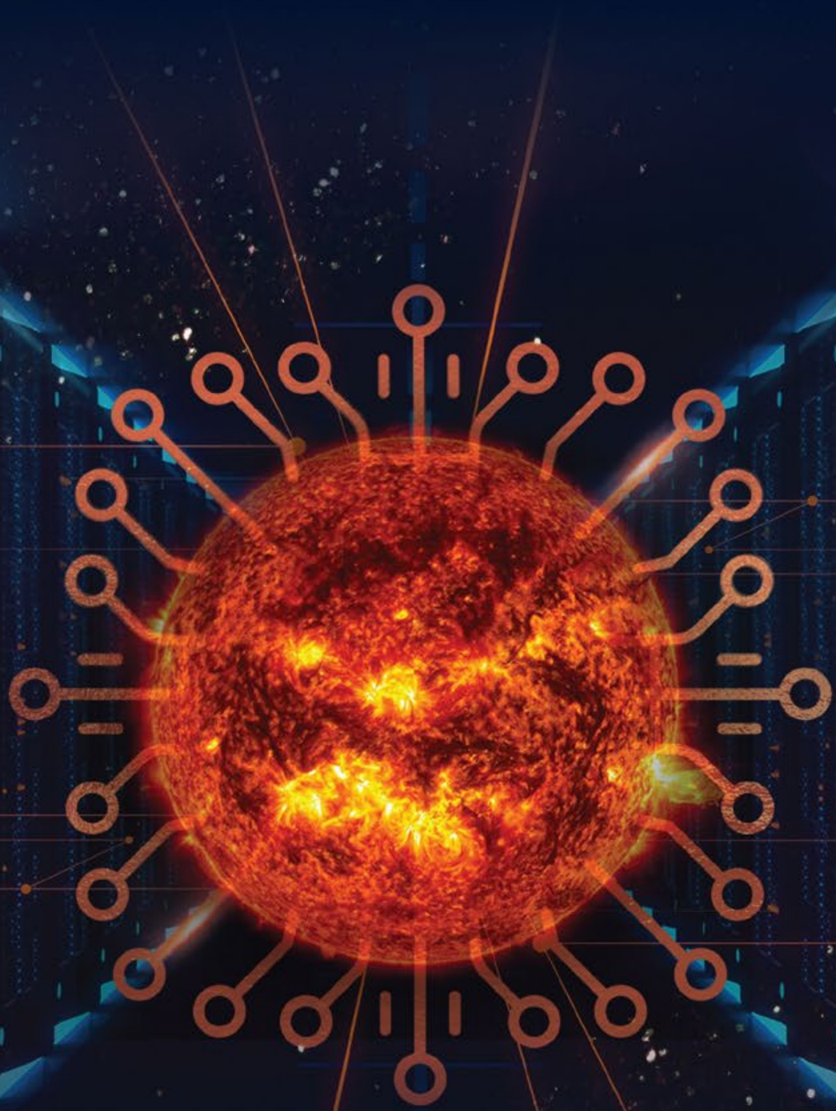
ABSTRACTS



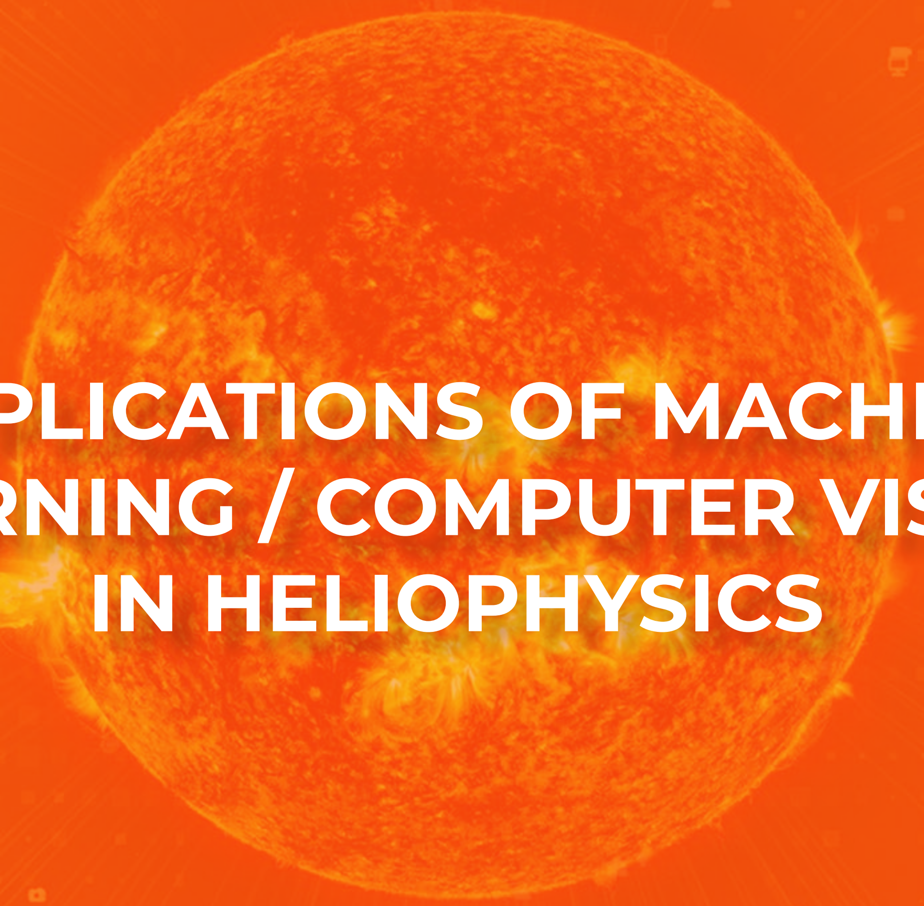
MACHINE LEARNING AND COMPUTER VISION IN HELIOPHYSICS

