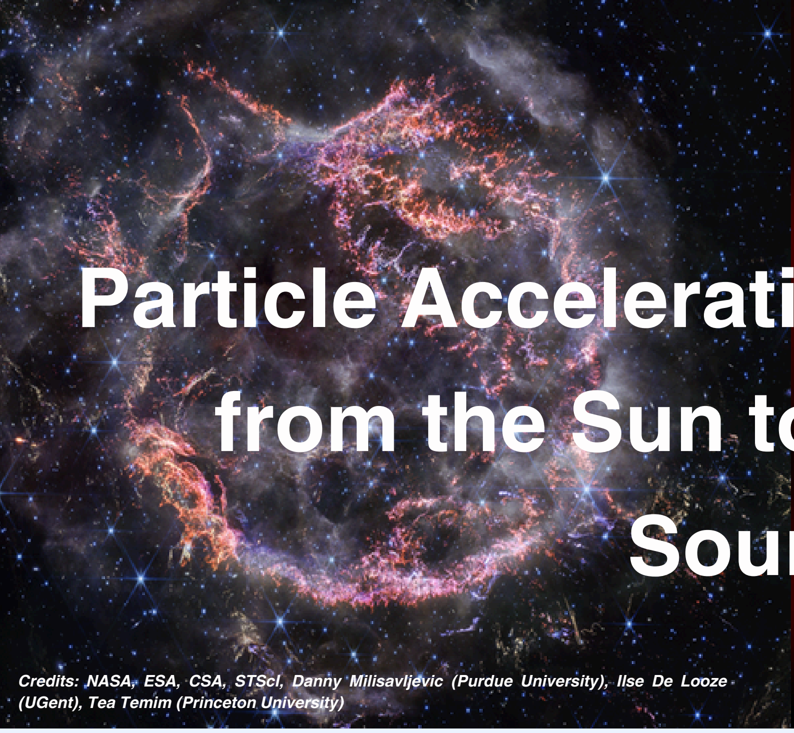

Particle Acceleration and Transport: from the Sun to Extragalactic Sources

Credits: NASA, ESA, CSA, STScI, Danny Milisavljevic (Purdue University), Ilse De Looze (UGent), Tea Temim (Princeton University)

Credits: EHT Collaboration

3-7 February 2025

Università della Calabria - University Club, Rende, Italy

Main Topics:

- Observations of energetic particles in the solar, heliospheric, galactic and extragalactic environments
- Properties of cosmic ray transport and acceleration from in-situ and remote observations
- Solar flares, Crab flares, flaring phenomena in astrophysics
- Shock acceleration: problems and advances
- Particle acceleration in magnetic reconnection, including the relativistic regimes
- Particle acceleration in black holes, accretion flows, and relativistic jets
- Transport and acceleration in non-linear regimes
- Magnetic turbulence in astrophysical plasmas: properties from large to small scales and effects on particle transport
- Theoretical models and numerical simulations of particle transport and acceleration

Scientific Organizing Committee (SOC):

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On anomalous transport and acceleration of high-energy particles

S. Aerdker[1], *L. Merten*[1], *F. Effenberger*[1], *H. Fichtner*[1], *J. Becker Tjus*[1]

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Abstract:

In recent years, there has been increasing evidence that high-energy particle transport can be anomalous. Such anomalous diffusion is characterized by a mean square displacement that depends on time in a non- linear way in contrast to normal or Gaussian diffusion. While superdiffusion describes processes for which the displacement grows faster, subdiffusive processes evolve slower than Gaussian diffusion. Non-Gaussian transport has been found in full-orbit test particle simulations in MHD turbulence and it has been suggested that the observed power-law profiles in space and time of high-energy particles at shock fronts in the heliosphere result from anomalous diffusion. Anomalous diffusion can be described by space- and time-fractional transport equations where superdiffusion is represented by Lévy flights and subdiffusion results from extended waiting times between scattering events. We present a modified version of the cosmic-ray propagation framework CRPropa 3.2 that solves space- and time-fractional Fokker-Planck equations by transforming them into corresponding stochastic differential equations. We investigate anomalous particle transport and acceleration at a shock and show that the expected power- law particle distribution upstream of the shock are obtained. Furthermore, we show that superdiffusion hardens the slope of the particles' energy spectrum at the shock and compare the results to the spectral slopes obtained with a Lévy walk model. Lastly, modeling particle transport at the level of pitch-angle scattering gives further insights on anomalous diffusion and allows for modeling superdiffusion without superluminal effects.

Small scale turbulence in the solar wind

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Abstract:

Turbulence in usual fluids is characterized by a well-defined energy spectrum as a function of scale and by the presence of coherent structures (or intermittency). We study magnetic turbulence in the solar wind from MHD to kinetic plasma scales. MHD inertial range stops at the vicinity of ion scales, where the turbulent spectrum changes its shape. At sub-ion scales and up to electron scales, we observe a general spectral shape with a power-law of -2.8, which has an exponential cut-off at the electron Larmor radius. We interpret this spectral curvature as dissipation in nearly collisionless plasma. This result was first found at 1 au, then confirmed at 0.3 au, and now we observe such a kinetic spectrum with Parker Solar Probe closer to the Sun. What is the nature of turbulent fluctuations which form such a spectrum? We show that coherent structures in the solar wind cover all available scales in the cascade: starting from the correlation scale and going up to electron Larmor radius. Magnetic vortices (Alfven vortices at MHD scales and kinetic vortices at smaller scales) seem to be an important building block of solar wind turbulence at all scales. We observe indications in the magnetosheath of the Earth that Alfven vortices at ~ few ion scales modify differently ion and electron temperature anisotropy. Does this mechanism work in the solar wind?

The source of the 2017 cosmic ray half-year modulation event, a solar solution to a cosmic problem

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Abstract:

In 2017, as the solar cycle was approaching solar minimum, an unusually long and large depression was observed in galactic cosmic ray (GCR) protons, detected with the Alpha Magnetic Spectrometer (AMS-02), lasting for the second half of that year. The depression, as seen in the Bartel rotation-averaged proton flux, has the form of a Forbush decrease (FD). Despite this resemblance, however, the cause of the observed depression does not have such a simple explanation as FDs, due to coronal mass ejections (CMEs), typically last for a few days at 1AU, rather than half a year. In this talk, we describe an investigation to seek the cause of the observed depression. To begin with, we identify the depression as being due to the solar modulation of GCRs. We then investigate two possibilities for the cause of the depression. First, we consider a minicycle - a temporary change in the solar dynamo that changes the behaviour of the global solar magnetic field and, by this, the modulation of GCRs. Secondly, we investigate the behaviour of solar activity, both CMEs and corotating/stream interactions regions (C/SIRs), during this period. To achieve this, we make use of a wide range of observational data from the Sun, interplanetary space and the Earth, to produce a detailed reconstruction of solar activity in this period. Our findings show that, although there is some evidence for minicycle behaviour prior to the depression, the depression is ultimately due to a combination of recurrent CMEs, SIRs and CIRs. A particular characteristic of the depression is that the largest impacts that help to create and maintain it are due to four CMEs from the same, highly active, magnetic source. In different solar rotations during

the depression, this source has the labels AR12665, AR12673 and AR12685. This active magnetic source is unusual given the closeness of the solar cycle to solar minimum, which also helps to make the GCR proton depression more evident.

First-principles Simulations of Black-hole Accretion: Recent Advances

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Abstract:

We present recent advances in first-principles simulations of black hole accretion. Using a localized approach, we perform shearing-box simulations of ion-electron plasma in black-hole accretion disks, where collisionless turbulence, angular-momentum transport, and nonthermal particle acceleration are captured self-consistently. Our simulations focus on the nonlinear development of the magnetorotational instability, which feeds off the central object's gravitational energy and provides a powerful driver for disk turbulence. For the first time, our simulations include vertical density stratification, showing a complex disk dynamics hinting at the formation of a magnetized corona. Moreover, we present the first ion-electron simulations with realistic proton-to-electron mass ratio, where a two-temperature state naturally emerges and the particle species are heated unequally. These results have important implications for global modeling using, e.g., magnetohydrodynamics with subgrid-heating prescriptions.

Cosmological simulations with a spectral cosmic ray model

L. M. Böss[1], *D. Caprioli*[1], *K. Dolag*[2,3], *U. P. Steinwandel*[4], *E. Hernández Martínez*[2], *I. Khabibullin*[2,3], *B. Seidel*[2], *J. G. Sorce*[5,6,7]

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7) Leibniz-Institut für Astrophysik (AIP)

Abstract:

Galaxy clusters and their role in the large-scale structure of the Universe, the cosmic web, have been studied extensively through observations and simulations. However, many of the high-energy process that happen in these structures still elude observations and pose significant challenges for simulations of large-scale structure formation. Most notably, the accretion of matter into the cosmic web and the collisions of galaxy clusters embedded in it dissipate a large fraction of their gravitational energy in the form of shocks. These shocks heat the intra-cluster medium to keV energies and can accelerate protons and electrons to relativistic velocities. Non-thermal emission from relativistic electrons gives insight into the strength and morphology of intra-cluster magnetic fields, as well as providing powerful tracers of structure formation shocks. Gamma-ray emission caused by CR protons on the other hand still challenges current observations and is therefore testing models of proton acceleration at intra-cluster shocks. Large-scale simulations which include the effects of CRs have been difficult to achieve since the difference between the scale where CRs interact with the thermal gas and the resolution of these simulations spans more than 20 orders of magnitude. In this talk, I will give an overview of how we work to improve the modeling of CRs in large-scale simulations of cosmological structure formation by employing a spectral cosmic ray model. I will introduce the model and show its application

to the constrained cosmological volume simulation set SLOW. These simulations allow us to study synchrotron emission and make predictions for CR electron populations within the cluster volume and the cosmic web, as well as potential diffuse gamma-ray emission caused by CR protons.

