circ$, and the optimal θ_Sun for reconstruction is close to $135\circ$. Based on the conclusion, we study the 3D reconstruction and evolution of real small-scale transients observed by COR-2 during Jan 2010 - May 2010. The valid transients are automatically detected according to the velocity uncertainty and image comparison. We confirm that the transients can be located and reconstructed well by comparing reconstructed structures with the corresponding transients fitted by the self-similar expanding model. The reconstructed transients generally have the typical acceleration characteristic of slow solar wind, which fits the trans-coronal radio observation and the previous researches of blobs. Most transients are located near the top of streamer belts, and can be traced into the boundaries of coronal holes or open-field regions on the photosphere. It supports the opinion that the slow solar wind originates from the interchange magnetic reconnection between open and closed field.

Identification of prominence materials by heavy ions compositions and interplanetary magnetic field

Shuo Yao

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The charge and abundance of heavy ions in ICMEs reflect the source information. Among the three parts of CME, how to identify the erupted prominence in the interplanetary space is still unclear. We present a series of statistical studies on the heavy ion compositions, IMF, and proton moments to investigate the signatures of prominence materials and the mechanisms of initiation. The data measured by ACE and WIND at 1 au is from 1998 to 2011 when more than 300 ICMEs are detected. Firstly, we use the carbon mean charge to set a solid and a relative criterion compared to quiet solar wind to identify the cold materials. About one third of the studied ICMEs contain these carbon-cold materials. And there are two significantly different types of cold materials. Further, we check the helium abundance and southward IMF related to these cold materials. Interestingly, the helium-enhanced cold materials with magnetic flux rope show the strongest IMF Bz in cumulation distribution, and they tend to drive strong level storms. Finally, we use a machine learning classifier to check the origin of cold materials without observations of CMEs. The key signatures of prominence cold materials against quiet solar wind, ICMEs, and both are selected by their weights in the classification model. Most unknown-origin cold materials are classified as prominence materials, while 3 are identified as others. The above results support the observed injection of enhanced twisted flux ropes to prominence and the significantly stronger geoeffectiveness of three-part CMEs. Besides, there are possibly different heating and collision processes beyond the carbon freeze-in height.

Corotation effects in solar energetic particle events

Silvia Dalla

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During gradual events, solar energetic particle (SEP) intensities can remain enhanced over timescales of the order of days. Corotation of particle-filled magnetic flux tubes with the Sun is generally thought to have a minor influence on the measured time-intensity profiles of gradual events. However recent 3D test particle simulations of SEPs injected by a propagating shock-like source show that corotation plays a major role, especially during the decay phase (Hutchinson et al A&A Lett., 670, L24, 2023). We highlight the effects of corotation on intensity profiles during gradual events, as derived from the simulations, by comparing with a situation when corotation is not included in the modelling. When corotation is included, the SEP decay time constant is reduced, and the distribution of peak intensity with longitudinal separation, Delta_phi, between observer footpoint and source active region, becomes broader. We use an extensive dataset of 239 front-side and far-side CME events of the STEREO era, and of their SEP effects (Kihara et al, ApJ 900, 75, 2020), to investigate possible signatures of corotation in SEP observations. We show that there is a strong asymmetry in the Delta_phi distribution of SEP event occurrence: outside of the well-connected longitude range, observers magnetically connected to the west of the source active region (i.e. where corotation sweeps the magnetic field lines towards the observer) are 76% more likely to detect an SEP event compared to observers connected to the east. We discuss possible additional corotation signatures in the statistics of properties of the intensity profiles such as time to maximum and event duration.

Core Electron Temperatures in the Venusian Ionosphere from the Third Venus Gravity Assist by Parker Solar Probe

Speero Tannous

Speero Tannous (Space Sciences Laboratories, UC Berkeley Astronomy), Marc Pulupa (Space Sciences Laboratories), Stuart Bale(Space Sciences Laboratories, UC Berkeley Physics)

During the third Venus gravity assist (VGA3) by the Parker Solar Probe(PSP), the spacecraft entered the Venusian ionosphere. While the halo electron density and temperature were measured, the core electrons could not be detected as they were below the SWEAP/SPAN electrostatic analyzer instrument energy threshold. However, there is another way to calculate the core temperature using quasi-thermal noise (QTN) data measured by the PSP/FIELDS RFS instrument. QTN spectroscopy offers an effective tool for measuring electron temperature and density when the electrons are too cold for other instruments to measure, as is the case with VGA3. While data from the entire ionospheric encounter is available, only QTN spectra where high-resolution data was available was selected to allow for better total electron density calculations and more accurate least-squares fits of QTN models. This limited the data to 15 spectra in the time range 3:23:04 to 3:24:01. In order to generate QTN models, open-source software developed by Yuguang Tong (2019) was adapted to be compatible with the PSP/FIELDS antenna geometry. The software takes into account the different antenna configurations and plasma conditions to generate a QTN model using a kappa distribution that mimics a bi-Maxwellian. Through linear regression and Bayesian analytics, the core electron temperature was determined for each of the spectra. We discuss the capability of such measurements in the terrestrial ionosphere for the AETHER instrument on the Geospace Dynamics Constellation (GDC) mission.

A measured dipole-like depletion of the open magnetic flux near the Sun

Stuart Bale

UC Berkeley

In this letter, we use magnetic field measurements from the NASA Parker Solar Probe (PSP) spacecraft to show that the in situ-measured radial component B_R of the heliospheric magnetic field (HMF) at low latitudes departs from the 'open flux' expectations within r ∼ 0.3 AU near the Sun. At the perihelion distance 13.3 R_S of PSP Encounter 12, this represents a ∼20% depletion of the flux expected from a 1/r^2 scaling and a departure of ∼200 nT from the expected field magnitude. The depletion reduces the magnitude of the radial field B_R independent of polarity and scales approximately like a dipole 1/r^3, however there is no clear corresponding signature in the transverse (T, N) components of the magnetic field, which are dominated by Alfvenic fluctuations. Due to the PSP orbit, this reduction occurs over a very large range of Carrington longitude, making it unlikely to be a local effect, but also making it difficult to separate radial from longitudinal variation. We consider several explanations for our measurement, including the dissipation of magnetic flux due to reconnection within the Heliospheric Current Sheet (HCS) and latitudinal (meridional) reorganization of the field from an initial dipolar state.

Interchange magnetic reconnection is the source of the fast solar wind

Stuart Bale
UC Berkeley

The fast solar wind that fills the heliosphere originates from deep within regions of open magnetic field on the Sun called 'coronal holes'. The energy source responsible for accelerating the plasma is widely debated; however, there is evidence that it is ultimately magnetic in nature, with candidate mechanisms including wave heating and interchange reconnection. The coronal magnetic field near the solar surface is structured on scales associated with 'supergranulation' convection cells, whereby descending flows create intense fields. The energy density in these 'network' magnetic field bundles is a candidate energy source for the wind. Here we report measurements of fast solar wind streams from the NASA Parker Solar Probe (PSP) spacecraft that provide strong evidence for the interchange reconnection mechanism. We show that the supergranulation structure at the coronal base remains imprinted in the near-Sun solar wind, resulting in asymmetric patches of magnetic 'switchbacks' and bursty wind streams with power-law-like energetic ion spectra to beyond 100 keV. Computer simulations of interchange reconnection support key features of the observations, including the ion spectra. Important characteristics of interchange reconnection in the low corona are inferred from the data, including that the reconnection is collisionless and that the energy release rate is sufficient to power the fast wind. In this scenario, magnetic reconnection is continuous and the wind is driven by both the resulting plasma pressure and the radial Alfvénic flow bursts

Characteristics of the IBEX ribbon and their implications for a source region outside the heliopause

