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PARASOL: A NOVEL SIMULATION MODEL FOR FORECASTING SOLAR ENERGETIC PARTICLE EVENTS

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Gradual solar energetic particle (SEP) events are attributed to particle acceleration in shock waves driven by coronal mass ejections (CMEs). These events have significant space-weather effects, prompting ongoing efforts to develop models capable of forecasting their characteristics. Here we present a new such model, PARASOL. PARASOL is an extension of the PArticle Radiation Asset Directed at Interplanetary Space Exploration (PARADISE) test-particle simulation model of SEP transport. Its key feature is a semi-analytical description of the inner foreshock region (near the shock), constructed using simulations from the SOLar Particle Acceleration in Coronal Shocks (SOLPACS) model, which simulates proton acceleration self-consistently coupled with Alfvén wave generation upstream of the shock. PARASOL requires magnetohydrodynamic (MHD) parameters of the solar wind and the shock as inputs. To evaluate the PARASOL performance, we simulated the 12 July 2012 SEP event using the EUropean Heliospheric FORecasting Information Asset (EUHFORIA) MHD simulation of the solar wind and CME for this event. The PARASOL simulation successfully reproduced the observed energetic storm particle (ESP) event ($E \geq 5$ MeV) near the shock, achieving an intensity within one order of magnitude of the observations.

Modelling coronal magnetic fields and investigating the "missing open flux problem" with project SOFTCAT

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The magnetic field in the solar corona consists of two distinct structures, the closed and the open magnetic field lines. The closed ones stay confined in the inner corona and can be traced between two opposite polarity foot-points in the photosphere. The open field lines extend beyond the corona and form the interplanetary magnetic field (IMF). Our current knowledge and understanding of the IMF come from in situ measurements at various locations in the interplanetary space and remote sensing observations of the photospheric magnetic field and plasma. According to the standard paradigm, the primary source of the open magnetic field are coronal holes (CHs). Open flux refers to the magnetic flux from the Sun that is carried away by the solar wind and permeates the whole heliosphere. Current estimations from measurements at Earth's heliodistance are approximately 2-3 times higher than the flux estimated to escape the Sun according to models and solar observations. This is known as the "missing open flux problem" and it is at the core of the SOFTCAT project which aims at identifying and quantifying sources of open flux. We follow three paths of investigation: (1) numerically quantify the open flux that is released due to interplay between open and closed field in the area surrounding a coronal hole, (2) investigate the observable properties of coronal holes and their surrounding region, focusing on microstructures that are not currently directly linked to open field topology but might play a significant role in the final open flux, and (3) explore the possibility of interplanetary open flux sources.

Magnetohydrodynamic simulations of coronal active regions initialized by Data-driven time-dependent Magnetofrictional model

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The data-driven time-dependent magnetofrictional method (TMFM) is a robust method for simulating the building up of pre-eruptive structures in the solar corona. Using this method to initiate magnetohydrodynamic (MHD) simulations can give us a powerful tool for studying the building up, evolution, and eruption of solar corona eruptive events.

The most important feature of TMFM is its capability of directly incorporating observational data. Additionally, the simplification of TMFM makes its computational cost much lower than MHD, however, these simplifications limit TMFM applicability to semi-steady evolving systems. To leverage these aspects of TMFM while capturing the fast dynamic evolution of the eruptive solar coronal events we have utilized data-driven TMFM, initialized with observational data to provide a more realistic initial condition for the magnetic field in MHD, then, close to the expected fast eruption, we carried out the simulation using MHD model. Our goal in choosing this approach was to use a fast and efficient data-driven model to provide more realistic initial conditions for the magnetic field in MHD and study the dynamic of the eruptive event in a more robust model, MHD.

To examine our approach, we studied the NOAA active region 12673. Our test combined data-driven TMFM with an ideal zero-β MHD model. In our simulations, we observed a raising twisted flux system. This flux system erupted in simulations in which the model was changed from data-driven TMFM to MHD close to the time of the eruption in observations. Our simulations also indicated that the primary factors in the eruptive event are the torus instability and the presence of the slip-running reconnection.

Our simulations indicate that the combined data-driven TMFM and zero-β MHD method is reliable for modeling coronal magnetic field eruptions.

