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Modelling and automatic detection of ICMEs to enhance real-time space weather predictions

Ute V. Amerstorfer[1], and the team of the Austrian Space Weather Office

[1] Austrian Space Weather Office, GeoSphere Austria, Graz, Austria

Coronal mass ejections (CMEs) are the primary cause of severe space weather at Earth, impacting both satellite operations and ground infrastructure. This highlights the need for accurate space weather predictions to enable timely responses. The complex processes affecting CMEs during their propagation through the heliosphere make it difficult to accurately forecast their arrival time and magnetic configuration near Earth.

By combining different approaches developed in our group, both ML and non-ML, we try to enhance our basic understanding of CMEs and our real-time space weather predictions. With the semi-empirical 3D coronal rope ejection (3DCORE) method we can reconstruct magnetic flux ropes of interplanetary CMEs (ICMEs) by fitting the model to in situ observations. We applied 3DCORE to multi-spacecraft events such as the Parker Solar Probe and Solar Orbiter lineup event in September 2022 to study the variability of CMEs. Recently, we tested the ability of 3DCORE to reconstruct the ICME magnetic field rotation from only the first couple of hours of L1 in situ data. In this way, we mimic a real-time application. We then feed the reconstructed magnetic field into our implementation of the Temerin and Li model to obtain predictions of the Dst index. Further, ARCANE is a framework that utilises deep learning to automatically detect ICME signatures in in situ data in real-time. Eventually, we plan to combine 3DCORE and ARCANE to have a prediction pipeline from the automated detection of ICMEs to their geomagnetic effects.

Can sub-flaring activity in solar active regions warn us of imminent major events?

André-Hoffmann, A.N.J.P.N.L.[1,2], Nindos, A[1], Patsourakos, S[1], Georgoulis, M.K.[3,4], and Erdélyi, R.[2],

[1] University of Ioannina, Greece
[2] University of Sheffield, UK
[3] Academy of Athens, Greece
[4] Johns Hopkins Applied Physics Laboratory, USA

The Sun is a dynamic star, displaying activities ranging from subtle, short-lived events to major coronal mass ejections (CMEs) and powerful flares. Differentiating between "flaring" and "non-flaring" active region (AR) configurations is critical for heliophysics research. This study investigates whether small to medium-scale activity in ARs holds clues about their eruptive potential and future behaviour. Using data from the Atmospheric Imaging Assembly (AIA) and the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO), we analyse transient brightenings and their relationship to the magnetic polarity inversion line (PIL) in ARs.

We observe significant differences between pre-flaring and non-flaring ARs in terms of the spatial distribution and temporal evolution of transient brightenings around the PIL. Key parameters include the number, intensity, and magnetic flux of brightenings over time, as well as their behaviour across multiple wavelengths. These variations offer insights into the Sun's atmospheric dynamics and the mechanisms driving major flares and – in case of coronal mass ejections – eruptions. By understanding the pre-eruptive activity in ARs, we aim to improve solar event prediction capabilities and advance our knowledge of the relevant dynamics.

Space climate predictions from the viewpoint of solar effects on climate

Asikainen, T.[1], Salminen, A.[1], Vokhmianin, M.[1], Juntunen, V.[1], Qvick, T[1]., Mursula, K.[1], Mantere, J.[1], Tähtinen, I.[1]

[1] Space Physics and Astronomy Research Unit, University of Oulu

There is ever growing evidence that long-term variability of solar activity (space climate) impacts not only Earth’s magnetic environment, but also the atmosphere and the climate system down to the ground level. This influence is exerted by solar irradiance and precipitation of charged particles from space into the atmosphere. For example, it has been shown that precipitation of auroral and more energetic particles from radiation belts leads to formation of HOx and NOx species in the atmosphere, which at mesospheric and stratospheric altitudes can destroy ozone during winter season. Ozone loss, on the other hand, changes the air temperature, winds and various types of atmospheric waves. One specific consequence of particle precipitation is its influence on northern stratospheric polar vortex that exerts a significant impact on wintertime ground weather, e.g., in Northern Europe and Finland.

This being said, it is clear that long-term predictions of solar activity and geomagnetic activity hold an interesting potential to improve seasonal to decadal scale forecasts of average weather conditions. In this talk, I summarize some of our recent efforts to develop solar cycle predictions for geomagnetic activity and sunspots, and show how they can improve long-term predictions of the polar vortex and resulting ground weather in the winter season.

The art and challenges of science communication

Asvestari, E.[1]

[1] Faculty of Science, Department of Physics, University of Helsinki

Science communication is an essential link between research and society. It helps engage the public with research, instil trust in research findings, inspires the next generation of researchers, and attract the interest of stakeholders. Whether you communicate your own research or promote scientific knowledge from a wide range of research areas, science communication is an art that one must master. During this talk, we will explore why it is important to engage in science communication, how to begin practising it, how to find your niche, and what challenges you will face along the way. We will learn the best practices in communicating science, such as filtering the information you communicate, aligning your language to that of your audience, the power of body language and emotions, and how to survive objectors and confrontations that may arise. The aim is to motivate you to engage in science communication and to provide you with some tools and practical examples for doing it effectively.