Sung Jun Noh

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The IBEX ribbon is a strong and banded energetic neutral atom (ENA) emission structure that was unexpectedly observed by IBEX at the outset of its mission in 2009. Although not unequivocal, a secondary ENA production mechanism is generally accepted as the source of the ribbon. It is also widely accepted that the source region of the ribbon is outside the heliopause and can extend up to several hundred AU, depending on the energy. Ribbon formation theories predict substantial differences in the detailed distribution of the ENA source region, but they mostly agree that the strongest emission is near the region where the interstellar magnetic field is perpendicular to the line-of-sight (B•R = 0). Since the observation of the ribbon is a result of radial integration through the ENA source region, sophisticated analysis of the ribbon shape is essential to understand not only the ribbon formation mechanism but also the configuration of the draped interstellar magnetic field. In this study, we investigate the mesoscopic and macroscopic shapes of the ribbon observed by IBEX-Hi and their energy and time dependence. Our analysis is twofold: First, we characterize the shape of the ribbon profile using statistical metrics. Second, we examine the global distribution of the entire ribbon structure and the location of the ribbon center in the sky. For all the measured parameters, we consider how they vary over the course of more than a full solar cycle. Analysis of the ribbon shape and structure is challenging due to the large statistical uncertainties in the observed ENA fluxes and the fact that the IBEX-Hi field of view has an angular resolution of $\sim 6.5^o$, which is a significant fraction of the ribbon width. This study makes use of a newly-developed 2D surface estimation technique for rendering ENA sky maps that is statistically rigorous and removes the blurring effect of the instrument's angular response. This allows us, for the first time, to reveal the true width of the ribbon. Furthermore, we employ a new method to separate the ribbon from the globally distributed ENA flux that uses a dynamically adjustable parametrization to capture more accurately the ribbon profile.

Observations of ion cyclotron waves and implications on a generation region in the inner heliosphere

Sung Jun Noh

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Ion cyclotron waves (ICW) are electromagnetic waves with left-handed polarization and a frequency below the proton gyrofrequency. ICWs are frequently observed in the solar wind and are known to contribute to the perpendicular heating of solar wind ions. Since the launch of the Parker Solar Probe (PSP), there have been several papers that report the observation of ion cyclotron waves in the young solar wind. Observational analysis of low-frequency kinetic scale waves in the solar wind is non-trivial due to the fact that we observe them in the spacecraft frame, but not in the solar wind rest frame. The relative motion between spacecraft and the solar wind bulk flow introduces Doppler shift effects; thus, the observed wave frequencies are different from the wave frequencies in the plasma reference frame. In the case where the wave propagates antiparallel to the solar wind flow but slower than the velocity of the solar wind rest frame, the polarization of the wave is reversed in the observer's frame. This can result in another wave branch near the ion's gyrofrequency with right-handed polarization that complicates the observational analysis. In this study, we investigate an ICW event with mixed polarization modes. The dispersion analysis gives compelling evidence that these modes are bi-directionally propagating waves generated locally in the solar wind. The ion cyclotron instability driven by an anisotropic ($T_{\perp}/T_{\parallel}>1$) proton distribution is a likely source of kinetic scale waves, in particular, these bi-directionally propagating ICW.

Heavy ion composition in the inner heliosphere from Solar Orbiter

Susan Lepri

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The Heavy Ion Sensor (HIS) onboard Solar Orbiter provides the first measurements of heavy ion composition in the inner heliosphere in the modern era. We present HIS measurements of heavy ion composition, examine several solar wind case studies, and compare statistical properties of the composition with heavy ion composition measurements made at L1. These high time resolution data have the potential to transform our understanding of the connections between the solar wind and its origin at the Sun.

The Heliospheric Current Sheet Observed by Parker Solar Probe

Szabo, Adam

Adam Szabo, Samantha Wallace, and Jaye Verniero [NASA GSFC]

The Heliospheric Current Sheet (HCS), separating the two magnetic polarities of the heliosphere, was encountered by Parker Solar Probe (PSP) closer to the Sun than any previous mission. The HCS near the Sun is much more variable and rich in internal structure than previous 1 AU observations revealed. The time and location of each observed HCS crossing by PSP have been compared to predictions based on the WSA Potential Field Source Surface (PFSS) model of the coronal magnetic field. Associated magnetic flux ropes, density enhancements, and electron heat flux dropouts indicate that the HCS is still significantly evolving as it is propagating outward.

Extended magnetic reconnection in kinetic plasma turbulence

Tak Chu Li

Tak Chu Li (Dartmouth College) , Yi-Hsin Liu (Dartmouth College), Yi Qi (LASP, University of Colorado), and Muni Zhou (Institute for Advanced Study, Princeton)

Magnetic reconnection and plasma turbulence are ubiquitous processes important for laboratory, space and astrophysical plasmas. Reconnection has been suggested to play an important role in the energetics and dynamics of turbulence by observations, simulations and theory for two decades. The fundamental properties of reconnection at kinetic scales, essential to understanding reconnection in turbulence, remain largely unknown at present. Here we present an application of the magnetic flux transport method that can identify reconnection in turbulence to a three-dimensional simulation. Contrary to ideas that reconnection in turbulence would be patchy and unpredictable, highly extended reconnection X-lines, on the same order of magnitude as the system size, form at kinetic scales. The extended X-lines develop through bi-directional reconnection spreading, and satisfy critical balance characteristic of plasma turbulence. This presents a picture of fundamentally extended reconnection in kinetic-scale turbulence.

Characterizing the source regions of the solar wind

Tamar Ervin

Tamar Ervin, UC Berkeley Space Sciences Lab

The novel in-situ measurements of magnetic and electric fields, particles, and ions from PSP and SO, when used in parallel with remote sensing measurements, allow for a deeper understanding of the near-Sun environment. Using a combination of data from Parker Solar Probe (PSP), Solar Orbiter (SO), and magnetograms from the Solar Dynamics Observatory Helioseismic and Magnetic Imager (SDO/HMI) and Global Oscillation Network Group (GONG) we seek to identify and characterize the solar wind emerging from different coronal source regions. We use PFSS and MHD modeling to determine the origins and evolution of the solar wind measured during radial conjunctions between PSP, SO and other remote sensing instruments. Specifically we look at enhancements in low first ionization potential (FIP) and particle density as a function of coronal source origin to characterize the difference in properties between wind emerging from coronal holes, coronal hole boundaries, and active regions.

Investigation of Interplanetary Coronal Mass Ejection Features: First Insights from PSP Observations

Tarik Mohammad Salman; Salman

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The historic Parker Solar Probe (PSP) mission has brought forward unprecedented observations and measurements of the young solar wind. With its unique orbit concept, PSP has been able to measure interplanetary coronal mass ejections (ICMEs) at uncharted heliocentric distances and in the process, reveal the nature of early propagation of ICMEs. In this project, we provide the first insights of more than 40 ICMEs sampled by PSP since its launch till 2022. Initial statistics confirm previously hypothesized concepts and reveal new discoveries of ICME evolution in the inner heliosphere. It is observed that the post-ICME solar wind is more perturbed at heliocentric distances farther out from the Sun. On a similar note, it is seen that magnetic configurations of ICMEs are more complex in general farther out from the Sun, whereas the magnetic configurations closer to the Sun are more flux-rope like. Multi-linear robust regression hints at a slower rate of magnetic field decrease with heliocentric distance. In a similar approach, linear least-squares regression only shows a modest correlation between ICME duration and heliocentric distance.