Comparing coronal densities and large-scale structure between solar rotational tomography and global 3D magnetohydrodynamic simulations

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Given the widespread use of magnetohydrodynamic (MHD) models in solar physics, ensuring their accuracy and reliability is crucial. Comparisons such as this study highlight their advantages and disadvantages as well as stress the importance of solar rotational tomography techniques to help place constraints on both current and future models. The motivation for this study is to provide a comparison between coronal electron density maps produced using the Magnetohydrodynamic Algorithm outside a Sphere (MAS) 3D global MHD model and a solar rotational tomography (SRT) technique. The study spans the duration of an entire solar activity cycle from March 2007 to late 2023. The dependence of the electron densities on latitude and heliocentric height is compared, with densities comparing best at the equatorial regions and lower heliocentric heights. The streamer and non-streamer regions are compared separately, as well as the average width of the streamer belt over the duration of solar cycle 24. The MHD model densities typically contain more fine-scale detail than the tomography, but there is a very good overall agreement in structure and location of high-density features between both sets of densities. The tomography densities are most accurate in the polar regions, since the MHD model uses photospheric magnetogram input which is unreliable at the poles due to projection effects.

SEP modelling with an advanced flux rope CME model

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The newest CME models introduced in the EUHFORIA solar wind software, developed at KU Leuven, include the computationally expensive Flux Rope in 3D (FRi3D) model. This CME model provides a more realistic description of the magnetic field structure of a CME since it is not radially symmetric and has no spherical shape like older models. Due to its separate legs, it allows for a more realistic prediction when a CME hits Earth with its flank.

However, these novel flux rope CME models are computationally expensive. To address this, an optimisation method has been developed to speed up the calculation of the FRi3D model by storing the 3D structure of the CME in a separate datacube that can be reused in various solar wind predictions. This method, called the datacube method, simplifies the calculations and reduces computation time by a factor of five in low resolution. This optimization also makes it possible to obtain high-resolution runs of the FRi3D model, which were previously difficult to achieve due to high computation times. Since these novel flux rope CME models provide more realistic representations of CMEs, whether they yield more accurate results regarding simulations of Solar Energetic Particles (SEPs) is being investigated. For this purpose, high-resolution solar wind predictions are required to serve as input values for simulations that include SEPs, for which the PARADISE software is utilized to solve the Focused Transport Equation (FTE).

Using PARADISE, electrons are injected into the legs of the simulated CME, which serve as probes for its three-dimensional structure as electrons flow along the magnetic field lines of the flux rope. As a result, bidirectional electrons are simulated at the front of the CME, appearing when electrons are injected into both legs and inside one leg. This observation is referred to as counterstreaming electron beams and corresponds to observations at Earth during the passage of a CME, proving the validity of the FRi3D CME model. Additionally, by altering the mean free path of the simulated electrons, simulations for which the value of the mean free path is around 5-10 AU provide the most accurate results compared to in-situ observations.

Open-Source Python Tools for the Analysis of Energetic Solar Eruptions

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The recently expanded fleet of heliospheric spacecraft presents unique opportunities for explor- ing solar eruptive phenomena such as coronal mass ejections (CMEs) and solar energetic particles (SEPs) from multiple vantage points. However, the task of integrating diverse obser- vations collected by different instruments across various spacecraft poses a notable challenge. To maximize the utilization of this data within the broader scientific community, the EU Horizon 2020 project SERPENTINE aimed to offer a versatile array of tools. These tools, provided as open-source Python Jupyter Notebooks, cater to scientists with limited programming expertise. Alongside comprehensive examples illustrating the utilization of the multi-spacecraft spatial setup and solar magnetic connection plotter Solar-MACH, an analysis platform for studying the energetic particle component of the in-situ observations of SEP events has been developed. This analysis platform comprises different visualization and analysis tools. Here we provide an overview of the available toolkit and instructions on its utilization, which can be seamlessly accessed on the project's dedicated JupyterHub server in the cloud. Although the SERPENTINE project has been concluded in 2024, the tools will be further supported and extended through the just launched EU Horizon Europe project SOLER.