Time Series Analysis of PILs in Pre-Flaring Ars

Shreeyesh Biswal

University of Sheffield, UK, University of Ioannina, Greece, Academy of Athen, Greece

Polarity Inversion Lines (PILs) are neutral lines that demarcate flux patches of opposite polarities in the lower solar atmosphere (LSA) of the Sun. In general, it is known that in flaring Active Regions (ARs), PILs are longer and more prominent when compared to flare-quiet ARs. It has been further shown that appearance of compactly spaced PILs arising out of collisional shearing between converging bipoles in complex sunspots is connected to flare productivity. In this regard, (i) the total length of PILs and (ii) the length of the longest PILs are widely studied as flare precursors. In the current presentation, we explore whether the temporal variation of these two parameters could offer hints about flare occurrence, and act as flare activity precursors. Assuming that PILs are closely related to physical processes occurring in the LSA such as flux emergence and flux cancellation due to collisional shearing, we also assess whether these parameters undergo significant changes in mean and variance prior to the occurrence of flares. Our assessment is based on binary classification checks using an autoregressive model for the stationarity or non stationarity, assuming that the evolution of these two parameters are stochastic processes.

Enhancing Solar Feature Detection and Exploring Activity Patterns with Mathematical Morphology

Slava Bourgeois[1,2], Simone Chierichini[2,3], Andreas Wagner[4,5], Teresa Barata[1], Ricardo Gafeira[1], Robertus Erdélyi[2,6,7], Szabolcs Soós[6,7], Marianna Korsós[6,8], and Jiajia Liu[9,10]

[1] Instituto de Astrofísica e Ciências do Espaço, University of Coimbra, Coimbra, Portugal
[2] Solar Physics and Space Plasma Research Centre (SP2RC), School of Mathematical and Physical Sciences, University of Sheffield, Sheffield S3 7RH, UK
[3] Department of Physics, University of Rome "Tor Vergata", Via della Ricerca Scientifica 1, Rome I-00133, Italy
[4] Department of Physics, University of Helsinki, P.O. Box 64, FI-00014, Helsinki, Finland
[5] CmPA/Department of Mathematics, KU Leuven, Celestijnenlaan 200B, 3001 Leuven, Belgium
[6] Department of Astronomy, Eötvös Loránd University, Pázmány Péter sétány, 1/A, Budapest, Hungary
[7] Gyula Bay Zoltan Solar Observatory (GSO), Hungarian Solar Physics Foundation (HSPF) Petőfi tér 3, Gyula H-5700, Hungary
[8] School of Electrical and Electronic Engineering, University of Sheffield, Sheffield S1 3JD, UK
[9] National Key Laboratory of Deep Space Exploration, Deep Space Exploration Laboratory/School of Earth and Space Sciences, University of Science and Technology of China (USTC), Hefei 230026, China
[10] CAS Key Laboratory of Geospace Environment, USTC, Hefei 230026, PR China

This study applies mathematical morphology (MM) algorithms to solar images from observations and simulations to identify and analyse key solar features associated with solar eruptions. Using MM, sunspots were automatically detected in Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) intensity images, achieving results comparable to established manual sunspot catalogues. Additionally, magnetic flux rope structures were extracted from simulation-derived twist number maps, improving understanding of their morphology and the conditions for confinement or eruption. MM algorithms were also employed to identify all coronal off-limb structures visible in the SDO/Atmospheric Imaging Assembly (AIA) 304 Å channel throughout Solar Cycle 24, encompassing coronal loops, jets, and prominences. This analysis yielded a dataset of 877,843 structures, enabling statistical studies of their properties, including area, latitude, longitude, and intensity (corrected for AIA charge-coupled device degradation). The results revealed significant patterns: a clear butterfly diagram in latitude and the presence of preferred longitudinal regions of activity, known as active longitudes (ALs). These ALs provide valuable insights into the spatial distribution of solar activity and suggest pathways for advancing space weather forecasting.

The Machine Learning Revolution in Space Weather Forecasting

Camporeale, E.[1,2]

[1] Queen Mary University of London, UK
[2] University of Colorado, Boulder, CO, USA

Space weather forecasting is experiencing a transformative shift driven by the integration of machine learning (ML) techniques. These methods provide powerful tools to tackle the inherent complexity and nonlinearity of the Sun-Earth system, enabling rapid, accurate, and interpretable predictions of critical space weather phenomena. In this presentation, we will explore how ML is revolutionizing the field, focusing on both operational forecasting and fundamental research.

We highlight recent advancements in solar flare and coronal mass ejection (CME) prediction, leveraging deep learning architectures trained on multi-wavelength solar observations. Novel techniques, such as explainable AI (XAI), are being applied to extract physical insights, bridging the gap between black-box models and domain expertise. Additionally, ML is enhancing the forecasting of geomagnetic indices and radiation belt dynamics, addressing critical challenges for satellite operators and power grid managers.

By showcasing examples from operational systems and research prototypes, we emphasize the potential of ML to complement traditional physics-based models. The integration of ML with physics-informed approaches promises to improve forecast reliability and lead to new discoveries in heliophysics. This revolution underscores the importance of interdisciplinary collaboration, combining expertise in data science, space physics, and machine learning to meet the growing societal demand for actionable space weather forecasts.

This abstract of exactly 200 words has been completely generated by ChatGPT as a response to the prompt ‘Based on the abstracts sent to various conferences by Enrico Camporeale, please write a 200 words abstract titled 'The Machine Learning revolution in Space Weather forecasting' to be sent to the SWATNet Final Conference’. However, it is *exactly* what I am going to talk about.

Large Values of Solar Wind Density: Filament Material or Interaction?