Quantifying the Uncertainty in the Wave Telescope Technique

Theodore Broeren

Theodore Broeren, University of Arizona

The upcoming NASA mission HelioSwarm will use nine spacecraft to make the first simultaneous multipoint measurements of solar wind space plasmas spanning multiple scales. Using the wave telescope technique, HelioSwarm's measurements will allow for both the calculation of the power in wavevector and frequency space and the characterization of the associated dispersion relations of waves present in the plasma at MHD and ion-kinetic scales. This technique has been applied to the four-spacecraft Cluster and Magnetospheric Multiscale missions, and its effectiveness has previously been characterized in a handful of case studies. We expand this uncertainty quantification analysis to arbitrary configurations of four through nine spacecraft for three-dimensional plane waves. We use Bayesian inference to learn equations that approximate the error in reconstructing the wavevector as a function of relative wavevector magnitude, spacecraft configuration shape, and number of spacecraft. Finally, we demonstrate the application of these equations to data drawn from example nine-spacecraft HelioSwarm configurations to both improve the accuracy of the technique, as well as expand the magnitudes of wavevectors that can be characterized.

Longitudinal dependence of Solar Energetic Particle onset times due to solar wind turbulence

Timo Laitinen

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Solar Energetic Particles (SEPs) are released into the solar wind during solar eruptions, and are often observed at a wide range of heliolongitudes by spacecraft in the interplanetary space. To access such locations, the SEPs must have either been accelerated at a wide particle source, or propagated across the mean Parker spiral magnetic field. To analyse how acceleration and propagation contribute to the spatial extent of SEP events, it is necessary to model SEP propagation within the turbulent solar wind magnetic field. We develop a novel analytic model of solar wind magnetic field turbulence and investigate how turbulence produces SEP transport across the mean field by means of test particle simulations. The model is novel because both the wave vectors and the fluctuating magnetic field vector of the dominant, transverse 2D turbulence component waves are normal to a background field with full Parker spiral geometry. We carry out test particle simulations of 100-MeV protons in this configuration. We demonstrate that turbulent meandering field lines allow 100 MeV protons to reach a 60-degree heliolongitudinal range within an hour of their injection at the Sun. The particles subsequently spread diffusively further across the mean Parker spiral. The SEPs are delayed in their arrival to 1 au from the Sun, with apparent path lengths of 1.5-1.8 au within 30 degrees of the well-connected longitude, 20-30% longer than the length of the meandering field lines, and 30-50% longer than the Parker spiral. At larger heliolongitudinal separation from the well-connected field lines, the apparent path lengths increase further, as the SEPs arrive to those longitudes diffusively. The global intensity peak of the spatial distribution is reached 15 degrees west from the well-connected longitude, 1.5 hours after injection at the Sun. We discuss implications of our results on understanding multi-spacecraft SEP observations.

The radial evolution and importance of isolated ion-scale structures in the solar wind

Timothy Horbury

Tim Horbury, Lorenzo Matteini and Ronan Laker (Imperial College London), Stuart D Bale and Davin Larson (UCBerkeley), Yuri Khotyaintsev (IRFU), Milan Maksimovic (OBSPM), Andrey Federov and Philippe Louarn (IRAP), Ben Chandran (UNH), Marco Velli (UCLA)

Ion-scale isolated phenomena such as Alfvenic vortices and solitons have long been postulated in the solar wind and indeed individual structures on these scales have repeatedly been observed. Here we report the observation of a particular class of such structures: they have a clear bipolar magnetic signature as well as a magnitude enhancement and an accompanying density decrease. Their small scale makes ion measurements challenging but they appear to have a velocity signature consistent with that in the magnetic field. Most significantly, using Solar Orbiter and Parker Solar Probe measurements, we have identified these in the same solar wind stream at three distances, including for the first time near perihelion at 14 solar radii. We show that their relative amplitude increases with distance, but their occurrence rate decreases. We discuss the nature of these structures, possible generation mechanisms and whether they could play a role in driving the MHD-scale turbulent cascade in the solar wind.

Connecting Signatures of Ion-Cyclotron Resonance to Solar Wind Heating

Trevor Bowen

Trevor A. Bowen, Stuart D. Bale, Benjamin D.G. Chandran, Alexandros Chasapis, Christopher H.K. Chen, Thierry Dudok de Wit, Alfred Mallet, M.D. McManus, Romain Meyrand, and Jonathan Squire

Wave-particle interactions are known to play a role in shaping kinetic plasma distribution functions in turbulent astrophysical environments. While evidence suggests that ion cyclotron resonant interactions may contribute to plasma heating in the solar wind, a direct coupling between magnetized turbulence and ion cycloton waves has yet to be demonstrated. We present evidence for the mediation of turbulent dissipation in the solar wind by ion-cyclotron waves. Our results show that ion-cyclotron waves interact strongly with magnetized turbulence and serve as a major pathway for turbulent dissipation, with significant consequences on the nature of sub-ion scale turbulence.The cross helicity correlates strongly with the presence of ion-scale waves, demonstrating that dissipation of collisionless plasma turbulence is not a universal processes, but that the pathways to heating and dissipation at small scales are controlled by the properties of the large-scale turbulent fluctuations. These observations are shown to persist in extended solar wind streams, suggesting that they are key in residual heating of the solar wind as it expands from the corona.

Occurrence and evolution of switchbacks between 13.3 to 70 solar radii: PSP Observations

Vamsee Krishna Jagarlamudi

Vamsee Krishna Jagarlamudi, Johns Hopkins University Applied Physics Laboratory.

Since its launch, the Parker Solar Probe (PSP) mission revealed the presence of numerous fascinating phenomena occurring closer to the Sun, such as the presence of ubiquitous switchbacks (SBs). The SBs are large magnetic field deflections of the local magnetic field relative to a background field. We investigated the statistical properties of the SBs during the first ten encounters between 13.3 and 70 Solar Radii using data from the SWEAP and FIELDS suites onboard PSP . We find that the occurrence rate of small deflections with respect to the Parker spiral decreases with radial distance (R). In contrast, the occurrence rate of the large deflections (SBs) increases with R, as does the occurrence rate of SB patches. We also find that the occurrence of SBs correlates with the bulk velocity of the solar wind, i.e., the higher the solar wind velocity, the higher the SB occurrence. For slow wind, the SB occurrence rate shows a constantly increasing trend between 13.3 and 70 solar radii. However, for fast wind, the occurrence rate saturates beyond 35 solar radii. Sub-Alfvenic regions encountered during encounters 8-10 have not shown significant SBs. This analysis of the PSP data hints that some of the SBs are decaying and some are being created in-situ.

Energy injection and cascade in Alfvénic streams with WIND data at 1AU.

Verdini Andrea

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The radial evolution of magnetic field spectra in the solar wind suggests that energy is supplied to the turbulent cascade by the slow erosion of the energy contained at large scales where the spectrum shows a 1/f power-law dependence. In this framework, the energy injection results from the sweeping toward smaller frequencies of the break between the 1/f and Kolmogorov part of the spectrum at smaller scales. This injection rate was recently found to be comparable to the heating rate required to maintain the non-adiabatic profile of proton temperature and suggests a passive or minor role of the large scales in feeding the cascade. We analyse solar wind turbulence in intervals of Alfvénic streams in WIND data at 1AU. In particular we use the Elsasser variables, z+ =u+b and z-=u-b (Alfvénicity being equivalent to z+ >> z-) to compute the relevant terms in the Politano-Pouquet relation. Using this relation we investigate the energy budget in the 1/f range, well above the average de-correlation time of fluctuations (being about 1 hour). We show that at these scales the energy damping is dominated by expansion but, at the same time, an energy cascade develops and is comparable to or larger than the energy supply from the sweeping of the large-scale frequency break Our findings imply a strong anisotropy and/or a development of the cascade in the 1/f range that occurs close to the Sun and is subject to a slow relaxation with distance. A key role is played by the magnetic energy excess that is forced by the radial expansion, which, by sustaining the subdominant z- reduces its radial decay thus maintaining a turbulent activity at large scales.