Galaxy clusters: the largest particle accelerators in the Universe

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Abstract:

Galaxy clusters are the largest gravitationally bound structures in the Universe. Radio observations have revealed the presence of diffuse radio sources associated with the intra-cluster medium which probe the existence of cosmic rays and magnetic fields distributed over Mpc scales. Despite significant progress in understanding extended synchrotron emission in clusters, key questions remain regarding the particle acceleration mechanisms operating in the dilute intra-cluster plasma. In this talk, I will review the observational evidence for the processes responsible for generating diffuse radio emission in clusters, including radio halos, relics, and bridges. I will discuss their connection to cluster-scale phenomena such as mergers, turbulence, and shocks, as well as the role of magnetic fields and fossil relativistic electrons in the intra-cluster medium. Finally, I will highlight recent results from state-of-the-art radio instruments that introduce new challenges for modeling particle acceleration and magnetic field amplification in these extreme environments.

Particle Acceleration at Shocks: Kinetic Simulations

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Abstract:

First-principles plasma simulations have been pivotal in helping developing a theory of ion and electron acceleration at shocks, from hello to astro scales. I discuss what we have learned about particle spectra and maximum energy, the dependence of acceleration efficiency on the shock strength and inclination, and the relative injection of ions and electrons.

Revisiting the turbulent damping of cosmic-ray driven Alfvén waves

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Abstract:

Alfvén waves (AWs) excited by the cosmic-ray (CR) streaming instability (CRSI) are a key factor in confining cosmic rays in the Galaxy. The effectiveness of this self-confinement depends on the balance between the CRSI growth rate and the damping mechanisms acting on quasi-parallel AWs excited by CRs. One potentially significant mechanism is turbulent damping, where an AW packet introduced into pre-existing turbulence undergoes a cascade process due to nonlinear interactions with background fluctuations. This talk revisits, revises, and extends the study of turbulent damping of AW packets in magnetohydrodynamic turbulence, incorporating the latest theories of MHD turbulence that include dynamic alignment and a reconnection-mediated regime [1].

[1] Cerri S. S., *Astronomy & Astrophysics*, 688, A182 (2024)

Investigation of CME-driven shocks observed through in-situ measurements and remote-sensing data from multi-spacecraft

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Abstract:

Shocks driven by coronal mass ejections (CMEs) are key accelerators of Solar Energetic Particles (SEPs) in the inner heliosphere. SEPs pose a significant natural hazard to the Earth's environment, affecting everything from the instruments on board spacecraft to the electricity networks and astronaut safety. In this study, we analyze energetic particle fluxes at CME-driven shocks, as measured in-situ by multiple spacecraft positioned at different radial distances and longitudes. We derive key shock parameters, including the compression ratio, the angle between the magnetic field and the normal to the shock, and the Mach numbers. By comparing the physical quantities derived from in-situ measurements with remote sensing observations from various instruments, we seek to improve our understanding of CME dynamics. Following the evolution of these parameters from the solar source to the interplanetary space plays a key role in enhancing space weather models and improving SEP arrival predictions at Earth. Additionally, we analyze the level of magnetic intermittency by investigating magnetic field turbulence through power spectral density and autocorrelation functions calculations. This study is achieved in the context of the research project "Data-based predictions of solar energetic particle arrival to the Earth" funded by the Italian Ministry of Research under the grant scheme PRIN-2022-PNRR.

Recent Observations of SEPs from Parker Solar Probe

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Abstract:

The orbit of Parker Solar Probe (Parker) provides a unique opportunity to make in-situ measurements at distances of tens of solar radii from the Sun. Over the course of the mission to date a number of solar energetic particles (SEP) events have been measured by the Integrated Science Investigation of the Sun (IS⊙IS) at these unprecedentedly close distances. Additionally, as solar cycle 25 progresses, the increase in solar activity has led to multiple opportunities for joint observations of SEP events between Parker and other spacecraft such as Solar Orbiter. This enables us to study these events from uniquely new composite views such as when two spacecraft were at similar distances but different longitudes or similar longitudes but radially separated. Here we present a range of IS⊙IS observations obtained during large and small, single- and multiple-spacecraft events and discuss the new insights (and puzzles) that are emerging.

Particle Acceleration in Highly Magnetized Plasmas

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Abstract:

Turbulence and magnetic reconnection are ubiquitous in astrophysical environments and are often invoked to explain the origin of non-thermal particles inferred to be accelerated in a variety of astrophysical sources. However, the mechanisms responsible for accelerating particles to ultra-relativistic energies remain poorly understood. In this talk, I will present recent insights from first-principles particle-in-cell (PIC) simulations that, thanks to significant computational advances, have successfully bridged the gap between microscopic/kinetic scales and macroscopic/MHD scales, enabling the direct application of first-principles results to astrophysical systems. In particular, I will revisit our understanding of particle acceleration in magnetic reconnection layers, which have now been shown to produce broken power-law distributions in particle energy, along with pitch-angle anisotropy. Additionally, I will present results from unprecedentedly large-scale PIC simulations of magnetized turbulence, highlighting the role of reconnection in turbulence and stochastic particle acceleration in large-scale turbulence fluctuations. Finally, I will discuss how highly magnetized turbulence may be responsible for the acceleration of ultra-high-energy cosmic rays.

Electrostatic waves in the Earth's magnetosheath: the role of kinetic electrons

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Abstract:

We present an analysis of data from the Magnetospheric MultiScale (MMS) mission to investigate the plasma dynamics from ion to electron scales within the near-Earth environment. We selected a 5-minute time interval during a MMS magnetosheath crossing. This interval was divided into sub-intervals characterized by intense electrostatic activity along the mean field direction. The power spectral density of the magnetic field components confirmed the electrostatic nature of the region. Within such intervals, the ion velocity distribution functions (VDFs) show a higher energy beam aligned with the mean magnetic field, while the electron VDFs exhibit the so-called "flat-top" distribution. Those findings were compared with recent numerical simulations of electrostatic turbulence, showing agreement with the simulated ion and electron VDFs, which are consistent with an interaction between particles and ion-bulk waves, thereby providing insights into the transfer of magnetic and electric energy towards small scales in space plasmas.

Analysing Turbulence in Coronal Mass Ejections Using Empirical Mode Decomposition

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Abstract:

Coronal mass ejections (CMEs), originating from the sun's corona, are large scale eruptions of plasma and magnetic flux that propagate into interplanetary space, and are capable of significantly influencing the dynamic environment of the inner solar system. Previous studies have established that CMEs exhibit turbulent behavior, characterized by energy cascades from larger to smaller scales through the formation of eddies. This study investigates the turbulence properties at different stages of a CME evolution. We divide the CME event into three intervals, characterised by the arrival of the CME shock and the magnetic cloud region. The magnetic field signal was decomposed using the method of empirical mode decomposition (EMD) into intrinsic mode functions (IMFs), which capture inherent oscillatory modes within the data. For each magnetic field component (Bx, By, Bz), we generated Fourier power spectra and Hilbert-Huang spectra, representing the power distribution across frequencies within the three intervals. These spectra can provide insights into the turbulent nature of the magnetic field during the different stages of CME evolution.

Parametric Study of Current Sheets in Relativistic Turbulence

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Abstract:

Turbulence is widely believed to play a critical role in particle heating and acceleration across a broad range of astrophysical phenomena. These range from the solar corona and Earth's magnetosphere to systems dominated by magnetic energy over plasma internal energy, such as relativistic turbulence in jets from active galactic nuclei (AGN) and gamma-ray bursts (GRBs). In this study, we use particle-in-cell (PIC) simulations to investigate how current sheets depend on plasma magnetization (σ) and the fluctuating magnetic field strength (δB / B_0). We utilize a self-organizing map (SOM) algorithm to systematically identify current sheets within the turbulent plasma. Our statistical analysis measures the properties of current sheets, such as their length, width, thickness, and peak current density, and examines how these properties scale with magnetization and fluctuation amplitude. We also explore the correlation between these properties and their relationship to local energy dissipation rates. Additionally, we investigate the spatial relationship between current sheets and regions of high vorticity and measure sheet filling factors. These findings are compared with previous studies that characterized dissipative structures in relativistic turbulence through scaling theories and intermittency analysis. By characterizing the properties and distribution of current sheets across different magnetization levels and fluctuating magnetic field strengths, we provide key insights into magnetic dissipation in turbulent plasmas. This systematic analysis of current sheet structure and dynamics may improve particle acceleration theories, addressing injection processes, anisotropic effects, and the spatial distribution of acceleration sites within turbulent systems.

From Microphysical Theory to Multi-Messenger Observations: A Semi-Analytic Approach to Diffusive Shock Acceleration

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Abstract:

Interpreting observations of extreme astrophysical phenomena requires a detailed understanding of the microphysical processes responsible for cosmic ray (CR) acceleration. In the standard picture, supernova remnants and other astrophysical shocks accelerate these particles via diffusive shock acceleration (DSA), an efficient mechanism that produces power-law distributions in momentum. However, both the multi-wavelength emission from astrophysical shocks--in particular, supernova remnants--and the populations of CRs detected at Earth reveal discrepancies between this standard theory and observations. To address these discrepancies, I will present a fast, semi-analytic modeling framework that self- consistently incorporates findings from state-of-the-art kinetic simulations. I will show how this model can address key tensions between theory and observations and make predictions for multi-messenger observations. In particular, I will apply this model to a variety of astrophysical objects, including supernova remnants, novae, and winds launched by active galactic nuclei.