CHALLENGES IN DETECTING THE MAGNETIC SWITCHBACKS WITH PARKER SOLAR PROBE OBSERVATIONS

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The magnetic field in the solar corona typically follows a Parker spiral topology with curvature dictated by the speed of the expanding plasma. This idealized picture is often interrupted by the localized deflections from the nominal direction of the magnetic field, often accompanied by an enhancement in the solar wind velocity. They were discovered with Ulysses observations at 2.4 au in 1976 and considered as rare events. However, with the launch of Parker Solar Probe in 2018, it became clear that they are abundant in smaller heliodistances (0.16 au) and raised attention in the literature due to its possibility to address some of the unanswered questions in heliophysics, such as the open flux problem we investigate with project SOFTCAT. Despite the interest, the rediscovery of switchbacks brings forth challenges, due to their unclear properties and being open to all forms of interpretations. In our case, the biggest challenge originates from the lack of consensus of its definition. Various methods and criteria for detecting switchbacks have been proposed, complicating efforts to standardize an identification algorithm. To address this, multiple algorithm versions are created based on a thorough literature review, aiming to assess how different definitions influence the detection and interpretation of switchbacks.

Quantifying Uncertainties in Solar Wind Forecasting Due to Incomplete Solar Magnetic Field Information

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Reliable solar wind forecasting requires robust modeling, yet significant uncertainties persist, particularly due to limited observational coverage of the Earth-Sun system. Current solar magnetic field maps, derived primarily from Earth-based observations, rely on assumptions that introduce errors, especially for poorly observed regions like the solar poles and far side.

To address these limitations, two approaches are widely used: synoptic charts, which introduce aging artifacts, and surface transport models, which simulate magnetic flux transport but lack observational data from unobserved regions. Advanced instrumentation, such as the Solar Orbiter's Photospheric and Magnetic Imager, offers partial far-side observations, yet comprehensive coverage remains rare. Missing far-side active regions can significantly influence both local and global magnetic structures, further complicating space weather forecasting.

This study quantifies the uncertainties in solar wind modeling arising from incomplete magnetic field information. Using artificial magnetograms to emulate key uncertainties in operational magnetic charts, we evaluate their impact across three solar wind models over one artificial solar rotation. The findings highlight the critical need for improved observational strategies and advanced modeling techniques to enhance the accuracy of space weather predictions.

Prediction of Extreme Space Weather Events Using Vigil-like Data

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The Vigil mission, planned by the European Space Agency, will monitor space weather activity, providing warnings about threats coming from the Sun earlier than current missions allow. Until the data from Vigil is available, we can use measurements from other missions of the heliophysics fleet and consider their similarities to Vigil. Specifically, we focus on the most extreme events of the last 30 years. Our goal is to answer the following questions: Would it be possible to predict the occurrence of extreme space weather events if the Vigil mission was in operation at that time? Is it beneficial to use Machine Learning (ML) techniques for these predictions? In our contribution, the concept of Vigil-like instruments is introduced to describe existing space-based instruments with capabilities similar to those planned for Vigil. Moreover, methods for the community to access and process this data is presented. Finally, the poster focuses on our major ML tasks, including how the segmentation of coronal structures can be useful and what is the potential of Vigil-like in-situ measurements in the early prediction of extreme events. These tasks are under development within the ongoing study supported by ESA through the RPA program in Slovakia.

Simulating electron acceleration in shocks

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The presence of energetic electrons in the heliosphere is associated with solar eruptions, but details of the acceleration and transport mechanisms are still unknown. We explore how electrons interact with shock waves under the assumptions of shock drift acceleration (SDA), diffusive shock acceleration (DSA), and stochastic shock drift acceleration (SSDA). Consideration of the shock wave parameter space, such as shock speed, shock obliquity, shock thickness, and plasma density upstream of the shock, helps determine electron spectra and their highest energies. With suitable simulation parameters, the model is able to accelerate thermal electrons to relativistic energies and, additionally, to produce an electron beam upstream of the shock wave, a requirement for the type II radio burst seen in radio observations associated with shock waves and particle acceleration.

This presentation delves into the results of the presented model in regards to electron acceleration and transport within shock waves, contributing to our understanding of solar and interplanetary phenomena and their practical applications in space weather forecasting.