The Fe/Mg abundance in the solar wind

Verena Heidrich-Meisner

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The elemental and charge state composition of the solar wind is determined in the lower levels of the solar atmosphere, the chromosphere or the lower corona. Elements with a low first-ionization potential (FIP) appear enhanced in the solar wind compared to the respective photospheric composition. Although Mg and Fe have a similar FIP, there are systematic differences in their long-term and short-term abundances. In addition, both can be affected by instrumental contamination from neighbouring ions, for example O6+ in the case of Mg or Ca ions in the case of Fe. Here, we investigate the relative abundance of Fe and Mg with the help of the Charge Time-Of-Flight instrument (CTOF) as part of the Charge, Element, and Isotope Analysis System (CELIAS) onboard the Solar and Heliospheric Observatory (SOHO) in comparison to the abundances measured by the Solar Wind Ion Spectrometer (SWICS) onboard the Advanced Compostion Explorer (ACE). A recent improvement of the CTOF instrument function (Janitzek 2021) takes the asymmetrical ion peak-shapes into account which are an inherent property of all composition instruments of this type (including the Heavy Ion Sensor (HIS) onboard Solar Orbiter). This improvement significantly reduces a potential cross-contamination of neighbouring ions. Thus, although CTOF was fully operationally only for a few months in 1996, the CTOF data set is very well suited to provide highly accurate elemental composition measurements. The CTOF abundances imply that Mg is typically more abundant than Fe in the solar wind.

Solar sources and expansion properties of Alfvénic slow wind streams: Potential field source surface and MHD study

Victor Réville

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Alfvénic slow wind is a strange beast. First observed by Helios, it has only been confirmed within the last decade, and it has challenged our usual understanding and classification of solar wind streams. With a high absolute cross-helicity, indicating an imbalanced proportion of outward Alfvén waves, it resembles the coronal hole fast wind. It could thus find its origin in the core of very rapidly expanding small coronal holes that are known to give birth to slower and denser wind streams. Close to the Sun, Parker Solar Probe and Solar Orbiter have found many examples of such streams that seem less likely to survive up to 1 AU. In this work, we focus on a series of slow Alfvénic wind streams followed by a fast wind stream observed by Solar Orbiter between March and April 2022. We study the sources of the solar wind through PFSS extrapolations of the photospheric magnetic field observed from different sources. We find that a number of equatorial coronal holes with rapid expansion could be the source point of magnetic field lines connected to the Solar Orbiter. However, for the last part of the interval, our extrapolations appear to show slow and fast wind sharing similar expansion ranges, with a possible origin for the slow wind stream nearby an active region. We run a full MHD model, with an Alfvén wave turbulence phenomenology, which provide self-consistently the solar wind speed, temperature and density, to complete the analysis.

On the Role of Solar Winds in the Origin of the CMEs Phenomena

Virendra Verma

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In the present paper, to understand the role of solar winds in the origin of the coronal mass ejections (CMEs) Phenomena we have studied the relationship between the Extreme Ultraviolet Imaging Telescope (EIT) waves phenomena with solar flares, coronal holes, solar winds, and CMEs events. The EIT/ SOHO instrument recorded 176 EIT events during the above period (March 25, 1997-June 17, 1998) and the EIT waves list was published by Thompson & Myers (2009). After temporal matching of EIT wave events with CMEs phenomena, we find that corresponding to 58 EIT wave events, no CMEs events were recorded and thus we excluded 58 EIT wave events from the present study. Out of 176 EIT wave events, only 106 are accompanied by CMEs phenomena. The correlation study of the speed of EIT wave events and CMEs events of 106 events shows poor correlation r= 0.32, indicating that the EIT waves and CMEs events do not have a common mechanism of origin, and also indicate that some other factor is working in the formation of CMEs from EIT waves. Further, We have also matched the spatial matching EIT wave sources as indicated by Thomson & Myers (2009) with CHs and flares and found that CMEs appear to be associated with EIT wave phenomena and CHs. Earlier Verma & Pande (1989), and Verma (1998) indicated that the CMEs may have been produced by some mechanism, in which the mass ejected by solar flares or active prominences, gets connected with the open magnetic lines of CHs (source of high-speed solar wind streams) and moves along them to appear as CMEs. Most recently Verma & Mittal (2019) proposed a methodology to understand the origin of CMEs through magnetic reconnection of CHs open magnetic field and solar flares. In the present paper, we proposed a scenario/ 2-dimensional model, in which the origin of CMEs through reconnection of EIT waves and solar winds coming from the CHs and also found that the calculated CMEs velocity after reconnection of EIT waves and solar winds coming from the CHs are in very close to the observed CMEs linear velocity. We also calculated the value of the correlation coefficient between the observed linear velocity of CME events and the calculated value of CMEs velocity after reconnection and found the value as r=0.884. The value of correlation as r=0.884 is excellent and supports the proposed methodology. Finally, we have also discussed the role of solar wind phenomena in the formation CMEs phenomena with other solar phenomena, in the latest scenario of solar heliophysics phenomena. References: Thompson, B. J. & Myers, D. C. (2009) APJS, 183, 225. Verma, V. K. & Pande, M. C. (1989) Proc. IAU Colloq. 104 Solar and Stellar Flares (Poster Papers), Stanford University, Stanford, USA, p.239. Verma, V. K.(1998) Journal of Geophysical Indian Union, 2, 65. Verma, V. K. & Mittal, N.(2019) Astronomy Letters, 45, 164-176.

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In the present paper, to understand the role of solar winds in the origin of the coronal mass ejections (CMEs) Phenomena we have studied the relationship between the Extreme Ultraviolet Imaging Telescope (EIT) waves phenomena with solar flares, coronal holes, solar winds, and CMEs events. The EIT/ SOHO instrument recorded 176 EIT events during the above period (March 25, 1997-June 17, 1998) and the EIT waves list was published by Thompson & Myers (2009). After temporal matching of EIT wave events with CMEs phenomena, we find that corresponding to 58 EIT wave events, no CMEs events were recorded and thus we excluded 58 EIT wave events from the present study. Out of 176 EIT wave events, only 106 are accompanied by CMEs phenomena. The correlation study of the speed of EIT wave events and CMEs events of 106 events shows poor correlation r= 0.32, indicating that the EIT waves and CMEs events do not have a common mechanism of origin, and also indicate that some other factor is working in the formation of CMEs from EIT waves. Further, We have also matched the spatial matching EIT wave sources as indicated by Thomson & Myers (2009) with CHs and flares and found that CMEs appear to be associated with EIT wave phenomena and CHs. Earlier Verma & Pande (1989), and Verma (1998) indicated that the CMEs may have been produced by some mechanism, in which the mass ejected by solar flares or active prominences, gets connected with the open magnetic lines of CHs (source of high-speed solar wind streams) and moves along them to appear as CMEs. Most recently Verma & Mittal (2019) proposed a methodology to understand the origin of CMEs through magnetic reconnection of CHs open magnetic field and solar flares. In the present paper, we proposed a scenario/ 2-dimensional model, in which the origin of CMEs through reconnection of EIT waves and solar winds coming from the CHs and also found that the calculated CMEs velocity after reconnection of EIT waves and solar winds coming from the CHs are in very close to the observed CMEs linear velocity. We also calculated the value of the correlation coefficient between the observed linear velocity of CME events and the calculated value of CMEs velocity after reconnection and found the value as r=0.884. The value of correlation as r=0.884 is excellent and supports the proposed methodology. Finally, we have also discussed the role of solar wind phenomena in the formation CMEs phenomena with other solar phenomena, in the latest scenario of solar heliophysics phenomena. References: Thompson, B. J. & Myers, D. C. (2009) APJS, 183, 225. Verma, V. K. & Pande, M. C. (1989) Proc. IAU Colloq. 104 Solar and Stellar Flares (Poster Papers), Stanford University, Stanford, USA, p.239. Verma, V. K.(1998) Journal of Geophysical Indian Union, 2, 65. Verma, V. K. & Mittal, N.(2019) Astronomy Letters, 45, 164-176.