AGN bubbles in merging galaxy clusters: contribution to diffuse radio emission

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Abstract:

AGN bubbles in cool-core galaxy clusters are believed to facilitate the transport of cosmic ray electrons (CRe) throughout the cluster. Recent radio observations are revealing complex morphologies of cluster diffuse emission, potentially linked to interactions between AGN bursts and the cluster environment. We perform three-dimensional magneto-hydrodynamical simulations of binary cluster mergers and inject a bi-directional jet at the center of the main cluster. Kinetic, thermal, magnetic and CR energy are included in the jet and we use the two-fluid formalism to model the CR component. We explore a wide range of cluster merger and jet parameters. We discuss the formation of various wide-angle-tail (WAT) and X-shaped sources in the early evolution of the jet and merger. During the last phase of the evolution, we find that the CR material efficiently permeates the central region of the cluster reaching radii of ~ 1–2 Mpc within ~ 5–6 Gyr, depending on the merger mass ratio. We find that solenoidal turbulence dominates during the binary merger and explore the possibility for the CR jet material to be re-accelerated by super-Alfvénic turbulence and contribute to cluster scale radio emission. We find high volume fractions, ≳ 70%, at which the turbulent acceleration time is shorter than the electron cooling time. Finally, we study the merger shock interaction with the CRe material and show that it is unlikely that this material significantly contributes to the radio relic emission associated with the shocks. We suggest that multiple jet outbursts and/or

off-center radio galaxies would increase the likelihood of detecting these merger shocks in the radio due to shock re-acceleration.

A new era of multi-spacecraft solar energetic particle observations in the heliosphere

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Abstract:

Solar energetic particles (SEPs) are energized within solar eruptions of our Sun. When these energetic electrons, protons, and heavier ions travel through interplanetary space they can reach Earth within minutes to hours, where they pose a radiation threat to human technology as well as humans in space. The different potential acceleration regions of SEPs provided in solar flares as well as shocks driven by coronal mass ejections (CMEs) together with particle transport processes form a complex system, still challenging our current understanding of the acceleration of SEPs. Until the current solar cycle only limited interplanetary space missions were available, usually only providing three well-separated viewpoints, which were not capable of constraining the entangled source and transport parameters. The launch of new missions like Solar Orbiter, Parker Solar Probe, combined with established spacecraft such as STEREO or near-Earth observers, as well as with planetary missions like BepiColombo, MAVEN, or JUICE offers unprecedented opportunities in the study of SEP events. We present multi-spacecraft observations of the new fleet

and discuss how these novel observations of SEP events allow us to gain new insights.

Particle Acceleration and Radiation in Solar Shocks - Insights from PSP

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Abstract:

Particle acceleration and radiation are fundamental cosmic processes that significantly contribute to the universe's energy density, driven by phenomena ranging from solar flares to supernova explosions. Shock waves, prevalent across various spatial scales, play a key role in converting kinetic energy into plasma heating and particle acceleration. Recent advancements from missions such as the Parker Solar Probe (PSP) have provided unprecedented insights into the dynamics of shock waves within the heliosphere, thereby enhancing our understanding of these critical energy conversion mechanisms. Here, we will present findings from two recent studies that leverage the PSP's unique proximity to the Sun and its advanced, high-fidelity instrumentation. First, we analyzed one of the fastest shocks ever observed in situ, revealing the efficient acceleration of electrons up to and exceeding 6 MeV and the collective

acceleration of ions from the thermal solar wind. Second, we made the surprising discovery of synchrotron radiation emanating from ultra-relativistic electrons in both a quasi-parallel and a quasi-perpendicular shock, with the quasi-parallel shock exhibiting significantly higher radiation intensities due to more effective electron acceleration. These results are consistent not just with theoretical models of strong cosmic shocks, but also observations. This offers an unprecedented opportunity to bridge in situ heliospheric observations with remote observations of phenomena such as supernova remnants.

Measuring Forbush decreases and probing CME evolution

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3) University of Zagreb
4) University of Kiel
5) IRF

Abstract:

Forbush decreases are one of the very common in-situ signatures of ICMEs throughout the heliosphere. These short-term reductions in the galactic cosmic ray flux are measured by ground-based instruments at Earth and Mars, as well as various spacecraft throughout the heliosphere (most recently by Solar Orbiter). We have recently developed an analytical model to explain CME-related Forbush decreases using an expansion- diffusion approach (ForbMod, Dumbovic et al., 2018; 2020). According to the model, the amplitude of the depression at a given point in the heliosphere depends on the initial CME properties as well as its evolutionary properties. We utilized ForbMod to develop a best-fit procedure and applied it to a dataset measured by detector F of the SOHO/EPHIN instrument with associations to 3D reconstructed CMEs to analyze CME evolution. We furthermore developed a scheme that will allow us to analyze CME evolution using in situ measurements only, as well as design a graphical user interface that will allow FD analysis throughout the heliosphere. This research was partly funded by the European Space Agency (projects ForbMod and ForbMod2) and partly by European Union (project SPEARHEAD, No 101135044). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency (HaDEA). Neither the European Union nor the granting authority can be held responsible for them.

Challenges in Modelling and Explaining Fermi Solar Gamma Ray Flares

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Abstract:

Gamma-ray emission during solar eruptive events is thought to be caused mainly by high-energy (MeV-TeV) protons propagating to the lower layers of the solar atmosphere, i.e. the chromosphere and photosphere, and the subsequent pion production and decay. A potential source of these high-energy particles are CME-driven shocks, followed by particle back-precipitation to the Sun. Alternatively, a scenario where particles propagate from a compact acceleration site along extended coronal loops towards the emission region is also a possibility. In both cases, the solar magnetic field configuration is a key ingredient to under- stand the origins of the gamma-ray emission as observed, e.g. by the Fermi Large Area Telescope (LAT). Here, we investigate the propagation of energetic protons and their subsequent gamma-ray production in a comprehensive modeling framework based on the CRPropa code, which is a well-established tool in high- energy astrophysics. The advantage of this approach is that the proton transport and gamma ray production can be studied with a single, unified code by following individual particle trajectories. We present first results of particle dynamics and the resulting gamma-ray distributions based on simplified field structures in a potential field (PFSS) model. We discuss further prospects of our approach, including outputs from detailed MHD simulations of CME evolution and extensions to other energy regimes.

A shock-compressed magnetic field revealed by X-ray polarimetry in RX J1713.7-394

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Abstract:

Supernova remnants (SNRs) are among the most important sources of non-thermal X-rays in the sky and likely contributors to Galactic cosmic rays and represent ideal targets to showcase the capabilities of the Imaging X-ray Polarimetry Explorer (IXPE) in performing spatially-resolved X-ray polarimetry. IXPE has found radial magnetic fields near particle acceleration sites in young SNRs Cassiopeia A, Tycho, and SN 1006. However, the observation of the northwestern rim of SNR RX J1713.7-3946 revealed the first instance of magnetic fields in particle acceleration sites oriented tangentially with respect to the shock front. These results are compatible with a shock-compressed magnetic field. Because of the lack of precise Faraday rotation measurements in the radio band, this is the first time that the geometry of the magnetic field of RX J1713.7-394 was mapped. The average measured polarization degree is lower than the one measured by IXPE in SN 1006, comparable to the Tycho one, but notably higher than the one in Cassiopeia A. In order to explain the observed PD, either a radial net magnetic field exists upstream of the shock, or the turbulence is re-isotropized downstream by radial magnetohydrodynamical instabilities. From comparison of PD and magnetic field distribution with gamma-rays and 12CO data, our results provide evidence in favor of a leptonic origin of the gamma-ray emission.

Plasma and turbulence modeling around supermassive black holes

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Abstract:

The event-horizon-scale observations of the shadows of the supermassive black holes Sgr A* and M87* by the Event Horizon Telescope collaboration mark the advent of a new avenue to study matter and turbulence under extreme conditions. The "millennium" images show large inhomogeneities in the plasma surrounding the black hole, which can be interpreted as density perturbations. In order to mimic such features, we performed high-resolution two-dimensional general relativistic magnetohydrodynamic simulations of a Fishbone-Moncrief torus around a Kerr black hole using the open-source Black Hole Accretion Code (BHAC). We studied several configurations where we added bubbles of plasma to the (unperturbed) initial density profile. We analyzed global properties of the system such as the black hole accretion rate and computed its power spectrum via the Blackman-Tukey technique, in order to describe turbulence in these extreme conditions.

Particle Transport in the Heliosphere

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Abstract:

The acceleration and transport of energetic particles are central topics of heliospheric research since more than half a century. Despite this long period, during which a lot of progress w.r.t. principal understanding and corresponding modelling has been made, various unsolved problems exist. This is partly due to comprehensive observations that, for some cases, put in doubt long-standing paradigms like the diffusive acceleration of charged particles at shocks, and partly due to the lack of sufficiently detailed in-situ measurements of particles and turbulence in specific regions of the heliosphere. In this talk recent progress that has been made will be reviewed, its significance for extra-heliospheric astrophysical systems will be highlighted, and open questions related to the physics and the corresponding modelling of various energetic particle species populating the heliosphere (e.g., Galactic and anomalous cosmic rays, solar energetic particles, pick-up ions, and energetic neutral atoms) will be addressed.

Using magnetic connectivity for predicting the locations of non-thermal emission sources in solar flares

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Abstract:

A combination of magnetohydrodynamics (MHD) and particle-drift methods makes it possible to investigate energetic particles in individual solar flares. I will use results of our MHD-particle modelling to discuss the transport of energetic particles in the flaring corona, focusing on the effects of cross-field particle drift and non-force-free magnetic field. Our simulations show that these factors can significantly affect the trajectories of energetic particles, their precipitation in the corona, and their escape into the heliosphere. I will demonstrate that the structure of the force-free magnetic field, which is often used as a proxy for energetic particle trajectories, cannot be used to reliably predict the connectivity between acceleration sites and non-thermal emission sources in solar flares.