Cid, C.[1]

[1] Space Weather Research Group, Universidad de Alcala

Large values of solar wind density are commonly associated with solar filament material. This material is expected to appear in the trailing part of interplanetary coronal mass ejections (ICMEs). However, in some cases these large values of density are identified in the nose of the ICMEs rising up an inconsistency in the spatial ordering of the filament material within the ICME. On the other hand, interaction between ICMEs has been pointed out as the necessary component to achieve large values of solar wind density. This presentation shows an analysis of the largest density values ever recorded in the solar wind at 1 AU aiming to determine if they are related to filament material or to interaction between solar wind transients.

Solar energetic particles studied within the SERPENTINE and SOLER projects

Dresing, N.[1], Vainio, R.[1], Jebaraj, I.[1], Wijsen, N.[2] Palmerio, E. [3], Rodríguez-García, L. [4], and the SERPENTINE and SOLER teams.

[1] Department of Physics and Astronomy, University of Turku, Finland
[2] Center for mathematical Plasma Astrophysics, KU Leuven, Kortrijk/Leuven, Belgium
[3] Predictive Science Inc., San Diego, CA, USA
[4] European Space Astronomy Centre, European Space Agency, Villanueva de la Ca{\~n}ada, Madrid, Spain

The two EU Horizons 2020 / Horizons Europe projects SERPENTINE (2021--2024) and SOLER (2024--2027), led by the University of Turku investigate the most energetic phenomena occurring at the Sun using the newly expanded unprecedented heliospheric spacecraft fleet including Solar Orbiter, Parker Solar Probe, BepiColombo, STEREO A, and near-Earth spacecraft. I will present the main efforts targeted towards gaining a new understanding of the generation of solar energetic particle events by exploiting multi-spacecraft measurements of the new fleet as well as analysis tools developed within the projects.

Challenges in understanding the evolution of CMEs from corona to heliosphere

Mateja Dumbovic[1]

[1] Hvar Observatory, Faculty of Geodesy, University of Zagreb

CMEs are magnetic plasma structures with twisted field lines that evolve in interplanetary space. They interact with the solar wind and heliospheric magnetic field which influence their propagation, expansion, and internal magnetic structure. We understand these processes on a global level; however, we are still lacking a detailed qualitative and quantitative understanding of the CME evolution on a level that could result in a reliable forecast. Our limitations are influenced by uncertainties in measurements as well as uncertainties in associating remote-to-insitu events and observation-to-model comparison. These challenges in understanding the evolution of CMEs from corona to heliosphere will be discussed in light of recent observational and modeling studies in which our group was involved.

Observations of Flares in the Lower Solar Atmosphere

Fletcher, L.[1,2]

[1] School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[2] Rosseland Centre for Solar Physics, University of Oslo, PO Box 1209 Blindern, NO-0315, Oslo, Norway

The overall paradigm of solar flares is well-known. An energy-bearing coronal magnetic field relaxes via magnetic reconnection to a lower energy state, and the energy released is converted and dissipated in the radiation flash that is a solar flare. The vast majority of the radiated energy comes from the solar chromosphere, and the structure and evolution of chromospheric features, such as flare "ribbons" provide vital clues to the `invisible' evolution of the magnetic field in the solar corona, on large and small scales. This talk will review observations of the flare chromosphere and discuss how they are interpreted to help us understand the development of coronal magnetic reconnection, and its consequence.

Improving Solar Flare Forecasts with Deep Learning

Francisco, G[1,2], Barata, T[2], Fernandes, J[3], and Del Moror, D[1],

[1] Department of Physics, University of Rome Tor Vergata, Rome, Italy

[2] IA, Instituto De Astrofisica E Ciencias Do Espaço, University of Coimbra, Coimbra, Portugal

[3] CITEUC, Geophysical and Astronomical Observatory, University of Coimbra and Department of Mathematics, Coimbra, Portugal

Solar flares are characterized by explosive releases of magnetic energy emitting radiation across the electromagnetic spectrum and are often accompanied by SEPs. Such intense emissions pose risks to Earth's technological infrastructure, including satellite communications, navigation systems, and power grids, as well as to human health in the context of space missions and high-altitude flights. Accurate and reliable solar flare prediction is therefore critical for effective space weather preparedness and risk mitigation. However, the complex dynamics underlying solar activity make precise fore- casting a persistent challenge. This project investigates the application of deep learning — a branch of artificial intelligence that includes artificial neural networks and computer vision techniques — to advance solar flare prediction capabilities. Key contributions include (i) identification of limitations in existing performance evaluation methods and proposal of tailored evaluation methods to better address major challenges in flare forecasting models, (ii) introduction of a statistically robust cross-validation method for machine learning models trained on solar full-disk images, (iii) development of weakly- supervised learning frameworks to resolve spatial mislabelling issues, (iv) implementation of multimodal, spatio-temporal models leveraging coronal EUV observations for enhanced predictive performances, and (v) prototyping of a generative AI model for probabilistic simulations of the solar corona evolution.