Solar wind signatures in the chromosphere

Vishal Upendran

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Coronal holes (CHs) are regions with reduced intensity and enhanced blueshifts when compared to Quiet Sun (QS) regions at coronal temperatures, with differences in transition region (TR) seen only for regions with similar magnetic flux density (—B—). In this work, we study the chromospheric Mg II h&k, the C II 1334 Å and TR Si IV line in CHs and QS as a function of —B—. We find the intensities and velocities of all lines increase with —B—. For both the chromospheric lines, we find reduced intensity, excess blueshifts and excess redshifts in CHs over QS for regions with similar —B—. In the Si IV line, CHs show excess blueshifts, but reduced intensity and redshift. On cross-correlating chromospheric and TR velocities, we find (a). Upflows, downflows in all the lines are tightly correlated. (b). Chromospheric upflows are not correlated with TR downflows. (c). Chromospheric downflows are correlated with TR upflows. The TR upflows (downflows) are preferentially larger in CHs (QS) for similar chromospheric flows. These results may be explained through impulsive heating in a stratified atmosphere causing larger upflow (downflow) acceleration (deceleration) in CHs (QS), with the impulsive event giving rise to bidirectional flows. The patterns of observed flows and intensities, may be explained by invoking interchange (closed loop) reconnection in CHs (QS). These results provide evidence on the formation of solar wind in the chromosphere and further hints towards the unified heating scenario of the solar corona in the QS and CHs.

Solar wind forecasting and source region inference using interpretable deep learning

Vishal Upendran

Vishal Upendran (IUCAA Pune, LMSAL, BAERI), Mark Cheung (CSIRO), Shravan Hanasoge (TIFR), Ganapathy Krishnamurthi (IIT Madras)

Emanating from the base of the Sun's corona, the solar wind fills the interplanetary medium with a magnetized stream of charged particles. Accurately predicting the solar wind through measurements of the spatiotemporally evolving conditions in the solar atmosphere is important but remains an unsolved problem in heliophysics and space weather research. In this work, develop a deep learning model to forecast solar wind speed measured at L1, using extreme ultraviolet images of the solar corona from space-based observations. We evaluate our model against autoregressive models and find that our model outperforms the benchmark models, obtaining a best fit correlation of 0.55 $\pm$ 0.03 with the observed data. Upon visualization and investigation of how the model uses data to make predictions, we find higher importance at the coronal holes for fast wind prediction ($\approx$3 to 4 days prior to prediction), and at the active regions for slow wind prediction. These trends bear an uncanny similarity to the influence of potetntial source regions on the fast and slow wind, and suggests that our model was able to learn some of the salient associations between coronal and solar wind structure without built-in physics knowledge. Such an approach may help us discover hitherto unknown relationships in heliophysics data sets.

Acceleration of the solar wind

Viviane Pierrard

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The physical mechanisms responsible for the heating of the corona and the acceleration of the solar wind remain a hot topic of research. Exospheric models provide a very simplified first approximation: considering only the effects of the external force, they show that the electric potential can accelerate the wind to supersonic velocities, even considering simple Maxwellian distributions for the particles at the exobase. Moreover, the possible presence of suprathermal particles in the corona has important effects on the plasma temperature increase, and an enhanced population of energetic electrons accelerates the solar wind to larger bulk velocities, especially in case of a low exobase. This gives a natural explanation for the fast wind originating from coronal holes, where the density is lower than in the other coronal regions. Differential heating and acceleration of minor ions can also be predicted using the exospheric approach, in agreement with ion observations in the solar wind. Effects of Coulomb collisions and other waves like whistlers will also be discussed, since plasma turbulence and instabilities help to understand the characteristics of the observed distributions, and especially their temperature anisotropies and heat fluxes. Links will be made with other approaches, like the first predictive thermally-driven solar wind model of Parker predicting high velocities even before any measurement could be made in space. Other solar wind acceleration processes have been proposed, involving waves and magnetic reconnection and we will see how these effects can be included using different conditions in the models. The observations of Parker Solar Probe (PSP) provide the unique opportunity to study the radial evolution of the solar wind in the inner heliosphere and to compare with predictions from different models. A deficit in the sunward direction is observed in the electron distributions at low radial distances, confirming the exospheric feature. PSP provides also information on the presence of suprathermal electrons at very low distance and the formation of the strahl and the halo. Typical distributions observed by PSP will be illustrated and compared to model predictions.

Modeling galactic cosmic rays in the global heliosphere and VLISM

Vladimir Florinski

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The Voyager space probes provided us with a global perspective on galactic cosmic ray transport through the heliosphere at low to moderate heliographic latitudes, as well as their behavior at the boundary with the very local interstellar medium (VLISM). There remain, however, multiple interesting region the Voyagers have not visited, including high latitudes and the distant flanks of the heliopause where long-term trapping of charged particles is though to take place. We attempt to fill the gaps in our understanding of the distant heliosphere using computer simulations. The Space Plasma and Energetic Charged particle TRansport on Unstructured Meshes (SPECTRUM) code is a versatile software platform to perform tracing of particle trajectories using multiple physics models and internal or externally provided MHD background data. We apply the model to the problem of galactic cosmic ray transport in the outer heliosphere and the surrounding very local interstellar medium (VLISM) using the MHD background provided on a adaptive block mesh from the Space Weather Modeling Framework (SWMF). We compare the guiding center and nearly isotropic (Parker) physics models and elucidate the role of perpendicular diffusion in cosmic-ray penetration through the heliospheric boundary.

Comparing Parker Solar Probe solar wind measurements with an empirical solar-wind model and WISPR remote sensing observations

Volker Bothmer

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In a previous study before the Parker Solar Probe (PSP) launch, we used near-Earth and Helios solar wind measurements to extrapolate the plasma and magnetic field values down to distances below 10 solar radii. The calculations take into account the properties of fast and slow wind streams over several decades during different phases of the solar cycle. Here, we compare our empirical solar wind model for the inner heliosphere with measurements from PSP taken during the first 13 orbits. We find a good agreement between the estimated magnetic field strength in the solar wind and less good consensus with the solar wind speeds, densities and temperatures, especially in the sub-alfvénic regimes below about 20 solar radii. The magnetic field strength follows the predictions very well, increasing with decreasing distance to the Sun slightly faster than r exp(-1.66). We also find that the solar wind speed is organized as slow and fast streams rather than showing a general radial dependence. Several coronal mass ejection (CME) events and PSP heliospheric current sheet (HCS) crossings are compared with coronal brightness variations observed in the WISPR-cameras. We find that each HCS crossing in the in-situ data is identifiable in WISPR images during the hours preceding and following the actual crossings, i.e., while the coronal streamers move towards the top and bottom of the field of view. Moreover, the large, fast CME that occurred on September 5, 2023 (Encounter 13) with its associated interplanetary shock can be identified by the overall increase of the median brightness of the images as the event traverses de field of view of the WISPR telescopes, without the need of a background subtraction.

Deciphering Type III Solar Bursts: Scattering Processes and Radio Wave Propagation

Vratislav Krupar

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Type III solar bursts result from impulsive electron acceleration associated with solar flares. They occur when suprathermal electron beams interact with ambient plasma, producing radio emissions at the plasma frequency or its second harmonic. Recent findings propose that the characteristic exponential decay profile of type III bursts could be attributed exclusively to scattering between the source and the observer. In this study, we present a rare occurrence of 2 type III bursts from September 2021 observed by Solar Orbiter, Parker Solar Probe, and STEREO-A when the spacecraft were nearly radially aligned and orbiting at distances of approximately 0.60 au, 0.76 au, and 0.96 au. Additionally, we report 12 other instances from November 2022 when Solar Orbiter and STEREO-A were in radial alignment once more. We analyze the characteristic exponential decay profile for common frequency channels and find consistency among the three spacecraft. This observation suggests that if scattering is responsible for long exponential decays, it primarily occurs near sources, with radio waves propagating along straight lines thereafter. Lastly, we compare radio data between Wind and STEREO-A for recent events as STEREO-A approaches Earth again.