MOSAIICS

07 - 09 APRIL 2025 SOFIA BULGARIA

INTERNATIONAL WORKSHOP

SESSION 1



APPLICATIONS OF MACHINE LEARNING / COMPUTER VISION IN HELIOPHYSICS

TITLE

Heliophysics and Machine Learning: Applications, Challenges, and Future Directions (INVITED)

AUTHORS

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ABSTRACT

The impact of data-driven machine learning (ML) methodologies over the past decade has strongly impacted Solar Physics and heliospheric research. By synergizing state-of-the-art neural architectures with the unprecedented availability of observational and simulation datasets, the performance and accuracy of ML models have seen remarkable advancements. These developments now enable rapid, high-precision solutions to complex classification and regression. In this contribution, I present a representative (though non-exhaustive) overview of cutting-edge ML applications in heliophysics. I further address key challenges hindering broader adoption, including interpretability gaps, dataset limitations, and the integration of domain-specific physical constraints.

TITLE

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

AUTHORS

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AFFILIATION

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ABSTRACT

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 framework's 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 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.

TITLE

Interpreting Transformer-Based CME Forecasting and the Role of Flare Associations

AUTHORS

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ABSTRACT

Coronal mass ejections (CMEs) pose a significant threat to critical infrastructure, making their accurate forecasting extremely important. While predicting CMEs is only the initial stage in forecasting their terrestrial impact, it offers valuable time for mitigation efforts. However, CME forecasting remains a persistent challenge. This study investigates the potential implications of coupling CME forecasts with flare predictions, a common approach in existing models. We employ a transformer-based architecture to develop two models: one for CME forecasting independent of flare occurrence (CME model) and another for predicting whether a >M class flare will be associated with a CME (flare-CME model), both using sequences of SHARP keywords and the same architecture. Consistent with previous research, neither model achieves a good performance when closely examined. However, the flare-CME model outperforms the CME model when evaluated on time periods containing >M flares, suggesting that each model relies on distinct precursors. We hypothesize that the CME model may focus on "easier" signatures, which become saturated during periods preceding >M flares, while the flare-CME model detects more subtle patterns.

ABSID: MCH25_021

TITLE

Forecasting Solar Wind Speed From Solar Images Using Distributional Regression

AUTHORS

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ABSTRACT

The solar wind, a stream of charged particles originating from the Sun, poses significant risks to technology and astronauts. It is driven by large structures on the solar surface like coronal holes and active regions, which can be identified in extreme ultra-violet (EUV) solar images several days before they become geoeffective. In this work, we propose to use a distributional regression algorithm to forecast the solar wind speed at the Lagrange 1 point from solar images. Instead of predicting a single value, this method models the entire conditional distribution as a function of input features. It allows computing the uncertainty of predictions and specifying the probability of the solar wind speed exceeding certain thresholds, which is especially useful for extreme event predictions like coronal mass ejections and high-speed solar wind streams. We employ a convolutional neural network to encode solar images from multiple wavelength channels into unstructured low-dimensional representations. Using a semi-structured distributional regression approach, we couple the deep learning encoder with structured physical input parameters, such as past solar wind properties and solar cycle information. Thereby, we incorporate physical knowledge into the model and enhance explainability. We predict the solar wind speed distributions with a one-hour cadence four days in advance. We train and evaluate our method using cross-validation on 15 years of data and compare it to current state-of-the-art models. We find that it provides an accurate forecast and especially models the heavy-tailed solar wind speed distribution well. We further show the advantages over standard regression approaches and how to use the predicted conditional quantiles to improve extreme event predictions, highlighting the potential for operational space weather forecasts.