Investigating magnetic turbulence in Supernova Remnants through X-ray jitter radiation

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Abstract:

Synchrotron radiation from relativistic electrons is usually invoked as responsible for the nonthermal emission observed in supernova remnants. Diffusive shock acceleration is the most popular mechanism to explain the process of particle acceleration and within its framework a crucial role is played by the turbulent magnetic field. However, the standard models commonly used to fit X-ray synchrotron emission do not take into account the effects of turbulence in the shape of the resulting photon spectra. In this talk I will present the results of the analysis of multi-instrument X-ray observations based on an alternative mechanism that properly includes turbulence effects in such spectra: the jitter radiation. This emission process leads to a photon spectrum that extends to higher energies compared to the standard synchrotron and provides critical information on the spectral distribution and scale-size of the magnetic turbulence downstream the shock. We found that the jitter model describes the X-ray soft-to-hard spectra of the young supernova remnant Cassiopeia A better than any of the standard cutoff models. Thanks to the jitter radiation model we measured the index of the magnetic turbulence spectrum and the minimum scale of the turbulence across several regions of Cassiopeia A. Finally, I will present future prospects about the application of this scenario to other young synchrotron-dominated SNRs and the link with the X-ray polarimetric results obtained with the IXPE telescope.

Nonthermal Particle Acceleration during Turbulent Magnetic Reconnection

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Abstract:

Magnetic reconnection has long been known to be one of the most important mechanisms not only for mixing plasmas by changing the magnetic field topology, but also for releasing magnetic field energy into plasma kinetic energy in astroplasma environments. In addition, a fraction of the heated plasma can be accelerated to energies that are much higher than the thermal energy during the reconnection process. Magnetic reconnection is believed to play an important role in high-energy astroplasma phenomena. So far, the efficiency of nonthermal particles in reconnection has been studied using particle-in-cell (PIC) simulations, and it has been shown that the acceleration efficiency of nonthermal particles increases with increasing plasma temperature from non- relativistic to relativistic temperature, and the nonthermal energy density occupies more than 90% of the total heated plasma when the Alfven velocity is close to the speed of light. In addition, another important agent of particle acceleration is turbulence in the three-dimensional (3D) topology of the reconnection. Here, we report on particle acceleration under 3D guide magnetic field reconnection using 3D PIC simulations and discuss that the efficiency of nonthermal particle acceleration decreases with increasing guide magnetic field for both 2D and 3D reconnection, but the decrease in nonthermal particle production is smaller for 3D guide field reconnection compared to 2D. More importantly, since patchy and turbulent structures are generated over a large area of the plasma sheet in 3D guide-field reconnection, 3D relativistic reconnection is able to maintain a hard nonthermal energy spectrum even in the presence of a strong guide magnetic field.

Modelling Coronal Mass Ejections and Energetic Particle Transport in the Corona and Inner Heliosphere

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Abstract:

The varying conditions in the heliosphere, caused by solar activity and collectively known as space weather, increasingly impact today's technology-driven societies. Coronal Mass Ejections (CMEs) are major contributors to severe space weather events. When directed towards Earth, CMEs are capable of generating geomagnetic storms, causing serious damage to satellites in near-Earth environment and to ground-based technologies. Additionally, shock waves driven by fast CMEs can accelerate Solar Energetic Particles (SEPs) to high energies, posing significant threats to spacecraft and astronauts. Considering the urgent need to understand the underlying physics of these phenomena, numerical models capable of simulating and forecasting CME and SEP events have proven invaluable. In this talk, we present recent advancements in our numerical tools for modelling complex and realistic CME and SEP scenarios. Using the magnetohydrodynamic (MHD) models EUHFORIA and Icarus, which is based on the MPI-AMRVAC framework, we solve the 3D ideal MHD equations to generate solar wind background configurations in the inner heliosphere (i.e., at solar radial distances $r > 0.1$ au). These configurations include transient structures such as stream interaction regions or CMEs. To model CMEs, we employ different approaches, ranging from a simple hydrodynamic cone model to more advanced spheromak and flux rope models. For simulating the propagation and evolution of CMEs in the solar corona (i.e., at $r < 0.1$ au), we utilise the 3D ideal MHD code COCONUT, which is part of the COOLFLuiD platform. To

study particle acceleration and transport in the corona and inner heliosphere, we have coupled all three MHD models to the PARADISE code. PARADISE uses the MHD snapshots as input to propagate energetic particles as test particles through the generated backgrounds by solving the focused transport equation in a stochastic manner. Finally, we highlight the potential of these models for future work, encompassing studies on CME dynamics as well as particle acceleration and transport, from the solar surface up to Earth's orbit and beyond.

Odd Radio Circles (ORCs): probing radio features at group scales with simulations

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Abstract:

Extragalactic radio astronomy has proven to be immensely useful in the study of high energy particle physics by constraining the acceleration of cosmic ray electrons and their subsequent synchrotron emission. Investigations of galaxy clusters have shown to be particularly fruitful, since such massive environments grant favourable conditions for efficient particle acceleration via merger driven shocks, reaching sonic Mach numbers of up to M~5. Yet, a new class of radio objects discovered only a few years ago imposes the question if also merger shocks in less massive systems can accelerate CR electrons to ~GeV energies. Specifically, a growing number of observations is pointing towards the existence of ring- and arclike features around small galaxy groups and even Milky Way-like objects, accordingly titled „Odd Radio Circles“ (ORCs) by Norris et al. (2021). Dolag et al. (2023) and Koribalski et al. (2024) proposed that these can be interpreted as radio analogs to the merger shocks observed in more massive systems, bridging the gap between galaxies and galaxy clusters. However, ORCs are appearing in a colder and less magnetised medium than the radio features in galaxy clusters, challenging particle acceleration mechanisms in more constraining environments. Now, by interpreting multiple observed ORCs at different stages as an evolutional time sequence and comparing them to simulations of such systems, one can infer underlying properties of these unique features, while simultaneously testing the limits of diffusive shock acceleration (DSA). To this end, we present the first of its kind zoom-in simulation of a galaxy group, utilising the on-the-fly Fokker-Planck solver for spectral cosmic rays (CRESCENDO) implemented in the magnetohydrodynamical SPH code OpenGadget3. We study the emerging radio arcs and discuss both similarities and differences to the observed

counterparts. Finally, we review the relative importance of DSA in the formation of ORCs compared to galactic sources of high energy particles, such as AGN outbursts.

Radio observations of particle acceleration and particle propagation in solar flares

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Abstract:

The Sun accelerates particles to a range of energies that may extend up to tens of MeV for electrons and tens of GeV for protons and heavy nuclei, depending on the event. Although these energies are far below those that can be reached in other astrophysical environments, the solar case is unique in that it enables us to study the particles with a broad range of radiative diagnostics and in situ measurements. In addition, the time evolution of the particle populations can be probed with a resolution that pertains to their propagation and constrains the time scales of acceleration. In situ measurements relatively close to the Sun with Parker Solar Probe and Solar Orbiter provide us with data that are much less affected by heliospheric particle transport than measurements near 1 AU. In addition, we have a number of complementary radiative diagnostics of the plasma environment where particles are accelerated. In this talk I will discuss how spectrography and imaging at radio wavelengths contribute to the understanding of particle acceleration and particle propagation in simple impulsive flares, and why the issue is far more complex in eruptive flares.

Towards a semi-analytical description of the heliosphere boundaries

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Abstract:

Determining the size and shape of the heliosphere is a challenging task to be performed from within the system. Early attempts to address such issues in the past employed semi-analytical models based on hydrodynamic considerations. For example, Parker estimated the distance to the termination shock distance and the global shape of the heliosphere by studying the pressure balance between the solar wind and the local interstellar medium at the heliopause. Taking advantage of the growing amount of in-situ and remote sensing data and the resulting advancement in understanding the plasma evolution in the heliosphere, the present work revisits Parker's analytical model. This model provides the long-term variation of the termination shock and the heliopause distance. The model's predictions are compared with the observations of the Voyager probes.

On the phase space cascade evolution in the inner heliosphere

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Abstract:

In space plasma, due to the absence of collisions, the phase space presents a complex structuring and strong deviations from thermal equilibrium. Previous works have highlighted this aspect in both magnetosheath data and numerical simulation through an hermite decomposition of the ion velocity distribution function. The hermite spectrum of the vdf is expected to have a precise spectral slope and to present anisotropy in a magnetic field dominated environment. Such a tool is particularly suited for the vdf representation since each order of the hermite decomposition corresponds to a moment of the vdf. In this work we study, by using the Parker Solar Probe ion vdfs, the evolution of the hermite spectrum and the vdf fine features with respect to radial distance and solar wind conditions. These results are useful to understand how the phase space evolves in the inner heliosphere and possibly improve our understanding of heating in collisionless plasma.

Particle acceleration and transport in astrophysical, magnetized turbulent plasmas

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Abstract:

The physics of particle transport in momentum space (acceleration) and configuration space (spatial diffusion) represents a cornerstone of modern high-energy and multi-messenger astrophysics. It is commonly described within a quasilinear model which ascribes pitch-angle scattering and momentum diffusion to resonant wave-particle interactions. This talk examines an alternative picture, in which coherent structures rather than waves control particle transport and acceleration. More explicitly, the present contribution will propose a modern implementation of the original Fermi (1949) picture in magnetized turbulence to describe momentum diffusion at large turbulent Alfvenic velocities. It will also discuss the possibility that the interaction of particles with localized, sharp magnetic field bends ensures pitch-angle diffusion at low turbulent Alfvenic velocities. Intermittency will be shown to play a key role in shaping transport in both cases.

Modeling fast charged particle transport in strong magnetic turbulence

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Abstract:

The transport of energetic charged particles in strong magnetic turbulence is a highly complex phenomenon. Inspired by recent work on the role of the fieldline curvature in this problem, we investigate the interplay between pitch-angle scattering and fieldline geometry by means of test particle simulations in isotropic MHD snapshots. We characterize the magnetic field as coherent when its local curvature radius is larger than the current gyroradius of the particle, and find distinct transport behavior in either case. Guided by our observations, we develop a stochastic model based on a competition between compound diffusion along coherent field lines and diffusive scattering. Finally, we discuss implications on synthetic turbulence models and avenues to a transport theory based on a generalized master equation.