Modelling Energetic Particle Transport in a Solar Coronal Flux Rope CME

Edin Husidic[1,2], Nicolas Wijsen[1], Immanuel Jebaraj[2], Luis Linan[1], Rami Vainio[2], and Stefaan Poedts[1,3]

[1]Centre for Mathematical Plasma Astrophysics, Department of Mathematics, KU Leuven, Celestijnenlaan 200B, 3001 Leuven, Belgium
[2]Department of Physics and Astronomy, University of Turku, 20014 Turku, Finland
[3]Institute of Physics, University of Maria Curie-Skłodowska, ul., Radziszewskiego 10,820-031 Lublin, Poland

Solar Energetic Particles (SEPs) can be accelerated at solar flares and at the fronts of shock waves driven by fast Coronal Mass Ejections (CMEs) to energies of several hundred MeV/nucleon. Their severe threat to spacecraft and astronauts has motivated the development of numerical models capable of improving our understanding of the underlying physics. A recent example is the PARADISE code, which has been extensively used in prior studies of particle acceleration and transport in the inner heliosphere (i.e., at solar radial distances $r > 0.1$ au). In this talk, we extend our studies to SEP transport in the solar corona (i.e., $r < 0.1$). Using the 3D MHD model COCONUT, we generate coronal background configurations, including a CME modelled as a modified Titov-Demoulin flux rope (TDFR). With PARADISE, we then inject energetic particles within the legs of the TDFR near their footpoints, and evolve the particles through the backgrounds. We also illustrate the effects of cross-field diffusion in these simulations. Finally, we highlight this model's potential for studies on CME dynamics, as well as particle acceleration and transport in an extended domain reaching from the solar surface up to Earth's orbit and beyond.

Particle Acceleration in Coronal Shocks

Annie John, Lidiya[1,2], Vainio, Rami[1], Afanasiev, Alexandr[1], and Poedts, Stefaan[2],

[1] University of Turku, Finland
[2] KU Leuven, Belgium

Solar Energetic Particles (SEPs), accelerated during solar flares and CME-driven shocks, are a critical concern due to their potential radiation hazards to spacecraft and astronauts. This study investigates the influence of adiabatic focusing, a process where magnetic field gradients guide particle motion, enabling SEPs to escape toward regions of weaker magnetic fields. Traditional Diffusive Shock Acceleration (DSA) models often overlook this mechanism, highlighting the need for a deeper understanding of its role in particle acceleration.

We incorporated realistic plasma parameters and magnetic field configurations from the COolfluid COroNal UnsTructured (COCONUT) model into our one-dimensional oblique shock framework which studies the effects of adiabatic focusing. Using Monte Carlo simulations, we analyzed how these realistic conditions compared to the impact of idealized homogeneous magnetic fields. The results highlight the significant role of magnetic field inhomogeneities in enhancing particle acceleration efficiency. This approach provides a foundation for refining mean free path models and further advancing the understanding of SEP transport and acceleration processes.

Assessment of Near-Sun CME Axial Magnetic Field Using Helicity Budget and Its Application in CME Propagation Models

S.Koya[1, 2], S.Patsourakos[1], M. K Georgoulis[3,4], A.Nindos[1] R. Sarkar[5], A.Maharana[6,7], A.Isavin[6], S.Poedts[6,2], K.Murawski[2]

Affiliations

1. University of Ioannina, Greece
2. University of M.ariia Curie-Skłodowska, Pl. M. Curie-Skłodowskaiej 11, Poland
3. Academy of Athens, Greece
4. Johns Hopkins Applied Physics Laboratory, USA
5. University of Helsinki, Finland
6. Centre for Mathematical Plasma Astrophysics, KU Leuven, Belgium
7. Royal Observatory of Belgium, Belgium

This work focuses on assessing the Coronal Mass Ejections (CMEs) axial magnetic field for forecasting purposes based on the conservation of magnetic helicity accumulated in active regions, which is transferred to CMEs upon launch. We studied a CME from 10 March 2022, observed in situ by both Solar Orbiter (SolO) and WIND, along with remote sensing observations. A helicity difference was observed in the pre- and post-eruptive source active region (NOAA AR 12962), which was transported by the CME. Assuming a Lundquist flux-rope model and using geometrical parameters (length and radius of the flux rope) from the Graduated Cylindrical Shell (GCS) CME forward-modelling technique, we estimated the near-Sun axial magnetic field of the CME at the GCS-fitted height. This estimate, along with in situ measurements from SolO and WIND at 0.43 AU and 0.99 AU, respectively, helps us understand the magnetic field evolution of the CME in the interplanetary medium. Our results align with studies that used near-Sun magnetic field measurements, such as those from the Parker Solar Probe mission.

Further, based on the CME's helicity budget, we introduce a new method to constrain the magnetic flux for inner heliospheric CME propagation models. To validate this method, we propagate the 10 March 2022 CME in the spheromak CME model within the EUropean Heliospheric FORecasting Information Asset (EUHFORIA) framework. This method uses the estimated magnetic helicity content of the CME to determine its axial field strength (B0), which is equated to the magnetic field strength (Bspheromak) at the spheromak's magnetic axis. From this, along with the radius estimate from CME's geometrical parameters, we derive the magnetic toroidal flux of the CME, which is then used in the EUHFORIA simulation. By modelling this CME from 21.5 Rs (insertion distance) to Earth, we assess how well in situ magnetic field measurements align with the model's predictions at 0.43 AU and 0.99 AU. The results show reasonable agreement, demonstrating the efficiency of our method.