ABSID: MCH25_011

TITLE

Fast Bayesian spectral analysis using Convolutional Neural Networks: Applications over GONG Hα solar data

AUTHORS

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ABSTRACT

Solar filaments (or prominences, when observed off-disk) are dense, cool plasma structures suspended in the Sun's corona. These structures often exhibit oscillatory motions, which have been observed since the advent of solar studies. Despite their prevalence, there has been a lack of systematic investigation into these oscillations. Recent advancements have demonstrated that spectral analysis of solar filaments provides a robust method for identifying these periodic motions. Specifically, by calculating the power spectral density (PSD) for each pixel in Hα images, oscillations can be detected. However, the presence of red and white noise in the background complicates distinguishing real oscillations from spurious ones, as most statistical tools are designed for white-noise PSDs. To address this, Bayesian statistics and Monte Carlo Markov Chains (MCMC) have been employed, as they provide an effective approach for analyzing red-noise-dominated PSDs. However, MCMC methods are computationally intensive, making them impractical for large-scale data analysis. To overcome this limitation, we developed Convolutional Neural Networks (CNNs) as a deep learning alternative. Our two CNN models were trained using both synthetic data and real outputs from MCMC methods. The results demonstrate that the CNNs achieve negligible differences to MCMC while reducing computational times by orders of magnitude. This significant speedup enables the efficient and scalable analysis of oscillatory behaviors in solar filaments, paving the way for broader and more systematic studies.

ABSID: MCH25_014

TITLE

Towards a robust algorithm for prominence detection: Optimising the YOLOv5 object detection network for 304 Å SDO/AIA observations.

AUTHORS

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ABSTRACT

Solar prominences are tenuous clouds of plasma suspended in the solar atmosphere, appearing as bright structures when observed on or above the solar limb. They exhibit a broad morphological variety and dynamical behaviour, and are intimately linked to other solar phenomena including flares and coronal mass ejections. Consequently, detecting and classifying such structures is an important task, but not trivial. Missions such as the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory have provided an enormous wealth of observational data on prominences during its over 15-year lifetime. Whilst existing databases of prominences have used and benefited from these data, accurate automated detection of prominences remains challenging, more so than other solar features. Machine learning offers a promising solution to deal with the large amounts of data, aiding the construction of a more robust detection and classification system for prominences. Previous machine learning based studies of solar prominences have struggled with poor detection, largely due to the challenging nature of the 304 Å channel, in which diffuse material from the hotter Si XI emission often obscures prominence observations off-limb. We show here a renewed effort to incorporate machine learning for prominence detection, using the YOLOv5 object detection model. Using the labelled SDO/AIA prominence dataset of Baek et al. (2021, SoPh, 296, 160), we conduct a series of detailed tests to investigate different model constraints. In particular, we show the power of transfer learning (using pre-training weights from a different model), dataset augmentation, and hyperparameter tuning for model optimisation. Our prominence model outperforms previous efforts, with a mAP50 (mean average precision at intersection over union threshold of 50) value of 0.85, demonstrating the ability to accurately detect and classify solar features with a high degree of precision and robustness.

ABSID: MCH25_015

TITLE

A unified framework for solar filament detection, classification, and tracking with deep learning

AUTHORS

Antonio Reche and Consuelo Cid

AFFILIATION

University of Alcalá

ABSTRACT

This research work introduces a deep learning framework that integrates the detection, classification, segmentation, and tracking of solar filaments, using Hα images from the Global Oscillation Network Group (GONG) data archive. The framework utilizes a DETR-based model for detection and classification, a U-Net for instance segmentation, and a custom-made tracking algorithm. The proposed methodology achieves state-of-the-art performance across all tasks, overcoming typical challenges in solar filament analysis. This approach will allow us to systematically study filaments over time, focusing on eruptive filaments, with potential applications in space weather forecasting. Additionally, this study introduces a new manually-labeled catalog of solar filaments, which will be published as open-source material for future researchers.

ABSID: MCH25_017

TITLE

Vortex detection in various solar magnetic field configurations

AUTHORS

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ABSTRACT

We investigate vortex dynamics in three magnetic regions, viz., Quiet Sun, Weak Plage, and Strong Plage, using realistic three-dimensional simulations from a comprehensive radiation-magnetohydrodynamics (MHD) code, MURaM. We find that the spatial extents and spatial distribution of vortices vary for different set-ups even though the photospheric turbulence responsible for generating vortices has similar profiles for all three regions. We investigate kinetic and magnetic swirling strength and find them consistent with the Alfven wave propagation. Using a flux tube expansion model and linear MHD wave theory, we find that the deviation in kinetic swirling strength from the theoretically expected value is the highest for the Strong Plage, least for the Weak Plage, and intermediate for the Quiet Sun at chromospheric heights. It suggests that Weak Plage is the most favoured region for chromospheric swirls, though they are of smaller spatial extents than in Quiet Sun. We also conjecture that vortex interactions within a single flux tube in Strong Plage lead to an energy cascade from larger to smaller vortices that further result in much lower values of kinetic swirling strength than other regions. Our findings indicate the potential of vortex-induced torsional Alfven waves to travel higher in the atmosphere without damping for weaker magnetic regions such as the Quiet Sun, whereas vortices would result in dissipation and heating due to the vortex interactions in narrow flux tubes for the strongly magnetized regions such as Strong Plage. Using Machine learning to detect these vortices in the solar atmosphere can help solve the long lasting puzzle of solar atmospheric heating.