Unusual propagation path of the type III radio bursts

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Abstract:

Dynamical processes in the solar corona, such as flares and coronal mass ejections (CMEs), can be accompanied with radio bursts of different types. Solar radio bursts are important because they can provide information on the processes associated with their generation, and they can be used to estimate coronal plasma parameters in the vicinity of the radio sources. This study is focused on the so-called type III bursts, radio signatures of fast electron beams. It is generally considered that the type III radio bursts propagate along the open and quasi open magnetic field lines roughly following the Parker Spiral. To test this hypothesis, we study the propagation path of the group of type III bursts using both ground-based and space-based radio observations. During April, 2019, several groups of type III radio bursts were observed by LOFAR (Low Frequency Array), and by instruments on Stereo A, Wind and Parker Solar Probe (PSP). We studied a well observed group of type III bursts, during the time interval 16:40-17:00 UT, on April 03. Using the radio triangulation method we obtained the 3D positions of the type III radio

sources, providing the trajectory of the associated fast electron beam. Our results show that the type III bursts do not follow, as generally considered, Parker spirals but they propagate strongly southward from their source region. We found that this unusual propagation path is induced by the faint CME that preceded the radio bursts and disturbed the ambient solar conditions.

Cosmic Rays acceleration and transport

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Abstract:

This review addresses the physics of cosmic ray acceleration and transport in the interstellar medium to Earth. Acceleration first, should be linked to strong collisionless shocks that occur in our Galaxy due to strong energy released episodes due to massive stars either because of their winds or after their explosion in supernova. We will discuss the specificity of cosmic-ray-modified shock waves and debate about recent numerical investigation of non-linear energetic particle acceleration processes. Then, we will discuss about the complex and yet unsolved problem of cosmic ray escape from their sources. We will conclude by considering some issues about the physics of cosmic ray propagation in the Galaxy. The review will also consider the importance of a correct description of the transport to properly address several important questions in modern astrophysics on top of them is the star formation rate.

The ESA M7 candidate mission Plasma Observatory

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Abstract:

We present the Plasma Observatory (PO) multi-scale mission concept tailored to study plasma energization and energy transport in the Earth's Magnetospheric System through simultaneous measurements at both fluid and ion scales. The Magnetospheric System is the complex and highly dynamic plasma environment where the strongest energization and energy transport occur in near-Earth space. Previous multi-point observations from missions such as ESA/Cluster and NASA/MMS have evidenced the fundamental role that cross-scales coupling has in such processes. In the Magnetospheric System, the electromagnetic energy is converted into energized particles and energy is transported mainly at the ion and fluid scales. Simultaneous measurements at both large, fluid and small, kinetic scales are required to resolve scale coupling and ultimately fully understand plasma energization and energy transport processes. PO will provide such measurements, which are currently unavailable. PO baseline mission includes one mothercraft (MSC) and six identical smallsat daughtercraft (DSC) in a two

tetrahedra formation with MSC at the common vertex for both tetrahedra. PO baseline orbit is an HEO 8x17 RE orbit, covering all the key regions of the Magnetospheric System including the foreshock, the bow shock, the magnetosheath, the magnetopause, the transition region and the plasma sheet. The spacecraft separation ranges from fluid (5000 km) to ion (30 km) scales. The MSC payload provides a complete characterization of electromagnetic fields and particles in a single point with time resolution sufficient to resolve kinetic physics at sub-ion scales and fully characterize wave-particle interactions. The DSCs have identical payload, simpler than the MSC payload, yet giving a full characterization of the plasma at the ion and fluid scales and providing the context where energization and transport occurs. PO is the next logical step after Cluster and MMS and will allow us to resolve for the first time scale coupling in the Earth's Magnetospheric System, leading to transformative advances in the field of space plasma physics. Plasma Observatory is one of the three ESA M7 candidates, which have been selected in November 2023 for a competitive Phase A with a mission selection planned in 2026 and launch in 2037.

Measures of Turbulence near Black Holes

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Turbulence in the vicinity of black holes represents a poorly understood, very complex challenge. We propose a novel analysis technique for the comprehension of turbulence in extreme gravitational fields, such as the ergosphere of compact objects. We develop a turbulence measurement that, in principle, can be valid in any curved spacetime. In a fully covariant formalism, taking into account the local spatial metric of Kerr-type black holes, we define a Proper Length Spectrum (PLS). We demonstrate that the new technique, based on the computation of structure functions on generic manifolds, can correctly capture the scaling laws indicative of an inertial range cascade. By applying the PLS to the turbulent density field coming from simulations of the Black Hole Accretion Code (**BHAC**), we estimate the scaling laws of turbulence in the disk, the wind, and the near-horizon regions.

Revisiting X-ray polarization of the shell of Cassiopeia A using spectropolarimetric analysis

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Abstract:

X-ray synchrotron radiation is expected to be highly polarized. Thanks to the Imaging X-ray Polarimetry Explorer (IXPE), it is now possible to measure the degree of X-ray polarization in sources such as supernova remnants (SNRs). Using IXPE data combined with high-resolution observations from Chandra, we conduct a spatially resolved spectropolarimetric analysis of the SNR Cassiopeia A (Cas A). Our focus is on the 3–6 keV energy band, specifically in regions near the shell dominated by nonthermal synchrotron emission. By combining IXPE's polarization sensitivity with Chandra's superior spatial and spectral resolution, we constrain the local polarization degree (PD) and polarization angle (PA) across the remnant. Our analysis shows PD values ranging locally from 10% to 26%, with significant regional variations that highlight the complex magnetic field morphology of Cas A. The polarization vectors point to a predominantly radial magnetic field, which aligns with previous studies. Using improved modeling of thermal contamination with Chandra data, we derive higher PD values compared to earlier IXPE analyses, with more significant detections compared to the standard IXPEOBSSIM analysis. Finally, we estimate the degree of magnetic turbulence (η) based on the measured photon index and PD, assuming an isotropic fluctuating magnetic field across the shell of Cas A.

Modeling focused pitch angle diffusion with stochastic differential equations

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Abstract:

Efficient modeling of cosmic-ray transport is key to understand the current detailed observational data. The publicly available cosmic-ray propagation framework CRPropa is one possibility to take up this challenge whenever a test particle approach is applicable. We present the latest developments of CRPropa's solver for the ensemble averaged approach, which is based on the integration of the corresponding stochastic differential equations. The new solver can handle different Fokker-Planck like equations, including the spatial and pitch-angle transport equation. First, the basics of modeling cosmic-ray transport by stochastic differential equations are briefly summarized, including advantages and disadvantages of various approaches. Furthermore, we discuss opportunities to disentangle drifts from superdiffusion. Afterwards we discuss how focused pitch angle diffusion could lead to super- and subdiffusive phases in the propagation of cosmic rays along magnetic field lines.

Tracing cosmic-ray acceleration in galaxy clusters and filaments: Cosmological MHD simulation and Lagrangian tracers

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Abstract:

The recent discoveries of the diffuse radio emission in galaxy clusters and cosmic filaments indicate that the relativistic particles are accelerated in the inter- galactic environment. The large extension and the steep-spectrum nature of those emission are compatible with the turbulent (Fermi II) acceleration model. However, there remain so many unresolved questions; how and when does the acceleration take place, what is the origin of "seed" particles prior to turbulent acceleration, how does the observed diversity in emission size emerge, what is the impact of cosmic- ray protons and secondary electrons, etc… The cosmological MHD simulation and the Lagrangian tracer method offer a promising avenue for addressing these questions. In a postprocess of a cosmological MHD simulation of merging galaxy clusters, we follow the spectral evolution of CRs along the trajectories of $\sim 10^5$ tracers by solving the Fokker-Planck equation. We take into account the radiative and Coulomb cooling, the adiabatic cooling/acceleration, the turbulent re-acceleration, and the pp collisions of cosmic- ray protons. We create intensity map and spectral index map along various line-of-sight, which can be compared to the observation. In the talk, I will illustrate the emergence and decay of the classical radio halo and the emission beyond the cluster scale during the dynamical evolution of the clusters. I will also discuss potential constraints on the acceleration efficiency and cosmic- ray protons.

Maximum Energy of Particles in Plasmas

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Abstract:
Particles are accelerated to extremely high, non-thermal energies in space, solar, and astrophysical plasma environments. In cosmic ray physics, the Hillas limit is often used as a rough estimate (or a necessary condition) for the maximum energy of particles. This limit is based on the concepts of one-shot direct acceleration by a system-wide motional electric field, as well as stochastic and diffusive acceleration in strongly turbulent environments. However, it remains unclear how well this limit explains the actual observed maximum energies of particles. In this study, we show, based on a systematic review, that the observed maximum energies of particles — in space, solar, astrophysical, and laboratory environments — often match the energy predicted by the Hillas limit. However, we also identify several exceptions, such as electrons in solar flares and jet-terminal lobes of radio galaxies, as well as protons in planetary radiation belts, where deviations from this limit occur. We discuss potential causes of these deviations, and we highlight the possibility of detecting ultra-high-energy (~100 GeV) solar flare electrons that have not yet been observed. We hope this study will encourage further interdisciplinary discussions about the maximum energy of particles and the mechanisms driving particle acceleration in various plasma environments.

Investigating the effect of thermal collisional plasma and turbulent acceleration in a simulated coronal acceleration region on heliospheric electron spectra

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Abstract:

Non-thermal particle acceleration in the solar corona is evident from both remote hard X-ray (HXR) sources in the chromosphere and direct in-situ detection in the heliosphere. Correlation of spectral indices between remote and in-situ energy spectra presents the possibility of a common source acceleration region within the corona, however the properties and location of this region are not well constrained. To investigate this we perform a parameter study for both the properties of the ambient plasma of a simulated acceleration region and the turbulent acceleration profile acting on an initially isotropic thermal electron population. These electrons are propagated out to 1.0 AU with their energy spectra compared between extremes of the tested parameters. We present results of this parameter search and discuss the relative sensitivity of spectral indices across the heliosphere subject to variation in individual plasma properties and turbulent acceleration profiles consistent with a hot, over-dense source region in the lower corona. We also discuss the suitability of the heliospheric spectral index in constraining the properties of an acceleration region and compare the simulated in-situ energy spectra to that of a simulated chromospheric HXR spectra produced with the same properties.