Remote Sensing of Large-Scale Coronal Shocks, and Their Relation to Solar Energetic Particles

Kozarev, K.[1], Yotov, V.[1], Zucca, P.[2], Stepanyuk, O.[1], Nedal, M.[3], and Miteva, R.[1]

[1] Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences
[2] ASTRON, The Netherlands Institute of Radio Astronomy
[3] Dublin Institute of Advanced Studies

The lower and middle solar corona, up to about 20 Rs, is the most important region for early acceleration and transport of charged solar energetic particles (SEP) by coronal mass ejection-driven shock waves. These large-scale compressive fronts, which can start as low as 0.05 solar radii from the solar surface, propagate into a highly variable dynamic medium with steep gradients and rapidly expanding coronal magnetic fields. This modulates significantly the acceleration of SEPs at the shock/wave surfaces, and the way they spread into the heliosphere. In this talk, I will describe our group's efforts to characterize coronal shock waves with remote sensing methods, and to use this information to model the early acceleration and transport of SEPs. I will present recent results from multi-instrument observations of coronal shock fronts in EUV, visible and radio wavelengths, and how we track them automatically. I will then present results of SEP modeling, based on such observations. Finally, I will briefly discuss a recent eruptive event with unambiguous in situ detection of energetic electron beams that also caused coronal radio burst emission.

TITLE: Numerical Experiment on the Influence of Granulation-Induced Waves on Solar Chromosphere Heating and Plasma Outflows in a Magnetic Arcade

M. Kumar,[1, 2] K. Murawski[1], B. Ku´zma[3], E.K.J. Kilpua[2], S. Poedts[4,1], and R. Erdelyi[5, 6, 7]

1. Institute of Physics, University of M. Curie-Sklodowska, Pl. M. Curie-Sklodowskiej 1, 20-031 Lublin, Poland

2. Particle Physics and Universe Sciences (PAPU), Department of Physics, University of Helsinki, Helsinki, Finland

3. Shenzhen Key Laboratory of Numerical Prediction for Space Storm, Institute of Space Science and Applied Technology, Harbin Institute of Technology, Shenzhen, People's Republic of China.

4. Department of Mathematics / Centre for Mathematical Plasma Astrophysics, KU Leuven, 3001 Leuven, Belgium

5. Solar Physics and Space Plasma Research Centre (SP2RC), School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Hicks Building, Sheffield, S3 7RH, UK

6. Department of Astronomy, Eotvos Lorand University, Pazmany Petersetany 1/A, H-1112 Budapest, Hungary

7. Hungarian Solar Physics Foundation, Petofiter 3, H-5700 Gyula, Hungary

Abstract: This paper offers a fresh perspective on solar chromosphere heating and plasma outflows, focusing on the contribution of waves generated by solar granulation. Utilizing the 2.5-D numerical experiment in the partially ionized lower solar atmosphere, we investigate the dissipation of these waves and their impact on plasma outflows and chromosphere heating via ion-neutral collisions. Employing the **JO**int **AN**alytical and **N**umerical **A**pproach (JOANNA) code, we **adopt** the two-fluid model equations, examining partially ionized hydrogen plasma dynamics, including protons+electrons and neutrals, **treated as two separate fluids that are** coupled through ion-neutral collisions. Our investigation focuses on a quiet solar chromosphere region characterized by gravitational stratification and magnetic confinement by an initially set single magnetic arcade. The primary source of the waves is the solar convection beneath the photosphere. **Our results demonstrate that ion-neutral collisions result in the dissipation of such waves, releasing thermal energy that heats the chromosphere plasma.** Notably, this is accompanied by upward-directed plasma flows.

Applications of Machine Learning in Solar-Terrestrial Physics

Liu, Jiajia[1],

[1] University of Science and Technology of China

Machine learning techniques have witnessed rapid development in recent years. With the advancements in high-performance and fast computing as well as graphics processing units, a series of machine learning techniques, including neural networks, have been widely applied in fields such as biomedicine, face recognition, astronomy, graphic games, image and video generation. In this report, I will briefly introduce some of our research in applying machine learning techniques to solar-terrestrial space physics over the past few years, including the automatic identification of coronal jets on the solar limb, the prediction of the arrival time of Coronal Mass Ejections, and the reconstruction of the horizontal velocity field in the solar photosphere.

Most Extreme and Most Quiet Space Weather Periods of the Past 30 Years

Mackovjak, S.[1], Kostárová, S.[1], Majirský, A.[1,2], Amrich, S.[1]

[1] Department of Space Physics, Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[2] Department of Cybernetics and Artificial Intelligence, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Košice, Slovakia

The ESA mission Vigil will monitor space weather activity with the ambition to provide a timely warning of extreme solar events. Intending to enhance the reliability and timeliness of Vigil mission predictions, we have started a study that is focused on the most extreme events by using the data-driven approach. The ultimate goal of this study is to answer the following question by using Machine Learning (ML) techniques: Would it be possible to predict the occurrence of extreme space weather events, such as 'Halloween storms', if the Vigil mission was in operation at that time? During the talk, we will present the methodology for the identification of the most extreme space weather events in the last 30 years. The concept of Vigil-like instruments will be introduced to describe existing space-based instruments with capabilities similar to those planned for Vigil. The pipelines that might simplify access and processing of these data for the community will be presented, too. On the other hand, quiet periods with minimal solar activity also provide very interesting opportunities for studies of space weather events that are not driven by the Sun but originated on Earth. This dataset will also be presented together with possible implications for future research. The presented studies are supported by ESA through programs in Slovakia.