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Time-dependent electrogram-driven modeling of the solar corona at global scales

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Time-dependent data-driven modeling of the solar coronal magnetic field has emerged as a new tool for unraveling the dynamics of solar active regions in particular. Driven directly by observed changes of the photospheric magnetic field, these models hold the promise of self-consistently capturing the complex chain of events from the formation to the destabilization and subsequent eruption of structures hosted in active regions. Detailed modeling of this kind has typically been carried out in local Cartesian domains, whereby any longer-range interaction between active regions is neglected and dynamics in the extended corona cannot be studied.

In this work, we discuss our efforts to extend our coronal modeling capabilities to global full-Sun domains while retaining high spatial resolution in localized areas via mesh refinement techniques. The use of a hierarchy of computational meshes requires special attention when constructing the photospheric electrograms that drive the model. More pressingly, constructing global photospheric electrograms over large spatiotemporal domains introduces unique challenges due to the limited availability of high-quality vector magnetogram observations. In this work, we describe our model and methodology and showcase recent results of eruptive structures that can now be followed to the upper corona and nascent solar wind.

Comparing Twist Metrics for Ideal Flux Ropes

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The onset and evolution of coronal flux ropes are key areas of space weather research. Understanding magnetic twist, a fundamental property of flux ropes, is essential for studying such areas. The winding number is approximated in literature to varying degrees of accuracy by a multitude of twist metrics. Such approximations are often used due to their relative simplicity. However, these have been shown to require careful interpretation due the approximations employed. In this study, we utilise the magnetic field analysis tools (MAFIAT) software to compare twist metrics to the winding number for several ideal flux rope models.

ARCANE: An Operational Framework for Automatic Realtime ICME Detection in Solar Wind In Situ Data

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Interplanetary Coronal Mass Ejections (ICMEs) are the primary drivers of space weather disturbances, necessitating accurate and timely detection to mitigate their impact. However, traditional identification methods often rely on post-event analysis, which limits their application in real-time forecasting scenarios.

We introduce ARCANE, an operational, modular framework for the automatic, real-time detection of ICMEs in solar wind in situ data. ARCANE combines machine learning models with physics-based approaches, leveraging data from multiple spacecraft to enable early detection and enhance forecasting capabilities. The first prototype of the framework, trained on OMNI data, has been evaluated on real-time solar wind datasets, demonstrating its potential for operational use.

This poster presentation outlines the methodology underlying ARCANE, highlights the challenges of adapting machine learning models for streaming data, and discusses the framework's operational implementation at the Austrian Space Weather Office. Future development directions include enhancing real-time performance, integrating early predictions of key ICME parameters, and extending ARCANE's applicability to multi-spacecraft data for improved global space weather forecasting.

Modelling the Sun-to-Earth Propagation of CMEs Using a Novel Flux-Rope Model

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One of the major challenges in space weather forecasting is to reliably predict the magnetic structure of interplanetary coronal mass ejections (ICMEs) in the near-Earth space. In the framework of global MHD modelling, several efforts have been made to model the CME magnetic field from Sun to Earth. However, it remains challenging to deduce a flux-rope solution that can reliably model the magnetic structure of a CME. Aiming to improve the space-weather forecasting capability, we implement a new flux-rope model in “European heliospheric forecasting information asset” (EUHFORIA). Our flux-rope model includes an initially force-free toroidal flux-rope that is embedded in the low-coronal magnetic field. The embedding technique adds a significant novelty to the state-of-the-art as it preserves the continuity condition of the magnetic field at the flux-rope boundary and maintains the force-free solution of the flux rope. The dynamics of the flux rope in the low and middle corona are solved by a non-uniform advection constrained by the observed kinematics of the event. This results in a global non-toroidal loop-like magnetic structure that locally manifests as a cylindrical structure. At heliospheric distances, the evolution is modeled as a MHD process using EUHFORIA. We assess our model results on several ICMEs, including cases of interacting events. Comparing the model results with the in-situ magnetic field configuration of the ICME at 1 au, we find that the simulated magnetic field profiles of the flux-rope are in very good agreement with the in-situ observations. Therefore, the framework of toroidal model implementation as developed in this study could prove to be a major step-forward in forecasting the geo-effectiveness of CMEs.