Analysis of CME-driven shocks properties as input for a data-based model of solar energetic particle transport

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Abstract:

One of the main goals of space weather science is to understand how energetic particles accelerated at the Sun, the so-called solar energetic particles (SEPs), propagate through the inner heliosphere eventually reaching the near Earth environment. Indeed, those particles represent a natural hazard for the functioning of commercial and scientific satellites. On the other hand, shock waves driven by coronal mass ejections (CMEs) are the most relevant particle accelerators in the interplanetary space, giving rise to SEP gradual events that can have a strong geomagnetic impact. In this study, we aim at investigating the transport properties of energetic protons up to energies of hundreds of MeV by means of an innovative test-particle model, where SEPs interact with a 3D anisotropic turbulence. Beyond this, we first analyze magnetic field turbulence close to CME-driven shocks by using in-situ measurements from different satellites, at different radial distances, in order to capture the main properties of the environment close to the acceleration source. Thus, parameters such as the power spectral density of magnetic field fluctuations, the level of intermittency, the degree of turbulence anisotropy will serve as input for the test particle numerical code, since all these parameters can be tuned in the simulations. The possibility in the model of adapting turbulence parameters to observations allows us to obtain a description of SEP transport throughout the inner heliosphere. We find a strong influence of turbulence properties on the spatial diffusion coefficients parallel and perpendicular to the mean magnetic field and on the distribution of the scattering times. This study is achieved in the context of the project "Data-based predictions of solar

energetic particle arrival to the Earth: ensuring space data and technology integrity from hazardous solar activity events" (PRIN-PNRR-2022).

Solar Orbiter observations in a slow Alfvénic wind of proton and alpha particle kinetic signatures close to switchbacks

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Abstract:

We statistically study magnetic switchbacks, large deflections of the magnetic field which occur simultaneously with a sudden increase in the radial solar wind velocity, in the first stream of slow Alfvénic wind observed by Solar Orbiter at a heliocentric distance of 0.64 au, and how ions, both protons and alpha particles, kinetically react to the presence of these strong deflections. We use ion data from an innovative method based on the statistical technique of clustering applied directly to the full three-dimensional velocity distribution functions measured by the Proton and Alpha Sensor to separate core and beam for both protons and alphas. Beyond the expected correlation between magnetic deflections and the increase in the ion velocity, related to the Alfvénic nature of the switchbacks, we find a certain correlation between switchbacks and both proton and alpha particle densities, which suggests wave activity. Related to the kinetic physics of protons and alpha particles, very interestingly we observe a clear correlation between switchbacks and alpha particle temperature, but not with proton temperature, suggesting a role of magnetic field deflections in preferentially heating heavy ions. Moreover, we investigate the presence of waves, namely fast magnetosonic modes, close to isolated switchbacks and their role in the generation of these deflections.

The role of large-scale plasma turbulence in influencing particle transport and energization in astrophysical contexts

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Abstract:

Populations of energetic particles, ranging from solar energetic particles to incredibly high-energy cosmic rays, are ubiquitous in space and astrophysical plasmas. Several intertwined phenomena, including shocks, magnetic reconnection, jets, and turbulence, are responsible for the efficient energization of particles and for determining their transport properties. Plasma turbulence produces patchy coherent structures, such as reconnecting current sheets, plasmoids, and vortices across a vast range of spatial scales. Under some circumstances, these structures can entrap particles, thus providing fast energization through, for example, drift acceleration. In this talk, I will review some of these mechanisms and outline recent numerical efforts aimed at investigating how the large-scale complexity of the turbulent magnetic field influences particle transport and how large-scale coherent structures impact particle energization. I will also comment on the applicability of these results in space and astrophysical contexts.

Acceleration of solar energetic particles by coronal shock waves

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Abstract:

The processes of energetic particle acceleration in solar corona are still debated despite decades of active research. During a solar eruption two distinct zones appear to efficiently convert some part of free energy into energetic particles: (1) flaring region where magnetic reconnection triggers the eruption and (2) shock front that develops during the expansion of the coronal mass ejection. In this presentation we will address some observational and modelling aspects of coronal shock reconstruction and their link with solar energetic particles which are measured in-situ by the heliospheric spacecraft fleet. The properties of the shock depend strongly on the state of the highly structured solar corona, modulating the efficiency of different parts of the shock in accelerating particles. We will present a couple of case studies that demonstrate a tight link between the evolution of the shock and properties of SEPs.

Numerical investigation of particle acceleration at interplanetary shocks for both normal and superdiffusive transport scenarios

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Abstract:

Energetic particles are ubiquitous in space and astrophysical plasmas. Heliospheric shocks are considered the main sources of particle acceleration in the heliosphere. Indeed, from in-situ measurements, energetic particle fluxes are observed to peak at the shock front. Furthermore, the time profile of energetic particle fluxes is highly influenced by particle transport properties upstream and downstream of the shock. We develop a test-particle numerical code to mimic the acceleration of particles at the heliospheric shocks. The transport of a 70 keV particle population is reproduced by integrating a Langevin-type equation upstream and downstream of an infinite planar shock. Particles can diffuse in the simulation box via random "kicks", which can obey either a Gaussian distribution (normal diffusion) or a Lévy distribution (superdiffusion). At each shock crossing particles gain energy. The code gives in output the energetic particle density upstream and downstream of the shock front, as well as the particle energy. We have performed different simulations by exploring a range of different parameter value in the model. The output densities have been compared with some energetic particle fluxes observed by the ACE spacecraft during interplanetary shock crossings. We show that the test-particle simulations with superdiffusive transport are in very good agreement with the observed energetic particle time profiles both upstream and downstream of interplanetary shocks.

Cosmic ray diffusion in isotropic magnetic turbulence plus a guide-field: a numerical study

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Abstract:

Cosmic ray diffusion in isotropic magnetic turbulence plus a guide-field: a numerical study We investigate the transport of cosmic rays in magnetic turbulence using numerical simulations. Particle trajectories are evolved in a synthetic turbulence magnetic field made of an isotropic turbulent component and a guide field. The synthetic turbulence model we use is wavelet-based and produces a magnetic field analytically defined at every point in space without needing a computational grid. The algorithm is fast enough to allow the study of the motion of particles with smaller Larmor radii than what was previously reported in the literature for this kind of problem. We run numerical simulations varying the amplitude of the turbulent fluctuations (db) with respect to the guide field (B0) from 0.3 to 1.0, and the particle Larmor radius (rL) from 2e-4 to 1e2 turbulence correlation length (lc). We observe that the parallel diffusion coefficient scales as r_L^(1/3) for rL.

Solar disk gamma-ray emission from turbulent magnetic structure of the solar atmosphere

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Abstract:

Our previous research highlighted how closed magnetic arcades can efficiently trap galactic cosmic ray (GCR) protons interacting with solar atmospheric protons, thereby contributing to gamma-ray production in the GeV- TeV energy range from the solar disk. In this work, we simulate a magnetic field structure evolving from a static, laminar state (with open field lines) in the upper solar atmosphere to a progressively turbulent configuration near the Sun's surface, where magnetic field lines become significantly distorted. The altitude-dependent variation in magnetic turbulence is described using a scalar function. Using 3D numerical simulations carried out with the PLUTO code, we explore the effects of magnetic field distortion near the Sun on the gamma-ray emission. Test-particle protons in the GeV to TeV energy range are injected into both the laminar and turbulent regions, systematically varying the ratio of turbulent to laminar magnetic field components. Our results reinforce the crucial role of magnetic turbulence in modulating the gamma-ray flux observed by Fermi-LAT and HAWC, particularly revealing a unique flux signature between approximately 30 and 100 GeV.

Cosmic Ray transport in the Galaxy

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Abstract:

The Galactic propagation of cosmic rays is due to the complex interaction of particles with the turbulent and magnetized interstellar medium. The resulting transport is characterized by a multi-scale and rich phenomenology, where the particle motion is typically anisotropy on scales comparable or smaller than the magnetic field coherence length and becomes isotropic on much larger scales. Moreover, cosmic ray themselves play a critical role in shaping their own propagation, by triggering plasma instabilities and possibly pushing the background medium to launch Galactic outflows. Here we review the main current theoretical models of Galactic particle transport, by illustrating the most relevant open problems. We also discuss possible future developments driven by recent data that may help in shedding light on these issues.

The Reciprocal Impact of Microscale Plasma Physics on Macroscopic CR Transport

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Abstract:

This contribution reveals a fundamental feedback mechanism in astrophysical plasmas: while macroscopic processes drive microscale phenomena, magnetic microscale fluctuations reciprocally modify large-scale CR transport. Using high- resolution, multi-scale simulations that bridge kinetic (PIC) and MHD regimes, we show how mirror-instability-induced perturbations significantly alter CR diffusion within the intracluster medium. Our theoretical predictions for CR diffusion coefficients match numerical results across multiple spatial scales. These findings underscore the importance of incorporating micro-instabilities and magnetic turbulence into CR- transport models, with implications for a wide range of astrophysical environments.