Solar Active Region Scaling Laws Revisited

Nogueira, G.A.L.[1,2], Erdélyi, R.[2], and Petrovay, K.[1]

[1] Eötvös Loránd University - Budapest - Hungary
[2] The University of Sheffield - Sheffield - United Kingdom

Solar Active Regions (ARs) are strongly magnetized regions in the solar atmosphere resulting from the emergence of flux tubes. They generally consist of bipolar structures with opposite polarity flux patches separated by a polarity distance (d) and oriented at a tilt angle (α) relative to the azimuthal direction. Understanding how AR characteristics such as d and α scale with the magnetic flux (Φ) and heliographic latitude (λ) is critical. These parameters play an important role while dealing with the source term in surface flux transport models, used to forecast the amplitude of the upcoming solar cycle.

This study revisits scaling laws for ARs using a newly constructed database (Wang et al. 2023) from Solar Cycles 23–25, derived from observations by the Michelson Doppler Imager on board the Solar and Heliospheric Observatory (SOHO/MDI) and the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory (SDO/HMI). Simple power-laws has been proposed such as $d=C_{d.}\Phi^{m}$ and $\alpha=C_{\alpha}(\sin\lambda)^{n}$, but there is still a debate about the values for the exponents m and n. Observational data often support m=0.5, suggesting self-similar flux distribution, but other studies propose m=1. For tilt angles, n=1 aligns with Joy's law, though deviations have been observed. The goal is to constrain these scaling laws by analyzing polarity separation and tilt angles. The findings have significant implications for improving solar activity modeling, flux transport simulations, and predicting future solar cycles.

Leveraging Multipoint Observations and Modelling to Understand Solar Transient Events

Erika Palmerio
Predictive Science Inc., San Diego, CA 92121, USA

The environment shaped by the Sun—the heliosphere—is extremely dynamic, with its structure being constantly shaped and altered by the solar activity over multiple time scales. Aside from changes that take place over longer intervals (such as the 11-year cycle), the large-scale structure of the heliosphere is affected by energetic transient events—solar eruptions. The loss of equilibrium of magnetic structures rooted on the Sun can result in a plethora of interconnected phenomena such as the release of solar flares, the liftoff of coronal mass ejections (CMEs), the formation of shock waves, and the acceleration of solar energetic particles (SEPs). As structures resulting from solar eruptions move away from the Sun, they interact with and affect the overall heliosphere as well as the magnetic environments of planets and other solar system bodies. Over the past years, the research community has been gradually shifting its main focus from the Sun–Earth chain to the Sun–heliosphere–planets interconnected system, thus taking advantage of multi-spacecraft and multi-point observations as well as modelling to build a comprehensive, holistic picture of how a given event influences different heliospheric regions and environments.

In this presentation, we will first provide a review of the advantages of multi-spacecraft observations of solar eruptive events and how they have helped us build the overall picture of CME structure and evolution as well as SEP acceleration and transport that forms our current knowledge. We will then showcase examples of detailed studies, both in the observational and modelling regimes, that have been made possible due to the availability of multi-point measurements. The selected samples will form an attestation of the power of combining multiple sets of spacecraft measurements with 3D global simulations to reach a deeper understanding of the structure and evolution of a given event as well as the overall heliospheric context through which it propagates.

SPEARHEAD: Advancing High-Energy Particle Research

Papaioannou, A.[1] and the SPEARHEAD Consortium [2]

[1] National Observatory of Athens/IAASARS, Athens, Greece
[2] https://spearhead-he.eu/partners/

SPEARHEAD (SPEcification, Analysis & Re-calibration of High Energy pArticle Data) is an Horizon Europe project aiming at unraveling the mysteries of high-energy particle acceleration and transport during solar eruptions. By leveraging unprecedented datasets from leading heliophysics missions and ground-based measurements, providing context for the ignored region of the spectra, the project seeks to address three pivotal science questions: (a) How are protons accelerated beyond 100 MeV and electrons beyond 1 MeV during solar eruptions? (b) What are the release times and spectral characteristics of near-relativistic particles from these events? and (c) How do coronal and interplanetary structures influence the transport of very high-energy particles? To achieve these goals, SPEARHEAD sets forth three technical objectives: (i) extend the energy range of particle flux measurements through newly determined response functions, (ii) cross-calibrating science-grade and monitoring instruments, and (iii) integrating observations with plasma modeling to facilitate deeper scientific analysis. A consortium of eight European partners collaborates on focused work packages, driving innovation in high-energy particle research. This talk highlights first-year achievements, including progress in creating novel datasets, cross-calibrating instruments, and combining observations with plasma models to produce event catalogs and tools. These initial findings demonstrate SPEARHEAD's potential to deliver revised datasets, robust methodologies, and open-access tools to the scientific community.

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Magnetic helicity as a marker of solar eruptivity

PARIAT, E[1,2]

[1] French - Spanish Laboratory for Astrophysics in Canarias (FSLAC), CNRS IRL2009, Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain
[2] Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris, CNRS, Laboratoire de Physique des Plasmas, Paris, France

The deterministic determination of the onset location and time of solar eruptions would represent a major breakthrough for the advance prediction of solar flares and coronal mass ejections. Unfortunately, to this date, no single criterion has been identified that can efficiently characterize the eruptivity of solar active centers. This results from the lack of understanding of the physical mechanism that trigger solar eruptions.