ABSID: MCH25_032

TITLE

The power of Artificial Intelligence in predicting the full chain of Space Weather events: the May 2024 Superstorm case study (INVITED)

AUTHORS

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AFFILIATION

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ABSTRACT

Space Weather, which encompasses the study of solar activity and its interaction with the Earth's magnetosphere, is a critical field of research due to its far-reaching impact on technological systems and human infrastructure. Solar flares and Coronal Mass Ejections (CMEs) are the primary drivers of Space Weather, capable of generating geomagnetic storms that can affect satellite operations, power grids, aviation, and even human health in space environments. Accurately forecasting these events and their impact on Earth's magnetosphere remains a challenge because of the complexity of solar-terrestrial interactions. This talk shows how Artificial Intelligence (AI) successfully predicted the full chain of events associated with the May 2024 superstorm, including extreme solar flares from NOAA active region 13644, multiple, interacting Earth-directed CMEs, and the resulted geomagnetic storm, the second most severe in the space era. Leveraging magnetogram cutouts from the active region allows a Vision Transformer to classify the evolution of its morphology, and a video-based deep learning method to predict solar flare occurrences. Additionally, an innovative physics-driven machine learning model enhanced the accuracy of CME travel-time prediction using coronal observations and solar wind measurements; and a data-driven method leveraged these in-situ measurements to sound alerts of the geomagnetic storm unrolled over time. The results revealed unparallel precision in alarm timing, particularly during the storm onset and showed an unprecedented accuracy of just one minute in predicting the CME arrival. These findings underscore the remarkable potential of AI, particularly of physics-driven machine learning, in space weather forecasting and its ability to mitigate the effects of extreme solar events on vital infrastructure.

ABSID: MCH25_020

TITLE

Investigating the Efficacy of Topologically Derived Time-Series for Flare Forecasting

AUTHORS

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ABSTRACT

The accurate forecasting of solar flares is considered a key goal within the solar physics and space weather communities. There is significant potential for flare prediction to be improved by incorporating topological fluxes of magnetogram datasets, without the need to invoke three-dimensional magnetic field extrapolations. Topological quantities such as magnetic helicity and magnetic winding have shown significant potential towards this aim, and provide spatio-temporal information about the complexity of active region magnetic fields. This study develops time-series that are derived from the spatial fluxes of helicity and winding that show significant potential for solar flare prediction. It is demonstrated that time-series signals, which correlate with flare onset times, also exhibit clear spatial correlations with eruptive activity; establishing a potential causal relationship. A significant database of helicity and winding fluxes and associated time series is generated using SHARP data processed with the ARTop code that forms the basis of the time-series and spatial investigations conducted here. Preliminary solar flare forecasting results are presented based on this dataset.

ABSID: MCH25_009

TITLE

The prediction of the MHD wave energies in stellar convection zones using neural networks

AUTHORS

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AFFILIATION

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ABSTRACT

It is widely believed that the origin of chromospheric heating is non-radiative. MHD waves generated as a result of the interaction between turbulent motion within the convection zones and the surrounding magnetic flux tubes are very strong candidates. Different theories and approaches can be implemented for simulating turbulence and their interactions with magnetic features. The current work is relying on modeling stellar convection zones, turbulences and their interactions by defining five main parameters, namely, the effective temperature Teff , surface gravity log g, magnetic field strength at the stellar surface B0 , the magnetic filling factor f.f., and the metal abundance Z. Our approach will be applied to a wide range of stars and the resulting MHD wave fluxes and spectra will be computed. For the first time, we will apply neural networks algorithms to predict the amounts of MHD wave energies and spectra for a given spectral type with known five parameters. This approach will eliminate the need for long computation times and facilitate the time dependent computations of the chromospheric heating.

ABSID: MCH25_023

TITLE

Bypassing the static input size of Neural Networks in flare forecasting by using Spatial Pyramid Pooling

AUTHORS

Philippe Vong, Laurent Dolla, Alexandros Koukras, Jacques Gustin, Jorge Amaya, Ekaterina Dineva, Giovanni Lapenta

AFFILIATION

Royal Observatory of Belgium

ABSTRACT

The spatial extension of active regions of the Sun can strongly vary from one case to the next. This inhomogeneity is a problem when studying solar flares with Convolutional Neural Networks (CNNs) as they generally use input images of a fixed size. Different processes can be performed to retrieve a database with homogeneous sized images, such as coarse resizing of raw images. Unfortunately, key features can be lost or distorted beyond recognition during these processes. This can lead to a deterioration of the ability of CNNs to classify flares of different soft X-ray classes, especially those from active regions with structures of great complexity. Our work aims to implement and test a CNN architecture that retains features of characteristic scales as fine as the original resolution of the input images. We compare the performance of two CNN architectures for solar flare prediction: the first one is a traditional CNN with resized input whereas the other implements a spatial pyramid pooling (SPP) layer and without any input resizing. Both are trained on the Space-weather HMI Active Region Patch line-of-sight magnetogram database. We also study two cases of binary classification: in the first case, our model distinguishes active regions producing flares in less than 24h of class ≥C1.0 from active regions producing flares in more than 24h or never; in the second case, it distinguishes active regions producing flares in less than 24h of class ≥M1.0 from the other active regions. Our models implementing an SPP layer outperform the traditional CNN models when predicting flares ≥C1.0 within 24h. However, their performances degrade sharply along the other models studied in this paper, when trained to classify images of ≥M1.0 flares. The degradation in SPP models when classifying only images of ≥M1.0 flares as positive may be attributed to its success in identifying features that appear in active regions a few hours before the flare, independently of their soft X-ray class.