Estimating the Total Energy Content in Accelerated Electron Beams that Escape the Sun

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Abstract:

The Sun accelerates electron beams during solar eruptive events like solar flares. Quantifying the energy content of these accelerated electron beams is a key outstanding objective that must be constrained to refine particle acceleration models and understand energetic particle transport. Previous energy estimations have used in situ measurements near the Earth, and consequently suffer from electron beam propagation effects. In this study, we deduce properties of a rapid sequence of around one hundred escaping electron beams that were accelerated during a solar flare on 2013 May 22, that produced type III radio bursts. Combining Extreme Ultraviolet, radio and X-ray observations, we estimate the path, speed and origin of the escaping electron beams, respectively. We deduce the electron number density using observationally constrained numerical simulations of electron transport. Our method provides the first remote-sensing estimates of energy contained in the electron beams, that ranged from 10^23-10^25 ergs over the 100 beams, each with an beam density around 300 cm^-3, which is comparable to energy estimates from in situ studies. Radio observations suggest the particles travelled a very short distance before they began to produce radio emission, implying a radially narrow acceleration region. We show how similar energy estimates can be obtained using the EUI and STIX instruments on-board Solar Orbiter, combined with radio interferometers based on Earth.

Particle Acceleration in Solar Eruptive Events

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Abstract:

Solar eruptive events (e.g. solar flares) are the most energetic events in the solar system, and provide our nearest real world laboratory for studying stellar particle acceleration and transport. The energy that drives these events is thought to be released via magnetic reconnection, of which particle acceleration is one of its earliest observable signatures. Despite valuable progress over the past two decades, the processes by which charged particles are accelerated by magnetically released energy remains poorly understood in solar eruptive events. Moreover, accelerated particles are a key mechanism for transporting the energy throughout the solar atmosphere, and hence driving solar flares and solar energetic particles that escape into the heliosphere. In this talk we explore recent advances in the field of solar particle acceleration, some of the open questions that remain, and instrument concepts that will help us answer them in the future. By better understanding solar particle acceleration, we will better understand space weather events as well as phenomena throughout the Universe that exhibit particle acceleration from magnetic reconnection.

Identifying Regions of Interest in Plasma Using Unsupervised Machine Learning

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Abstract:

Velocity distribution functions (VDFs) measured by space missions are complex 3D datasets that can be represented as a superposition of multiple beams (Goldman et al., 2020). Recent papers (Dupuis et al., 2020; De Marco et al., 2023) proposed the use of the Gaussian Mixture Model (GMM) to identify different populations. Here, we applied the method to space data of the Earth's magnetosphere to differentiate between simple and more complex regions (Sanò et al, 2025). We found that GMM is capable of detecting the presence of multiple beams within an overall distribution. Indeed, the GMM can define reliably the complexity of a measured dataset in terms of the number of optimal beams provided by information theory criteria. In particular, complex shaped electron distributions have been shown to be good indicators for processes of interest such as magnetic reconnection and turbulence (Shuster et al., 2014; Hoshino et al., 2001).

Coherent Structures and Particles Acceleration in Special-Relativistic Turbulence

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Abstract:

The understanding of regions inaccessible to humans by direct exploration, such as accretion disks, relativistic jets, and magnetospheres that surround compact objects, represents today a critical challenge for the scientific community. Strong gravitational fields and fully developed turbulence characterize these systems, where weak plasma collisionality and phenomena like pair production (electron and positron) may complicate the dynamics. The state-of-the-art numerical modeling of black hole accretion flows is mostly represented by large- scale general relativistic magnetohydrodynamics. However, the microphysical, kinetic properties of astrophysical plasmas near accreting compact objects are still poorly understood. We here present a very comprehensive campaign of two-dimensional kinetic particle-in-cell simulations of special-relativistic turbulence to investigate the microphysical properties of the plasma and particle acceleration mechanisms in the transrelativistic regime. We show how particles get trapped and accelerate near persistent coherent structures naturally developing in turbulence. Finally, we concentrate on the formation of long-lived vortices with a profile typical of macroscopic, magnetically dominated force-free states. We describe these metastable solutions with a self-consistent kinetic model. Turbulence and particle energization are mediated by the long-lived structures, accompanied by transients in which such vortices merge and form self-similarly new metastable equilibria. This process can be relevant to the comprehension of various astrophysical phenomena, going from the formation of plasmoids in the vicinity of massive compact objects to the emergence of coherent structures in the heliosphere (M. Imbrogno et al.).

Production of the unstable cosmic-ray isotope 60Fe in remnants of clustered supernovae

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Abstract:

The unstable isotope 60Fe, with a half-life of 2.6 million years, is produced primarily in supernova explosions. The observed presence of 60Fe in cosmic rays and its detection in deep-sea crusts and sediments suggest two possible scenarios: either the direct acceleration of 60Fe from supernova ejecta or its enrichment in the circumstellar material surrounding supernova progenitors, which indicates cosmic ray production in clusters of supernovae. Focusing on the latter scenario, we consider an environment shaped by successive supernova explosions, reminiscent of the Local Bubble around the time of the most recent supernova explosion. We independently tracked the evolution of the 60Fe mass ratio within the Local Bubble using passive scalars. To investigate the spectra of protons and 60Fe, we explicitly modelled cosmic-ray acceleration and transport at the remnant of the last supernova by simultaneously solving the hydrodynamical equations for the supernova outflow and the transport equations for cosmic rays, scattering turbulence, and large-scale magnetic field, using the time-dependent acceleration code RATPaC. The main uncertainty in our prediction of the local 60Fe flux at about pc=1 GeV/nuc is the magnetic-field structure in the local bubble and the cosmic-ray diffusion beyond the approximately 100 kyr of evolution covered by our study. If the standard Galactic propagation applies, then the

local 60Fe flux would be around 3% of that measured. If there is a sustained reduction in the diffusion coefficient at and near the local bubble, then the expected 60Fe flux could be up to 3% of that measured.

Uphill Transport and Fractional Fick's Law for Energetic Particles at Interplanetary Shocks

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Abstract:

The prevailing theory of particle acceleration at shocks, known as diffusive shock acceleration (DSA) is based on the standard diffusion equation and predicts that, upstream of the shock, the energetic particle intensity exhibits an exponential growth, while downstream, it should form a constant, flat profile. However, these predictions often conflict with observations around shocks in interplanetary space which indicate a long power-law-like upstream density profile, while the downstream region exhibits a decreasing, non-flat density profile. This discrepancy leads to consider of a modified version of the ordinary Fick's law relating the macroscopic diffusive flux of energetic particles with the number density. As described by Calvo et. al (2007), in this formulation the spatial derivative of the number density is replaced by an extended spatial integration of a function depending on the density profile multiplied by a statistical weight that decreases with increasing distance from the point where the flux is being evaluated, which yields a non-local diffusive flux. Such expression is called the Fractional Fick's Law as it involves fractional order derivatives. We use a numerical Fortran90 code for evaluating the fractional flux using the trapezoidal rule for integration. This code is tested using the density profiles of accelerated particles at a numerically simulated shock in two scenarios: one involving normal diffusion and the other involving superdiffusion. Notably, in both cases, a downstream negative flux is observed, indicating the presence of uphill transport, i.e., transport in the same direction as the density gradient. Finally, the fractional flux is numerically evaluated using data from the ACE and Wind spacecrafts for two different shock crossings. In both events, uphill transport is observed, a quite interesting and counterintuitive result that allows for the correct interpretation of satellite observations, as well as shedding light on the physical processes underlying the acceleration of energetic particles at space and astrophysical shocks.

Magnetic field generation and particle acceleration in turbulent plasmas

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Abstract:

Magnetic fields and cosmic-ray electrons (CRe) play a crucial role in shaping the energetic environments of galaxy clusters and beyond. Using fully kinetic particle-in-cell simulations, we explore two interconnected phenomena: the genesis and growth of magnetic fields in initially unmagnetized turbulent plasmas and the reacceleration of fossil CRe in the intracluster medium (ICM). Magnetic fields in collisionless turbulent plasmas are generated through the Weibel instability and amplified via turbulence-driven dynamo action, achieving near-equipartition with the turbulent kinetic energy at saturation. Concurrently, CRe in the ICM—potential contributors to cluster radio halos, relics, and phoenices—can be reenergized through magnetic pumping facilitated by ion cyclotron (IC) waves during compression and dilation of the plasma. Our findings reveal that turbulence not only magnetizes collisionless plasmas but also boosts the energy of CRe by up to 30% per compression cycle, providing a pathway for explaining large-scale magnetic fields and diffuse synchrotron emission in galaxy clusters.

Welcome to Solar Maximum! Solar Orbiter observations of accelerated particles at interplanetary shocks

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Abstract:

Interplanetary (IP) shocks are important sites of particle acceleration in the Heliosphere and can be observed in-situ utilizing spacecraft measurements, thus providing one of the missing links to remote astrophysical environments. Solar Orbiter opened a new observational window for such shocks and their link to energetic particle production, yielding direct measurements at different locations in the inner heliosphere with unprecedented time and energy resolution in the suprathermal (usually above 50 keV) energy range. First, I will present the statistical properties of the first 100 shocks observed by Solar Orbiter up until the solar maximum of cycle 25, for which a full parameter characterization (shock normal, speed, Mach numbers, compression ratio, shock normal angle) was performed. I will briefly report on the link between shock parameters and acceleration efficiency. Finally, I will present two cases where IP shocks were found to accelerate protons (first case) and electrons (second case) to energies > 5 MeV. I will discuss the particle acceleration mechanisms inferred from such observations and how such insights may be relevant to other astrophysical shocks.

Bridging Simulations of Kink Instability in Relativistic Magnetized Jets with Radio Emission and Polarisation

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Abstract:

Relativistic outflows emanating from active galactic nuclei can extend up to kiloparsec scales in length, displaying a variety of complex morphologies. This study explores the intricate morphologies of such relativistic jets, mainly focusing on creating a bridge between magnetic instabilities in jets with observational signatures from complex radio galaxies. In particular, we aim to study the role of dynamical instabilities in forming distinctive morphological features by employing 3D relativistic magnetohydrodynamic (RMHD) simulations of rotating jets. Our simulations have further used the hybrid Eulerian-Lagrangian framework of the PLUTO code and generated the synthetic synchrotron emission and polarisation maps to compare with the observed signatures. Our analysis based on simulations of a continuously injected jet suggests that current-driven instabilities, notably the $|m|=1$ mode, generate rib-like structures that are seen in some of the recent radio galaxies using MeerKat, e.g. MysTail. In our contrasting simulations of the restarted jet, the kink- instability driven rib-like structures were formed relatively near the nozzle. In both cases, the jet dissipates its pre-existing magnetic energy through these instabilities, transitioning to a more kinetic energy dominant state. The turbulent structures resulting from this dissipation phase are filamentary and resemble the tethers as observed for the case of MysTail. This pilot study essentially provides a plausible qualitative explanation by bridging simulations of kink instability to produce synthetic radio features resembling the observed complex radio morphology of MysTail.