Solar Observation Link: Space and Terrestrial Integrated CubeSat Experiment (SOLSTICE)

Vratislav Krupar

Vratislav Krupar, UMBC/GPHI & NASA/GSFC

The Solar Observation Link: Space and Terrestrial Integrated CubeSat Experiment (SOLSTICE) project aims to revolutionize solar radio observations by synergistically harnessing space and ground-based technologies. Utilizing a global network of CubeSat fleets and strategically positioned terrestrial radio stations across five continents, SOLSTICE seeks to enable continuous, round-the-clock monitoring of solar radio emissions in the 10 MHz to 1 GHz frequency range.

Located in Svalbard (Europe), McMurdo (Antarctica), Perth (Australia), Curacao (North America), and Kenya (Africa), these terrestrial stations promise constant coverage and a diverse geographical spread. This setup, in concert with the CubeSats, offers an unparalleled opportunity to study type II and III solar radio bursts, thereby significantly enhancing our understanding of solar activities and their interplay with Earth's space environment.

Beyond its global solar monitoring capability, SOLSTICE also endeavors to create a long baseline for interferometry, enabled by the collaborative work of the CubeSats and terrestrial stations. This innovative approach aims to yield high-resolution data, offering deeper insights into solar phenomena.

While the primary focus of SOLSTICE is solar radio observation, the integrated system is also poised to contribute valuable data for auxiliary planetary astronomy during nighttime observations. As such, SOLSTICE not only represents an ambitious step towards future solar research but also a paradigm shift in leveraging CubeSat and ground-based technologies for broader astronomical studies.

Origin of solar wind 1/f noise: theory and observational constraints

William Matthaeus

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In this paper, I review the observations of 1/f noise in the heliosphere and discuss the theoretical background of generic 1/f noise models as they may be relevant to the solar wind. The planning for Parker Solar Probe has emphasized that understanding the appearance of 1/f "noise" in the solar wind may inform central problems in heliospheric physics such as the solar dynamo, coronal heating, the origin of the solar wind, or the nature of low-frequency interplanetary turbulence [1]. It is of significance that 1/f noise can occur in a great variety of physical systems ranging from Johnson noise in vacuum tubes and semiconductors, fluctuations in heart rates, brain waves sandpiles [2], and solids [3], the spectrum of music and economic indicators, and many other examples. An appealing generic mechanism that can explain many of these phenomena is the superposition principle [4,5] in which a composite signal is formed from a collection of individual signals that are characterized by scale-invariant correlation times. In the solar wind context, it was proposed [4] that such a superposition might occur in the corona due to scale-invariant reconnections, thus explaining the observed 1/f signal in the interplanetary magnetic field that spans the approximate frequency range 2 x 10ˆ-6 Hz to several times 10ˆ-4 Hz. at 1 au. Subsequent observational analyses showed that signals in the photosphere and the corona [5,6] exhibit 1/f signatures at frequency ranges compatible with the 1 au observations. This suggests a possible origin in the dynamo itself and indeed this possibility is supported by both dynamo experiments and simulations [7]. Recently there has been interest in employing Parker Solar Probe observations to address the question of whether interplanetary 1/f noise is generated by local dynamics [as proposed e.g., in 8] or if it originates at lower altitudes in the corona or in the solar dynamo. Some examples are found in [9,10]. Here we present theoretical arguments that interplanetary 1/f noise extending to low frequencies is not explained by the recent observations, thus casting doubt on the utility of the proposed mechanisms for local generation.

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Quantifying the Effects of Electron Shot Noise on a Current Biased Antenna

Winry Ember

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Using PSP's FIELDS Radio Frequency Spectrometer (RFS) data and quasi-thermal noise spectroscopy (QTN), we can determine the temperature and density of electrons in heliospheric plasma. The FIELDS antennas on PSP are current-biased to improve the antenna response to low-frequency electric fields. The applied current bias varies slowly with solar distance and is rapidly varied during periodic calibration activities known as bias sweeps. PSP, joined recently by Solar Orbiter, is the first spacecraft to conduct QTN on current-biased antennas, so this is a unique problem not completely described by current antenna response models. Electron shot noise is observed when electrons impact a spacecraft antenna. Adding a bias current to the antenna generates electrons which change the antenna voltage and impact the antenna as they leave. The high-frequency signature of these electrons impacting the spacecraft antenna generates shot-noise in RFS data. The presence of shot-noise makes QTN analysis more difficult by obscuring the plasma line and plasma frequency peak. To reduce the effects of shot noise, QTN is best conducted on an antenna with zero bias current. We present PSP/FIELDS RFS data during antenna bias sweeps throughout Solar Encounter 7, comparing the ideal zero bias with nominal bias and quantifying the effect of this bias current on the electric field shot noise spectrum. Observing changes in electron shot noise given variation in current can improve determination of electron parameters from QTN.

Effect of the heliospheric current sheet on the propagation of solar energetic particles

Wu

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The question about whether or not the heliospheric current sheet (HCS) forms a barrier to the propagation of solar energetic particles (SEPs) is still not settled. Here we study three SEP events on July 12, 2012 (JUL12), April 3, 2010 (APR03), and March 15, 2013 (MAR15) in detail to address this issue. The three SEP events are associated with coronal mass ejections (CMEs) and share a number of similar properties: All CMEs (1) were of halo type and were originated near the Sun-Earth line, (2) were fast ($>\sim$1000 km/s initially) and had similar Sun-to-Earth transit time, (3) were accompanied with shocks at 1 AU, and (4) induced large geomagnetic storms. However, the onset time (relative to the CME/flare onset) and intensity profile of the SEP ($\sim$3–41 MeV/nuc. He) at the L1 orbit were quite different. Using magnetohydrodynamic simulations in conjunction with in situ measurements of the interplanetary magnetic field at L1, it is shown that delays of SEP flux for the studied events are due to the presence of the HCS between the CME source and the observer. It is also shown that elevated SEP fluxes can occur after part of the CME expands into the same magnetic sector as the observer or the observer moved across the HCS. While we do not show explicitly the effect, this study suggests that the HCS may limit the propagation of energetic particles, at least in the energy range studied here, in the heliosphere.

Solar Wind Synoptic Velocity Map at Heliocentric Distance between 20 and 60 Rs Based on White-Light Imaging of Solar Wind Transients from Dual Perspectives in a Solar Rotation Cycle