Using an orthogonal approach, we recently analyzed the link between magnetic helicity and eruptivity using both numerical simulations and observations. Magnetic helicity is a physical quantity related to the level of entanglement of the magnetic field lines in a system and is one of the few invariants in ideal magneto-hydrodynamics (MHD). We have analyzed the properties of magnetic helicity in diverse series of parametric 3D MHD simulations of eruptions, resulting either from line-tied boundary forcing or from flux emergence. We observed that a quantity based on magnetic helicity was able to efficiently characterize the eruptivity of the simulated magnetic systems. This helicity eruptivity index is defined as the ratio of the non-potential magnetic helicity to the total relative magnetic helicity. Our preliminary analysis of a limited set of observed active regions also demonstrates that the helicity eruptivity index can indeed mark the eruptivity of solar active regions.

While reliable measures of magnetic helicity in observed active regions remains difficult, our analysis shows that magnetic helicity represents a promising tool to predict solar eruptions, giving insights into the key mechanisms triggering eruptions.

Artificial Intelligence for the prediction of the May 2024 superstorm space weather events

Piana, M.[1,2], Guastavino, S[1,2], Legnaro, E[1], and Massone, A. M.[1],

[1] MIDA, Dipartimento di Matematica, Università di Genova

[2] Osservatorio Astrofisico di Torino, Istituto Nazionale di Astrofisica

With focus on the May 2024 solar superstorm, this talk will show that artificial intelligence could have been able to predict the whole chain of events associated with it. Specifically, using magnetogram cutouts, a Vision Transformer can classify the evolution of the active region generating the solar flares, video-based deep learning can predict the occurrence of the flaring events, a physics-driven model can notably improve the prediction of CME travel time prediction, and machine learning can exploit in-situ measurements to sound alerts of the geomagnetic storm unrolled over time. These findings highlight the potential of artificial intelligence even for operational space weather forecasting and as a tool to mitigate the impact of extreme solar events on critical infrastructure.

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Dynamic processes in the solar wind

Victor Réville[1]

[1] IRAP, Université Toulouse III - Paul Sabatier, CNRS, CNES, Toulouse, France

The solar wind is the most fundamental component of space weather. Its properties shape the inner heliosphere and constitute the background medium in which coronal mass ejections propagate. Yet, we are stil far from understanding everything about its dynamics. If the slow solar wind acceleration profile resembles the well known Parker pressure driven solution, it is pervaded by many coherent structures that are thought to be related to reconnection events in the corona. The fast wind is, in a sense, more steady, but wave turbulence is necessary to explain its terminal speed and acceleration profile. In this keynote lecture, I will go back to the early work of Parker's and explore important but often not well known results about the solar wind dynamical properties. I will speak about its inherent stability to acoustic perturbations, which is the very reason of its existence. I will then introduce the concept of Alfvén wave turbulence and the implication of the expansion of the solar wind on the cascade of waves from large to small scales. Finally, I will present recent results about turbulence and reconnection driven structures in the light of Parker Solar Probe and Solar Orbiter's observations.

Probabilistic Drag Based Model (P-DBM) in Heliosphere: Data and Tools

Authors: Ronish Mugatwala[1,2], Simone Chierichini[2,1], Gregoire Francisco[1,3], Robertus Erdélyi[2,4,5], Dario Del Moro[1]

1. University of Rome “Tor Vergata”, Rome, Italy
2. University of Sheffield, Sheffield, England
3. University of Coimbra, Coimbra, Portugal
4. Gyula Bay Zoltán Solar Observatory (GSO), Hungarian Solar Physics Foundation (HSPF), Gyula, Hungary
5. Eötvös Loránd University, Budapest, Hungary

The Probabilistic Drag-Based Model (P-DBM) is a Monte Carlo-based framework designed to simulate the heliospheric propagation of coronal mass ejections (CMEs), a key driver of space weather disturbances. The model provides probabilistic predictions of CME arrival times and speeds, along with associated measures such as the probability of impact and quantitative uncertainty estimates.

Although P-DBM is a robust method, its prediction flexibility is restricted by some input limits brought on by observational limitations. To address these challenges, a data-driven approach has been implemented, leading to the creation of a comprehensive catalog of geo-effective CME/ICME characteristics and a CME-ICME Lineup catalog as valuable by-products. These enhancements boost the model's predictive capabilities while also broadening its applicability.

Additionally, a specialized P-DBM desktop program has been developed to promote greater accessibility and collaboration between space weather forecasters and researchers. The goal of this application is to improve space weather prediction by expediting the incorporation of P-DBM into operational and research procedures.

CME Arrival Modelling with Machine Learning

Supervisors: Prof. Robertus Erdélyi, Prof. Dario del Moro

ESR 11 – Simone Chierichini

This work investigates the use of Machine Learning (ML) and Bayesian inference to improve the prediction and understanding of CME, a critical aspect of space weather forecasting.

Several ML techniques, including Supervised Learning methods such as Support Vector Machines, Decision Trees, and Ensemble Methods, are used to develop predictive models based on CME data, aiming to enhance the accuracy of CME arrival time forecasts. A key focus is placed on model interpretability, achieved through SHAP values, which provides insights into the feature space and allows for a better understanding of how different variables influence model outputs.

Additionally, the thesis applies Bayesian inference and MCMC techniques to refine probabilistic models of CME propagation using drag-based models, further improving the robustness and reliability of the predictions.

The tools and methods developed in this work hold considerable promise for future applications, with the potential to substantially improve the accuracy of predictions and mitigate the impacts of space weather on technological systems.