ABSID: MCH25_024

TITLE

Deep Learning Techniques for Sunspot Classification

AUTHORS

Edoardo Legnaro, Sabrina Guastavino, Michele Piana, Anna Maria Massone, Paul Wright, Shane Maloney

AFFILIATION

University of Genova

ABSTRACT

Solar active regions can significantly impact the Sun–Earth space environment, driving extreme space weather events such as solar flares and coronal mass ejections. Sunspots serve as key indicators of these regions, with certain sunspot types closely linked to such events. Consequently, the automatic classification of sunspot groups plays a crucial first step in enhancing the accuracy and timeliness of solar activity predictions. In this talk, we present our results on leveraging deep learning techniques to detect and classify active regions. We address both the task of classifying active regions from magnetogram cutouts and the detection and classification of active regions from full-disk magnetograms. This research is conducted as part of the Active Region Classification and Flare Forecasting (ARCAFF) project.

ABSID: MCH25_046

TITLE

Machine Learning for Faraday Cup Calibration and Optimization of Ion Parameter Estimation

AUTHORS

Lidiya Y. Ahmed, Michael L. Stevens, Kristoff Paulson, Samuel Badman, Anthony Case

AFFILIATION

Smithsonian Astrophysical Observatory and Harvard University

ABSTRACT

We propose a novel scheme for analyzing particle detector measurements when a well-calibrated, similarly instrumented spacecraft is present in a similar orbit. The method uses dynamic time warping (DTW) to prepare ground truth from measurements provided by a reference spacecraft. An artificial neural network (ANN) is then trained to reproduce this ground truth from measurements at the target spacecraft. Unlike previous approaches, this procedure is insensitive to calibration errors in the target data stream, as the neural network may be trained from poorly calibrated particle spectra or even directly from low-level data in engineering units. We demonstrate a proof-of-concept by training an ANN to estimate solar wind proton densities, temperatures, and speeds from the DSCOVR PlasMag Faraday Cup, using Wind SWE as a reference. We discuss applications for Parker Solar Probe, Helioswarm, and other missions.

ABSID: MCH25_035

TITLE

In search for strongly non-thermal flares: applying machine learning to find non-thermal electron acceleration signatures

AUTHORS

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ABSTRACT

Solar X-ray flares can hardly be considered an uniform group of events, and their spectral characteristics may range from entirely thermal to exhibiting a strong, impulsive, non-thermal component. X-ray can be considered a radiative footprint of electron acceleration and subsequent energy deposition in the chromosphere, therefore studying the impulsive phase is crucial for understanding the physics of these processes. Finding flares with an outstandingly high ratio of non-thermal to thermal emission, including the “cold flares” where the thermal response is weaker than expected, would be beneficial for the future works, that include determining the physical processes driving them. The Neupert effect is a classic, empirical relation between the time evolution of soft and hard X-ray luminosity of the impulsive flares, which may be used as a proxy to estimate the fraction of non-thermal emission, allowing to find events with strong non-thermal signature. Recent development of data science has brought novel approaches to time series processing. In our work, we study the feasibility of utilizing neural networks to identify strongly nonthermal flares among ca. 70000 entries in STIX Flare Catalog. We use the quicklook lightcurve profiles for classification, since this data product is available for the entire span of STIX operation, as well as spectrograms which are available for the more recent observations. We test whether a simple 1D convolutional autoencoder is able to learn the “average flare profile” and effectively help us to find events that deviate from it. We discuss the results and explore the advantages and pitfalls of that approach in comparison to classical signal processing methods.

ABSID: MCH25_036

TITLE

Detection and Statistics of High-frequency QPPs in Solar Flares

AUTHORS

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ABSTRACT

Quasi-periodic pulsations (QPP) are one of the well observed and studied modulations in the emissions coming from the solar flares. They are detected across different wavelengths, e.g., microwaves, ultraviolet, X-rays, and even gamma rays during the flare emission. The presence and properties of QPPs provides clues on the underlying mechanisms responsible for the flaring process. In particular, when a QPP has multiple periods spanning on the various phases of a flare, they can be classified into a different category of physical mechanisms, modulations, and stationarity. Previous works on determination of QPP period in different wavelengths of the solar flares resulted in detection of periods in the range of 10-100 seconds. Detecting period in a time-series is very much dependent on the cadence, however, there are limited studies on the detection and occurrence of high-frequency QPPs, which are seen mostly in radio emissions from the flaring regions. This work focuses on the search and detection of QPPs that have periods < 10s. Although there are several methods to estimate QPP period, we do not use one particular method. Instead, an ensemble of different detection methods are used to search for the high-frequency QPPs. We present the detection procedure and the statistical results obtained from the analysis of burst-mode solar flare data, spanning almost 3 solar cycles, from Konus-Wind instrument. We also explore whether such QPP events are connected to heliospheric processes like CMEs and SEPs, from a space weather perspective.