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Solar wind transients, especially small-scale transients (STs), are the typical solar wind tracers in imaging observations. Previously we developed a correlation-aided reconstruction method to recognize and locate solar wind transients[1] observed by the Heliospheric Imager-1 (HI1) on board the Solar Terrestrial Relations Observatory, and then developed a technique to infer the radial velocity distribution in each solar wind transient[2]. Considering that the common field of view of HI1 may cover the full longitudes through the solar rotation, we further apply these methods to STs in a complete Carrington rotation to reconstruct a synoptic map of the solar wind radial velocity. Our test suggests that the reconstructed synoptic map is in agreement with the preset synthetic STs in latitude, longitude and radial velocity. Then Carrington rotation 2095 between 2010 March 26 and April 22 is selected to demonstrate the new technique. The derived synoptic map shows that the solar wind radial velocity corresponding to STs is in the range of 250-550 km/s between 20 and 60 Rs in the low-to-middle latitudes. We extrapolate the in-situ observation near 1 au to 20 Rs and find that it matches the synoptic velocity map well. The magnetohydrodynamic simulations of solar wind radial velocity are consistent with the synoptic map near the HCS but usually overestimate the velocity values for STs far away from the HCS. We apply this technique to more solar rotations with Carrington rotation number from 2081 to 2104 when solar activity rose from its minimum to ascending phase. The statistical results suggest two kinds of sources of the solar wind with STs embedded in. The major kind of sources stay around the HCS with radial velocity at 60 Rs of about 300 km/s, while the minor kind of sources normally leave far away from the HCS in angular space with radial velocity at 60 Rs of more than 400 km/s. It supports the theory of two potential slow solar wind origins: the solar coronal streamers and the boundaries of weak coronal holes. We expect that this technique will be a powerful tool to learn about and monitor the solar wind in the inner heliosphere where the number of human probes is limited. [1] Li, X., Wang, Y., Liu, R., Shen, C., Zhang, Q., Lyu, S., . . . Chi, Y. (2020). Reconstructing Solar Wind Inhomogeneous Structures from Stereoscopic Observations in White Light: Solar Wind transients in 3-D. Journal of Geophysical Research: Space Physics, 125(7). [2] Li, X., Wang, Y., Guo, J., Liu, R., and Zhuang, B. (2021). Radial Velocity Map of Solar Wind Transients in the Field of View of STEREO/HI1 on 3 and 4 April 2010. Astronomy and Astrophysics, 649, A58.

Effect of intermittent structures on the spectral index of the magnetic field in the slow solar wind

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Intermittent structures are ubiquitous in the solar wind turbulence, and they can significantly affect the power spectral index (which reflects the cascading process of the turbulence) of magnetic field fluctuations. However, to date, an analytical relationship between the intermittency level and the magnetic spectral index has not been shown. Here, we present the continuous variation in the magnetic spectral index in the inertial range as a function of the intermittency level. Using the measurements from the Wind spacecraft, we find 42272 intervals with different levels of intermittency and with a duration of 5–6 min from 46 slow-wind streams between 2005 and 2013. Among them, each of the intermittent intervals is composed of one dominant intermittent structure and background turbulent fluctuations. For each interval, a magnetic spectral index αB is determined for the Fourier spectrum of the magnetic field fluctuations in the inertial range between 0.01 and 0.3 Hz. A parameter Imax, which corresponds to the maximum of the trace of the partial variance increments of the intermittent structure, is introduced as an indicator of the intermittency level. Our statistical result shows that, as Imax increases from 0 to 20, the magnetic spectrum becomes gradually steeper and the magnetic spectral index αB decreases from -1.63 to -2.01. Accordingly, for the first time, an empirical relation is established between αB and Imax: αB = 0.4exp(-Imax/5) − 2.02. The result will help us to uncover more details about the contributions of the intermittent structures to the magnetic power spectra and, furthermore, about the physical nature of the energy cascade taking place in the solar wind. It will also help to improve turbulence theories that contain intermittent structures.

ULF waves upstream of interplanetary shocks

Xochitl Blanco-Cano

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Interplanetary (IP) shocks can be driven in the solar wind by fast coronal mass ejections and by the interaction of fast solar wind with slow streams of plasma. These shocks can be preceded by extended waves and suprathermal ion foreshocks. Shocks' characteristics as well as the level of wave activity near them change as they propagate through the heliosphere and this can impact particle acceleration, and modify the solar wind. In this work, we study IP shock evolution and the wave modes upstream of them using a multi-spacecraft approach with data of Solar Orbiter, STEREO, Parker Solar Probe and Wind. We find that upstream regions can be permeated by whistler waves (f$\sim$1 Hz) and/or ultra low frequency (ULF) right-handed waves (f$\sim 10^{-2} - 10^{-1}$ Hz). While whistlers appear to be generated at the shock, the origin of ULF waves is most probably associated with local kinetic ion instabilities. In contrast with planetary bow shocks, most IP shocks have a small magnetosonic Mach number (<4) and most of the upstream waves studied here are mainly transverse and rarely steepening occurs. We find that in some cases the foreshocks of IP shocks can encounter ion cyclotron waves intrinsic to the solar wind.

Unlocking the Secrets of the Sun: Early Discoveries and Future Prospects of the Solar Orbiter Mission

Yannis Zouganelis

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The ESA/NASA Solar Orbiter mission was launched in 2020 and commenced its nominal science operations in 2022. So far, it has successfully completed three close encounters with the Sun, with the most recent one taking place in April 2023 at a distance of 0.29 au. The mission has yielded an abundance of unique data combining high-resolution imaging and spectroscopy of the Sun with detailed in-situ measurements of the surrounding heliosphere. Solar Orbiter enables us to study the Sun's corona in an unprecedented level of detail, allowing us to determine the link between observed solar wind streams and their source regions on the Sun. Over the course of the ten-year mission, the highly elliptical orbit will progressively become more inclined to the ecliptic plane. Thanks to this new perspective, Solar Orbiter will deliver images and comprehensive data of the unexplored Sun's polar regions and its far side. This presentation will offer an overview of the mission and summarise the science results obtained during the first three years in orbit. Furthermore, it will provide insight into future science opportunities, particularly in collaboration with other space- and ground-based observatories.

Simulations of type II solar radio bursts

Yihong Wu

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Type II radio bursts are produced upstream of shocks: electrons accelerated at shocks and radiating in their vicinities. Here we present a simulation of a type II radio burst. A first implementation of the model is carried out for the 2014 September 1 event. We first compute electron acceleration at a CME-driven shock propagating along a large coronal magnetic loop. Accelerated electrons form beams in velocity space. Langmuir waves are generated via wave particle interactions due to the electron beam instability. Langmuir waves produce electromagnetic emission by various linear and nonlinear processes, leading to the type II burst. We compare the observed dynamic spectrum against our simulated dynamic spectrum.

Coronal Holes, Footpoint Reconnection, and the Origin of the Slow (and Fast) Solar Wind

Yi-Ming Wang

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The tendency for low-speed ($v < 450$ km/s) solar wind to show greater spatiotemporal variability and different compositional properties from high-speed ($v > 500$ km/s) wind has led to the prevailing idea of a bimodal solar wind, in which fast wind comes from coronal holes and slow wind comes from coronal streamers. We present observational evidence that most of the slow wind originates from small coronal holes or from just inside the boundaries of large holes, with the rest ($< 20\%$) leaking out from coronal streamers and confined to the immediate vicinity of the heliospheric current and plasma sheets. Although this conclusion was suggested earlier by outward extrapolations of photospheric field maps, additional support comes from (1) observations of slow wind at Earth following the central-meridian passage of small equatorial holes; (2) observations of slow wind with high Alfvenicity at 1 au by Wind, and more recently near the Sun by Solar Orbiter and PSP; and (3) the finding that 80% of the solar wind observed by Helios at 0.3–0.4 au during 1974–1978 was Alfvenic. We show that compositional properties such as charge-state ratios vary over the solar cycle and may depend on parameters such as the footpoint field strength B_0, and thus cannot be used alone to distinguish between coronal hole and non-coronal hole wind. Finally, we note that magnetograms greatly underestimate the amount of small-scale flux emerging inside coronal holes and other unipolar regions. If this rate is taken to be the same as in the quiet Sun, the energy flux density resulting from interchange reconnection with open field lines is on the order of 3×10^5 erg cm^{-2} s^{-1} (B_0/ 10 G), sufficient to drive the solar wind. The wind speed depends on the rate of flux-tube expansion, with slower expansion leading to more energy deposition at greater heights and faster wind.