CHARACTERIZING PROPERTIES OF SOLAR ERUPTIONS WITH X-RAY SPECTROSCOPY

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The temporal evolution of elemental abundances during solar flares has been studied extensively from soft X-ray observations. These parameters are of particular interest because of the coronal first ionization potential (FIP) bias: the abundances of low FIP elements are observed to increase at flare onset when X-ray emission from the flare dominates the solar X-ray spectrum, and decrease towards photospheric values during the impulsive phase of the flare. Recovery times appear to depend on the time plasma is trapped within the magnetic field. Recent results suggest that the recovery time depends on CME occurrence, but the details of this connection are not currently understood.

In this work, we employ X-ray spectroscopy to provide a detailed account of flare characteristics in relation to properties of the associated CME. Our aim is to demonstrate how the CME affects the evolution of the soft X-ray spectrum. We use soft X-ray data from the SUNSTORM 1 X-ray Flux Monitor for CubeSats (XFM-CS) to study the temporal evolution of plasma parameters and elemental abundances. These results are supported by hard X-ray image reconstructions made with the The Spectrometer Telescope for Imaging X-rays (STIX) instrument on board Solar Orbiter, and connected to CME kinematics.

Straight Outta Photosphere: Open solar flux without coronal modeling

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We present a new method for reconstructing the open solar flux (OSF) directly from the photospheric magnetic fields without making assumptions about the corona or using coronal hole observations. We apply the method to the synoptic magnetograms of six instruments to find the OSF from solar cycles 21–24. The method produces a sum vector depicting the strength and orientation of the global solar magnetic field. The magnitude of the sum vector closely matches the OSF from the PFSS model both by the absolute scale and the time evolution for each of the six magnetograms. The latitudinal evolution of the sum vector aligns with the Hale cycle, while the angle between the sum vector and the solar rotation axis closely corresponds to the tilt angle of the heliospheric current sheet. The sum vector longitude coincides with the location of the coronal holes of the McIntosh Archive. We find multi-year periods during which the sum vector longitude slowly drifts or remains stationary in the Carrington frame. By varying the source surface height of the PFSS model, we find that the best match between the vector sum and OSF is produced when the source surface height is set to 2.4–2.5 $R_\odot$.

Efficient and Quasi-realistic Magnetohydrodynamic Modeling of Coronal Mass Ejection Propagation and Evolution

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Abstract:

Coronal mass ejections (CME) are one of the main drivers of space weather. However, quasi-realistic and efficient numerical modelling of the CME propagation and evolution process in the whole solar-terrestrial space, especially in the sub-Alfvénic corona, is still lacking. Recently, we have made some attempts to improve our ability to model CMEs. 1. We developed an efficient and quasi-reliable time-evolving MHD coronal model which can be used to provide inner-boundary conditions for the inner heliosphere models in practical space weather forecasting. 2. We developed an efficient and time-accurate MHD model of the solar corona and CME to timely and accurately simulate time-varying events in solar corona with low plasma β. 3. We developed an extended magnetic field decomposition strategy to improve the numerical stability of the time-evolving MHD coronal models in solving low-β issues. 4. By extending the coronal model to 1 AU or coupling the coronal model with an inner heliosphere model, we are now conducting some faster-than-real-time CME simulations from the solar surface to 1 AU. These MHD models are demonstrated to be very efficient and numerically stable and are promising to timely and accurately simulate time-varying events in solar-terrestrial space for practical space weather forecasting.

ESTIMATION AND LIMITS OF MHD SIMULATIONS FOR PREDICTING EXTREME EVENTS

TITLE OF THE PRESENTATION

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Many questions have to be answered before understanding the relationship between the emerging magnetic flux through the solar surface and the extreme geoeffective events. Which threshold determines the onset of the eruption? What is the upper limit in energy for a flare? Is the size of sunspot the only criteria to get extreme solar events?

Based on observations of previous solar cycles, and theory, the main ingredients for getting X ray class flares and large Interplanetary Corona Mass Ejections e.g. the built up of the electric current in the corona, are presented such as the existence of magnetic free energy, magnetic energy/helicity ratio, twist and stress in active regions. The upper limit of solar are energy in space research era and the possible chances to get super- flares and extreme solar events can be predicted using MHD simulation of coronal mass ejections (EUHFORIA). Arrival time of eruptive flares/CMEs are discussed in this context versus examples (events of May 2024).