ABSID: MCH25_037

TITLE

Mitigating hallucination with non-adversarial strategies for image-to-image translation in solar physics

AUTHORS

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ABSTRACT

Image-to-image translation using generative adversarial networks (GANs) has become a standard approach across numerous scientific domains. In solar physics, GANs have become popular to reconstruct some unavailable modalities from physically related modalities that are available at the time of interest. However, the scientific validity of GANs generated outputs has so far been largely overlooked. In particular, it is known that generative deep learning models have a tendency to produce visually and statistically convincing outputs that may nevertheless be physically inconsistent with the input data. In this work, we measure the discrepancy between GAN-generated solar images and real observations in two applications: the generation of chromospheric images from photospheric images, and the generation of magnetograms from Extreme Ultraviolet images. Next, we investigate non-adversarial training strategies and network architectures whose behavior may adapt to the input at hand. Specifically, we propose an architecture that modulates the generative model's internal feature maps with input-related information, thereby favoring the transfer of input/output mutual information to the output. Our results show that GANs consistently fall short of non-adversarial U-net translation models in physics-constrained applications due to the generation of visually appealing features, termed as 'hallucinations', that do not have any physical correspondance. Additional conditioning the U-net model based on modulation of internal feature maps significantly enhances cross-modal image-to-image translation.

ABSID: MCH25_019

TITLE

Polar faculae and their relationship to the solar cycle

AUTHORS

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ABSTRACT

This work presents faculAI, a deep learning framework using a U-Net architecture to automate the detection and analysis of polar faculae (PFe) in solar images from NASA's Solar Dynamics Observatory (SDO). Trained entirely on synthetic data to bypass the need for labor-intensive manual labeling, this model achieves high performance and processes single images in seconds, which enabled us to do a systematic analysis of over 13 years of SDO data. By applying faculAI to linear polarization measurements, we were able to study in high detail the solar cycle and the magnetic field at the Sun's poles, obtaining several results that agree with previous observations: (1) we observed a strong linear correlation between PFe counts and polar magnetic field strength, (2) an anti-phase behavior between PFe and sunspot cycles, and (3) a systematic migration of magnetic polarities from mid-latitudes to the poles. Our methodology also found hemispheric asymmetries; we observed that the southern pole presents a higher number of PFe in average, but with smaller average sizes, likely due to instrumental biases. This work shows the potential of computer vision techniques in heliophysics, providing an open-source tool for efficient, large-scale solar feature analysis.

ABSID: MCH25_034

TITLE

Towards Automating Type II Solar Bursts Measurement in LOFAR Dynamic Spectra

AUTHORS

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AFFILIATION

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ABSTRACT

The IDOLS project has gathered 2.5 years of continuous solar dynamic spectrum observations using a single LOFAR station. To make best use of this dataset it is necessary to develop an automated pipeline for the detection, measurement and extraction of physical parameters from solar events. Machine learning algorithms are suitable for the detection and classification of solar activity in the time-frequency domain. Once classified, the events need to be measured. Here we present our effort to test classical computer vision algorithms to aid the measurement of a type II event. We explore the benefits and limitations of using image binarization, segmentation and linear regression in the estimation of type II burst parameters. The results of this work will inform and contribute to our efforts to prepare efficient processing pipelines for solar observations with the soon-to-be-built LOFAR-BG station.

MACHINE LEARNING AND COMPUTER VISION IN HELIOPHYSICS

ABSID: MCH25_025

TITLE

Deep Learning study into sunspot evolution for use in flare forecasting

AUTHORS

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ABSTRACT

Solar flares are large eruptions of electromagnetic radiation from the Sun that can affect Earth's atmosphere and some of our technologies (e.g., radio communications). Flares are identified by the arrival of their energetic photons at Earth, meaning that their space-weather effects commence at the same time we become aware that a flare is in progress - this makes it essential for us to forecast them in advance. This work aims to forecast solar flares within an upcoming time window (24 hours) by training a Deep Learning model. We use 3D vector magnetic images obtained from the Solar Dynamics Observatory (SDO) Space-weather HMI Active Region Patch (SHARP) data series, specifically the solar-vertical component of the magnetic field. By using whole active region images as input we want to improve our understanding of the physics leading up to flares and thus also improve our ability to forecast them. We use vertical-field images from 2013 to 2023, inclusive, at a cadence of 24 hours along with the corresponding Geostationary Operational Environmental Satellites (GOES) X-ray flare events in the next 24 hours to create the image and flare-outcome label pairs. Filtering is performed to limit our data set to images containing only one NOAA-numbered active region within ±75° longitude. With HARP separated data sets for training and testing, we implement a Fully Convolutional Network (FCN) for the binary classification of flare events with GOES X-ray flare class above C1.