Magnetograph Saturation as the Solution to the Open Flux Problem

Yi-Ming Wang

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Extrapolations of photospheric field measurements tend to underestimate the radial interplanetary magnetic field (IMF) strength by factors of 2–4. Proposed solutions to this ""open flux problem"" include: the presence of large amounts of open flux outside of coronal holes, (implying the complete breakdown of the current-free corona approximation); large amounts of open flux hidden at the Sun's poles; a large contribution to the open flux from CMEs; the presence of large amounts of disconnected flux far from the Sun. However, the elephant in the room—the magnetograph measurements themselves—is often overlooked. Here, it is important to recognize that the total open flux is determined mainly by the dipole component of the photospheric field, which is sometimes best measured with low-resolution magnetographs such as those at the Mount Wilson Observatory (MWO) and the Wilcox Solar Observatory (WSO), both of which employ the magnetically sensitive (Lande g = 3.0) Fe I 520.0 nm line. To correct for magnetograph saturation (where the Zeeman shift becomes comparable to the width of the line profile), measurements in Fe I 525.0 nm have customarily been compared with those made in the nonsaturating (g = 1.3) Fe I 523.3 nm line. This gives a correction factor ranging between ∼1.8 and ∼5.5 at disk center, depending on where along the 523.3 nm line wing the exit slit is placed. If the slit is positioned such that the 523.3 and 525.0 nm signals originate from the same height (∼180 km), the saturation correction is ∼4.5 at disk center, falling to ∼2 at the limb. When the MWO and WSO photospheric measurements are scaled upward by this factor and a PFSS extrapolation with source surface at r = 2.5 R_Sun is applied, the variation of the total open flux matches that of the radial IMF strength throughout the interval 1968–2021. CMEs contribute an additional ∼20% to the open flux during the rising and maximum phases of the solar cycle.

On the Generation and Evolution of Switchbacks and the Morphology of Alfvénic Transition: Low Mach-number Boundary Layers

Ying Liu

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We investigate the generation and evolution of switchbacks (SBs), the nature of the sub-Alfvénic wind observed by Parker Solar Probe (PSP), and the morphology of the Alfvénic transition, all of which are key issues in solar wind research. First we highlight a special structure in the pristine solar wind, termed a low Mach-number boundary layer (LMBL). An increased Alfvén radius and suppressed SBs are observed within an LMBL. A probable source on the Sun for an LMBL is the peripheral region inside a coronal hole with rapidly diverging open fields. The sub-Alfvénic wind detected by PSP is an LMBL flow by nature. The similar origin and similar properties of the sub-Alfvénic intervals favor a wrinkled surface for the morphology of the Alfvénic transition. We find that a larger deflection angle tends to be associated with a higher Alfvén Mach number. The magnetic deflections have an origin well below the Alfvén critical point, and deflection angles larger than 90° seem to occur only when $M_{\mathrm{A}} \gtrsim 2$. The velocity enhancement in units of the local Alfvén speed generally increases with the deflection angle, which is explained by a simple model. A nonlinearly evolved, saturated state is revealed for SBs, where the local Alfvén speed is roughly an upper bound for the velocity enhancement. In the context of these results, the most promising theory on the origin of SBs is the model of expanding waves and turbulence, and the patchy distribution of SBs is attributed to modulation by reductions in the Alfvén Mach number. Finally, a picture on the generation and evolution of SBs is created based on the results.

Parse the Solar Wind with Normality Test

zesen huang

Zesen Huang, UCLA; Shi Chen, UCLA; Nikos Sioulas UCLA; Marco Velli UCLA; Trevor Bowen UC Berkeley

In situ observations from the Parker Solar Probe reveal that solar wind originates from various regions on the Sun, emphasizing the need to distinguish between different streams to improve our understanding of the Sun's magnetic field. This study demonstrates that by detrending the magnetic field strength (—B—) based on the heliocentric distance (r) with a power law (not necessarily Rˆ-2, due to super radial expansion and stream-stream interaction), we can effectively separate the rescaled magnetic field strengths into closely n ormally distributed intervals. The associated plasma parameters confirm that these intervals correspond to distinct streams. Furthermore, 3D Magnetohydrodynamic (MHD) turbulence simulations initialized with randomly phased Alfvén waves support the notion that normal distribution represents a stable asymptotic end state for the —B— distribution. Elucidating the origins of these streams enhances our comprehension of solar wind magnetic field structures, ultimately contributing to a deeper understanding of heliophysics.

New Observations of Solar Wind 1/f Turbulence Spectrum from Parker Solar Probe

Zesen Huang

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The trace magnetic power spectrum in the solar wind is known to be characterized by a double power law at scales much larger than the proton gyro-radius, with flatter spectral exponents close to -1 found at the lower frequencies below an inertial range with indices closer to $[-1.5, -1.6]$. The origin of the $1/f$ range is still under debate. In this study, we selected 109 magnetically incompressible solar wind intervals ($\delta|\boldsymbol{B}|/|\boldsymbol{B}| \ll 1$) from Parker Solar Probe encounters 1 to 13 which display such double power laws, with the aim of understanding the statistics and radial evolution of the low frequency power spectral exponents from Alfvén point up to 0.3 AU. New observations from closer to the sun show that in the low frequency range solar wind turbulence can display spectra much shallower than $1/f$, evolving asymptotically to $1/f$ as advection time increases, indicating a dynamic origin for the $1/f$ range formation. We discuss the implications of this result on the Matteini et al. (2018) conjecture for the $1/f$ origin as well as example spectra displaying a triple power law consistent with the model proposed by Chandran et al. (2018), supporting the dynamic role of parametric decay in the young solar wind. Our results provide new constraints on the origin of the $1/f$ spectrum and further show the possibility of the coexistence of multiple formation mechanisms.

The Average Energy Deposition Rate in the Open Field Regions

Zhenguang Huang

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The energy deposition rate into the solar atmosphere plays a key role in determining the solar wind acceleration and terminal velocity. However, this quantity is difficult to observe and has a large uncertainty. Sokolov et al. (2013) suggested that the Poynting flux per B ratio for the Alfven wave energy density to be approximately 1.1 MWm-2T-1 based on the Hinode observations by De Pontieu et al. (2007). Recently, Huang et al. (2023) used the Alfven Wave Solar atmosphere Model (AWSoM) to simulate different phases of the last solar cycle. They found that the required Poynting flux per B ratio necessary to reproduce the observed solar wind must be adjusted based on the area of the open field regions so that the simulated solar wind can best match the OMNI solar wind observations. Moreover, the average Poynting flux for the Alfven wave energy density, which is described as the energy deposition rate for the model, is approximately constant in the open field regions in the last solar cycle. This new discovery needs to be validated with observations and can shed light on how Alfven wave turbulence accelerates the solar wind during different phases of the solar cycle.

Spacecraft charging effects on solar wind electron measurements on board Solar Orbiter spacecraft

Štěpán Štverák

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Any spacecraft immersed into the solar wind builds up a non-zero electric potential with respect to the local environment by continuous collection of charged particles from ambient plasma populations and emissions of newborn charged particle populations from its surface materials, represented namely by photo-electrons and/or secondary electrons. These electrons of spacecraft origin as well as the electric fields induced in the vicinity of the spacecraft body by the so called spacecraft potential may in turn significantly distort the local plasma conditions and therefore affect any in-situ electron observations and thus potentially modify the derived electron properties. Here we present an observational analysis of these effects as seen by the SWA-EAS electron analyser in the complex plasma and electrostatic environment of the Solar Orbiter spacecraft. We provide some characteristic properties of these parasitic electron populations in order to later develop possible correction methods applied to the SWA-EAS measurements for deriving unperturbed ambient plasma properties. The analysis is performed on a statistical basis using a large set of SWA-EAS 3D electron velocity distribution functions and in comparison to other relevant in-situ measurements acquired namely by other two complementary on board plasma instruments – SWA-PAS and RPW. Results of the data analysis are compared to preliminary numerical PIC simulations of the plasma interaction with the Solar Orbiter S/C using the Spacecraft Plasma Interaction Software (SPIS).

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