Transport of thermal and suprathermal electrons in the structured solar wind

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Abstract:

Electrons are a subsonic plasma species in the solar wind. Their kinetic behaviour is - to a much greater extent than the proton behaviour - the result of an interplay between global properties of the heliosphere and local plasma processes. The global properties of the heliosphere include the interplanetary electrostatic potential, the large-scale interplanetary magnetic field, and the density profile of the plasma. The local plasma processes include collisions, wave-particle interactions, and turbulence. Through this interplay, the electron distribution function develops interesting kinetic features that are observable in situ. In addition to a quasi-Maxwellian core, the distribution exhibits suprathermal populations in the form of the strahl and halo components as well as cut-offs due to loss effects in the interplanetary potential. We discuss the processes that shape the electron distribution in the solar wind, the interaction of electrons with local structures such as compressive waves and magnetic holes, and the impacts of these structures on the global electron transport in the heliosphere. The regulation of the electron heat flux is of particular interest in this context. We support these results with observations from Solar Orbiter and Parker Solar Probe. The presented results are an outcome of a two-year Italo-British collaboration project that was funded by the Royal Society and the Consiglio Nazionale delle Ricerche.

Connecting energetic electrons at the Sun and in the Heliosphere through X-ray and radio diagnostics

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Abstract:

One of the main objective of the Solar Orbiter mission is concerned with the production of energetic particles in the heliosphere, in particular with understanding how particles are released from their acceleration sources and distributed in space and time in the heliosphere. For energetic electrons, part of this question can be addressed by combining X-ray and radio observations. Indeed, while downward moving electrons produce X-rays in the chromosphere, upward moving electrons may generate coherent radio emissions when propagating through the corona, such as radio type III bursts. The launch of the Solar Orbiter in early 2020 marked a significant milestone, as it is equipped with the capability to simultaneously capture both types of emission. In this contribution, we shall present the first results derived from the comparison of X-ray flares observed by STIX in the 4-150 keV range on Solar Orbiter with radio type III bursts detected by RPW below 10 MHz on Solar Orbiter. The study focuses on 15 Interplanetary Type III radio bursts (IT3s) associated with HXR emission peaks, observed during the second commissioning phase of the STIX from November 17 to 21, 2020. Changes in the X-ray source morphology are found coinciding with the occurrence of IT3 emissions, and combined observations with the EUI instrument suggest a delayed access to existent open magnetic field lines within the active region. In the second part of the presentation we will investigate the link between the speed of the electron beams traveling outward (deduced from radio) and the energy density of the electrons traveling downward (deduced from X-rays). Indeed, assuming both electron populations share properties from a common acceleration region, some correlations should be found between these two quantities. Higher velocities in type III bursts are thus expected to be associated with a harder electron spectrum and larger beam density, as

inferred from X-ray observations, indicating a larger amount of high-energy electrons interacting with Langmuir Waves. We shall present results derived from the comparison of more than 20 flares observed by STIX and associated in time with radio type III bursts detected by RPW below 10 MHz.

Probing magnetic field geometries and turbulence in the immediate postshock regions of young supernova remnants using the Imaging X-ray Polarimetry Explorer (IXPE)

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Abstract:

The Imaging X-ray Polarimetry Explorer (IXPE) was successfully launched in December 2021. IXPE is the first X-ray satellite mission dedicated to X-ray polarization measurements with an imag- ing resolution of ~25″. For supernova remnants (SNRs) this in particular important to probe the magnetic field configurations in young SNRs, which emit X-ray synchrotron radiation from >10 TeV electrons. These relativistic electrons are only present near the acceleration sites, as they lose their energy rapidly. The acceleration also needs a high level of magnetic-field turbulence, in order to accelerate electron fast enough . So X-ray synchrotron emission comes from near the shock regions, unlike radio synchrotron radiation. It is long known from radio synchrotron polarization measurements that young SNRs have radially oriented magnetic fields, whereas older SNRs have tangentially oriented magnetic fields. The origin of the radial magnetic fields in young SNRs is not well understood. So the prime science for IXPE observations of young SNRs are: 1) what is the level of magnetic- field turbulence close to the shocks, given the turbulence needed for fast acceleration? 2) what is the magnetic- field topology close to the shocks, where a priori we expect tangential magnetic fields at the shock itself? IXPE has observed now a number of SNRs: Cas A, Tycho's SNR, SN 1006 (NE), RX J1713.7- 3946, RCW 86, and RX J0852-4622. Surprisingly, IXPE observed some SNRs with radial magnetic fields, indicating a stretching of magnetic-field lines very close to the shock, but also some with tangential magnetic fields lines. The inferred magnetic-field turbulence is high. I will discuss these findings in the context of theories magnetic-field turbulence generation, and theories about the origin of radial orientation of magnetic fields in young SNRs.

Exploring the Viability of Fluid Simulations as a PIC Alternative for Relativistic Reconnection

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Abstract:

Magnetic reconnection in relativistic plasmas is a key process driving particle acceleration in high-energy astrophysical environments. While particle-in-cell (PIC) simulations are the standard approach for studying these mechanisms, their computational cost is significant. We explore an alternative strategy using the relativistic 5-moment fluid model, solved with a finite-volume code, to investigate whether fluid simulations can capture particle acceleration mechanisms typically observed in kinetic simulations. By integrating tracer particles into the fluid framework, we extend its diagnostic capabilities to study individual particle dynamics, including energy spectra and acceleration processes. We present results from simulations of relativistic reconnection and compare them to PIC-based findings, highlighting the potential of fluid models as computationally efficient tools for understanding astrophysical particle acceleration.

Observations of Solar Energetic Particles (SEPs)

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Abstract:

The Sun occasionally accelerates particles (electrons, protons and heavier nuclei) up to relativistic energies. Today these are routinely measured at multiple locations in the heliosphere, that gigantic bubble that is carve d out of the very local interstellar medium by the solar wind. As the solar particles propagate through the heliosphere they are scattered off irregularities in the interplanetary magnetic field. With spacecraft at multiple – and constantly changing – locations in the heliosphere, we live in a "golden age" because the Sun and heliosphere offer an accessible laboratory to study the universal physics of particle acceleration and transport in situ. In my talk I will review recent observations of solar energetic particles (SEPs) which are made possible by measurements at multiple spacecraft and by new, high-resolution measurements.

The role of electrons in the propagation of nonlinear electrostatic waves

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Abstract:

This study explores the role of kinetic electrons in the excitation and sustainment of ion-bulk (IB) electrostatic waves in collisionless plasmas using Vlasov-Poisson simulations. We show that energy supplied by an external driving electric field, used to trigger IBk wave excitation, is transferred to electrons, resulting in the formation of a characteristic "flat-top" velocity distribution commonly observed in the solar wind and magnetosphere. Additionally, long-lived electrostatic structures, associated with phase-space holes in proton and electron distributions, persist well after the external driver is removed. To support these findings, we employ a virtual instrument technique simulating spacecraft measurements, demonstrating how deviations from Maxwellian distributions arise in plasma turbulence. These results highlight the critical role of kinetic electrons in driving and sustaining nonlinear electrostatic fluctuations, providing new insights into small-scale turbulence in space plasmas.

Flux Ropes, Turbulence, and Collisionless Shocks

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Abstract:

Using a combination of theory, numerical simulations, and observations, we have undertaken an extensive investigation of the interaction of magnetized turbulence with collisionless shocks in the solar wind. The nature and character of turbulence is of course critical to the energization of particles at shock waves throughout the universe. We will begin by presenting new theoretical approaches to the transmission and generation of turbulent fluctuations at a collisionless shock before discussing supporting simulations of the theory. We will conclude with an extensive set of observations using a variety of different techniques, including a recently developed extension of a linear mode decomposition analysis, to illustrate the effectiveness of the theory in explaining a range of observed features downstream of interplanetary shocks.

Study of the September 5, 2022, coronal mass ejection event with remote observations, numerical simulations, and in situ measurements: the puzzle of energetic particle spectra

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Abstract:

A very fast coronal mass ejection (CME) was ejected on September 5, 2022, which was measured in situ by Parker Solar Probe (PSP) and Solar Orbiter, and observed remotely by Stereo-A, SOHO and PSP. Here, we carry out the reconstruction of the CME in the corona by using SOHO/LASCO, STEREO-A/COR2, and PSP/WISPR data. The obtained CME parameters are used as an input for an MHD simulation of an erupting flux rope with the PLUTO code starting from RIMAP, a method which reconstructs the heliosphere on the ecliptic plane from in situ measurements acquired by spacecraft with heliocentric orbits. Then we analyze in-situ Solar Orbiter measurements at 0.7 AU to check the results of the RIMAP simulation and to study the CME-driven shock properties and the level of magnetic turbulence around the shock. Large fluxes of energetic particles accelerated in situ are measured by Solar Orbiter/EPD instrument in the 111 keV-3700 keV energy range; such energetic particles cause an amplification of magnetic fluctuations. Analyzing the upstream energetic particle time profiles, the transport regime of accelerated particles is found to be normal, although non Gaussian features are also present. As a surprising result, we find that the energetic particles differential flux at Solar Orbiter has a spectral index harder than that predicted by diffusive shock acceleration for the measured compression ratio. The possible reasons for such a discrepancy are discussed.