ABSID: MCH25_039

TITLE

Deriving solar HXR fine structure from UV images through machine learning

AUTHORS

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AFFILIATION

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ABSTRACT

The emission of HXR, EUV and UV in the chromosphere during the impulsive phase of a solar flare is an observed consequence of magnetic reconnection in the solar corona. According to the thick-target model, accelerated non-thermal electrons bombard the chromosphere producing so-called footpoint sources visible in a wide range of electromagnetic radiation. Collisions of non-thermal electrons with chromospheric particles produce non-thermal HXR radiation (bremsstrahlung) and heat the plasma, resulting in UV and EUV emission. Although the same physical processes generate HXR and UV emissions, their morphology and distribution can show significant differences. HXR emission regions typically appear as single or double compact sources within much more complicated UV ribbons.

Several active space missions continuously observe the Sun in the short-wavelength part of the electromagnetic spectrum. The STIX instrument aboard the Solar Orbiter monitors X-ray radiation in the range from 4 to 150 keV. The reconstruction of X-ray images is based on Fourier optics, using photon flux modulation with a set of 30 sub-collimators. The AIA instrument aboard the Solar Dynamics Observatory provides UV and EUV images of the Sun. These two missions can complement each other in the analysis of processes occurring during the impulsive phase of a solar flare. In over 70,000 events observed by STIX, 30-40% were also recorded by AIA. It allows investigating details of HXR-UV relations to derive the real fine structure of HXR foot point sources via machine learning techniques. In our project, we use STIX and AIA UV images to compare a large number of individual HXR and UV sources' brightness. Having general correlations we can prepare approximated fine detailed HXR maps and compare them with STIX data. Thus, we can test the hypothesis of the existence of multiple small-sized (< 1 arcsec) HXR footpoint sources.

MACHINE LEARNING AND COMPUTER VISION IN HELIOPHYSICS

ABSID: MCH25_040

TITLE

Short-Term Solar Energetic Proton Flux Forecasting: Preliminary Deep Learning Insights and Future Directions with Transformer Architectures

AUTHORS

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AFFILIATION

Dublin Institute for Advanced Studies (DIAS)

ABSTRACT

Accurate short-term forecasting of Solar Energetic Proton (SEP) flux is critical for mitigating the effects of space weather on satellite operations, telecommunications, and human spaceflight. In this work, we present preliminary results of a Bidirectional Long Short-Term Memory (BiLSTM) neural network for predicting hourly-averaged SEP integral flux across three energy channels. Our model incorporates key input features—such as the F10.7 index, sunspot number, solar wind speed, and interplanetary magnetic field strength—collected from NASA's OMNIWeb database and GOES satellite observations, spanning four solar cycles. Additionally, we include active region characteristics from NOAA daily reports, thereby providing a more comprehensive depiction of solar activity. The BiLSTM model, trained using a Multi-Input Multi-Output (MIMO) approach, yields promising preliminary results in forecasting the logarithm of the SEP flux in three standard GOES channels (>10 MeV, >30 MeV, and >60 MeV). Notably, the model demonstrates robust performance over a 6-hour forecasting window, showing low mean-squared errors (MSE=0.012-0.011) and reliable correlation (R=~81%) across various solar conditions. This work builds on our previous SEP forecasting efforts (Nedal et al., 2023), improving short-term prediction accuracy through an expanded feature set and refined data-partitioning strategies. Encouraged by these initial findings, our next phase involves developing a Transformer-based deep learning architecture to potentially capture long-range dependencies and improve model generalization. We will benchmark this upcoming approach against our BiLSTM model and other existing methods, to establish a state-of-the-art framework for near-real-time SEP forecasting. Ultimately, these efforts advance our understanding of SEP behavior and enhance operational space weather monitoring and risk mitigation strategies.

ABSID: MCH25_045

TITLE

High-Frequency Signal Absorption in the Ionospheric D-Layer: Modeling and Future Prospects for AI