Connecting Solar and In-Situ Properties of Coronal Mass Ejections

M. Temmer

Institute of Physics, University of Graz, Austria

Coronal Mass Ejections (CMEs) are massive eruptions of plasma and magnetic fields from the Sun, capable of impacting Earth's space weather environment. Understanding their evolution from the Sun to interplanetary space requires connecting solar-origin observations to in-situ measurements. This talk covers investigations on the relationships between CME properties, such as speed, magnetic field structure, and plasma density, as observed in remote sensing image data and their counterparts detected in-situ by spacecraft. Specifically, we focus on the examination of the role of solar wind and interplanetary magnetic field interactions in shaping CME dynamics. These results also provide new insights in how solar magnetic fields and plasma conditions govern the geoeffectiveness of CMEs.

Extreme Solar Eruptive Events: Knowns and Unknowns

Usoskin, I.G.[1]

[1] University of Oulu, Finland

Solar energetic eruptive processes, such as flares and coronal mass ejections, are relatively well-studied during the past decades of direct observations. Their maximum strength/energy is not constrained by direct data because of a too-short period of observations. However, it is known from terrestrial cosmogenic proxy data that extreme solar events, which are several orders of magnitude stronger that the solar flares we experienced recently, can occur rarely on the Sun roughly once per 1500 years. It is also known that sun-like stars can produce super-flares roughly once per 100 years per star. On the other hand, it is unknown whether these two types of events reflect the same process and whether they are *Black Swans* or *Dragon Kings*. These outstanding issues will be discussed.

MAGNETIC FLUX ROPE IDENTIFICATION AND ANALYSIS IN THE SOLAR CORONA

Andreas Wagner[1,2], Daniel Price[1], Jens Pomoell[1], Stefaan Poedts[2,3], Ranadeep Sarkar[1], Farhad Daei[1], Anshu Kumari[4], Slava Bourgeois[5,6], Teresa Barata[5], Robertus Erdélyi[6,7,8], Orlando Oliveira[9], Ricardo Gafeira[5] and Emilia Kilpua[1]

[1] Department of Physics, University of Helsinki, Helsinki, Finland
[2] CmPA/Department of Mathematics, KU Leuven, Leuven, Belgium
[3] Institute of Physics, University of Maria Curie-Skłodowska, Lublin, Poland
[4] Udaipur Solar Observatory, Physical Research Laboratory, Udaipur, India
[5] Instituto de Astrofísica e Ciências do Espaço, University of Coimbra, Coimbra, Portugal
[6] School of Mathematics and Statistics, University of Sheffield, Sheffield, United Kingdom
[7] Department of Astronomy, Eötvös Loránd University, Budapest, Hungary
[8] Gyula Bay Zoltan Solar Observatory (GSO), Hungarian Solar Physics Foundation (HSPF), Gyula, Hungary
[9] CFisUC, University of Coimbra, Coimbra, Portugal

Magnetic flux ropes (MFRs) are the fundamental magnetic structures involved in solar eruptions. To understand their physical evolution from formation until their destabilisation, time-dependent magnetic field modelling is crucial. However, correctly identifying the magnetic field lines of the MFR in such simulation data is not trivial. Therefore, an MFR extraction scheme was created with which one can semi-automatically identify and track MFRs through time. This scheme involves the combination of an MFR proxy (such as the field line twist) in a suitable 2D slice of the modelling domain with mathematical morphology algorithms, such as the opening algorithm or the morphological gradient. For better applicability, the extraction scheme is wrapped into a graphical user interface (GUI) called GUITAR (GUI for Tracking and Analysing flux Ropes). We showcase the tool by applying it to a time-dependent data-driven magnetofrictional simulation of active region AR12473, which models the corresponding MFR eruption. This event is then analysed in terms of general and dynamical properties (size, height evolution, deflection) and stability properties (twist and decay index).

Radio eyes for the Sun, Heliosphere and Ionosphere: Status and plans for the LOFAR2.0 era

Dr. Pietro Zucca

The Low-Frequency Array (LOFAR) has established itself as a formidable instrument in the field of solar physics and space weather, providing a unique vantage point for observing the Sun, heliosphere, and ionosphere. As we transition into the LOFAR2.0 era, this abstract outlines the current status and future plans for leveraging LOFAR's capabilities, and the LOFAR IDOLS (Incremental Development of LOFAR Space-weather) project.

LOFAR's current work in solar physics involves high-resolution imaging and dynamic spectral analysis, enabling detailed observations of solar radio bursts and other coronal heliosphere and ionosphere phenomena. These observations are critical for understanding the mechanisms behind solar activity and improving our predictive models of space weather events. The LOFAR IDOLS station, a dedicated space-weather science facility, has been instrumental in advancing this work. It currently provides continuous monitoring of the ionosphere and Sun, tracking disturbances that can affect space wetaher on Earth, but also the astronomical observations of LOFAR itself.

The LOFAR2.0 upgrade promises to enhance these capabilities significantly. Plans include improving the sensitivity and spatial resolution of the array, and the simoultaneus observations in LBA and HBA, which will allow for even more precise and broad imaging and tracking of solar phenomena. This will enable researchers to dissect the fine structures within the solar corona and track the development of space weather events with greater accuracy.

Furthermore, the LOFAR IDOLS project is set to continue observation during the period of transition to LOFAR2.0 enabling us to test the monitorning capabilities.
In conclusion, the LOFAR2.0 era opens a new opportunity for solar and space weather research. With the ongoing work and future plans for the LOFAR IDOLS station and LOFAR2.0 observations, we are preparing to gain deeper insights into the Sun's influence on our space environment and to develop more robust forecasting capabilities for space weather phenomena.