AUTHORS

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Kuldeep Pandey

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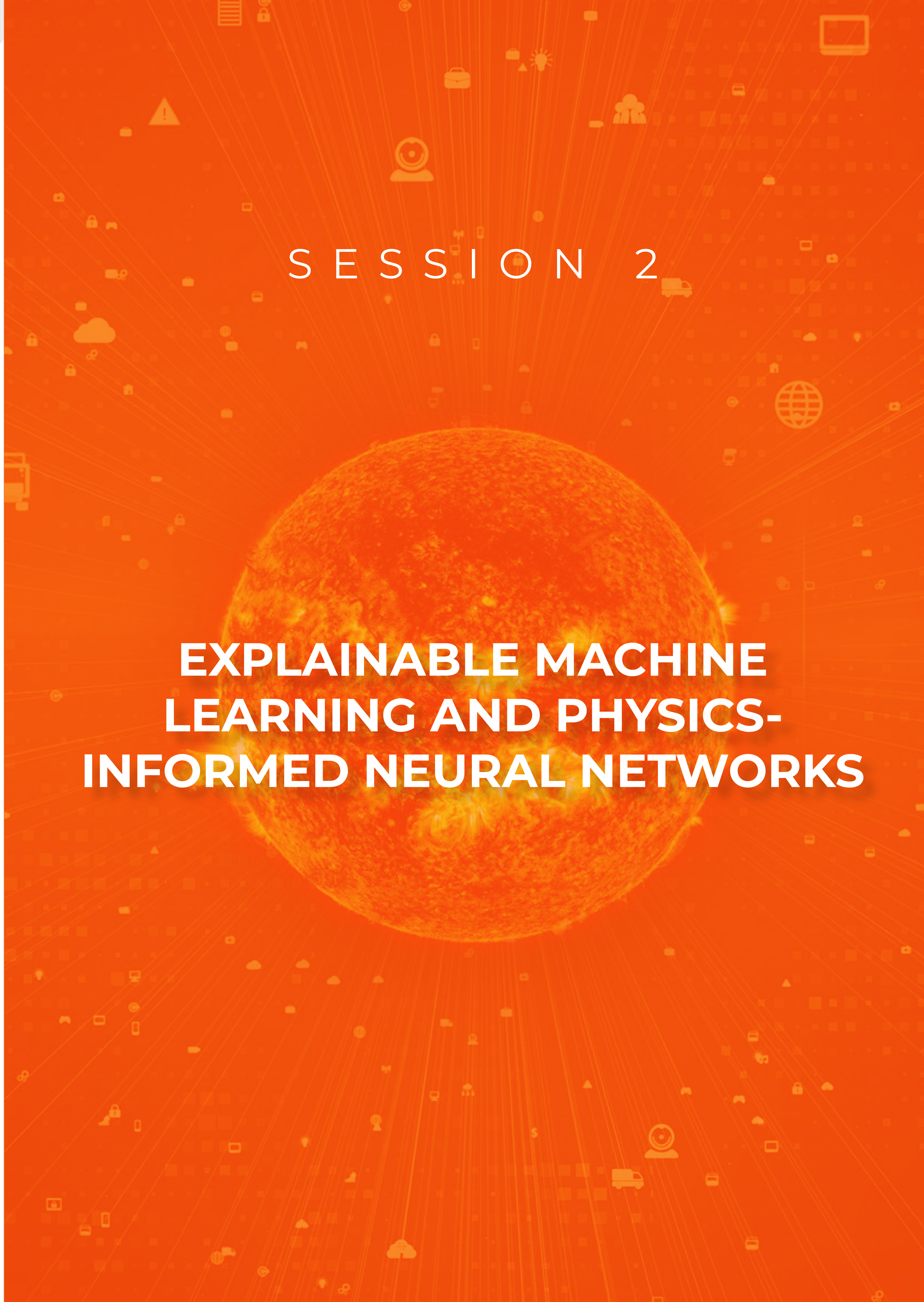
The American University in Cairo

ABSTRACT

High-frequency (HF) radio wave propagation is a crucial tool for studying ionospheric behavior and space weather dynamics. Understanding how HF signals interact with the ionosphere is essential for both scientific research and communication systems. In this study, we model HF signal propagation and absorption along two well-calibrated communication paths between the standard transmitting station WWV (Fort Collins, Colorado) and two Personal Space Weather Stations (PSWS): W2NAF (Scranton, Pennsylvania) and K6KPH (Point Reyes, California). These stations utilize Great Radio Amateur Propagation Experiment (GRAPE) GPS-disciplined receivers to measure standard time signals with high precision. To analyze HF wave propagation, we use the Provision of High-Frequency Raytracing Laboratory for Propagation Studies (PHaRLAP), a MATLAB-based ionospheric ray tracing toolbox. Simulations at 5, 10, and 15 MHz are performed, launching a fan of rays at varying elevation angles to determine signal reachability. Additionally, we compute ionospheric HF absorption and compare the modeled values with observed signal strengths recorded by the PSWS throughout the day. Our goal is to assess whether the predicted absorption remains within one order of magnitude of real-world observations. As a next step, we aim to incorporate Artificial Neural Networks (ANNs) with seven hidden layers to predict D-layer absorption loss during nighttime, addressing the multivariate nature of the ionosphere at this altitude and time. Furthermore, we have preprocessed data from the most recent April solar eclipse, collected using GRAPE receivers in Cleveland, Ohio, to serve as a reference for validating our modeling efforts. These advancements will contribute to a more refined understanding of HF signal absorption and its variability under different space weather conditions.



SESSION 2

EXPLAINABLE MACHINE LEARNING AND PHYSICS-INFORMED NEURAL NETWORKS

ABSID: MCH25_001

TITLE

Hybrid Optimization of Space Weather Parameters using Machine Learning and Explainable AI

AUTHORS

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ABSTRACT

Space weather forecasting is a critical challenge due to the complex dynamics of solar activity and its impacts on Earth's infrastructure. This research develops a hybrid framework for optimizing space weather parameters using Physics-Informed Neural Networks (PINNs) and Explainable AI (XAI). By integrating domain-specific equations with machine learning, PINNs ensure physical consistency in predictions, while XAI enhances model interpretability, enabling actionable insights. The proposed framework improves the prediction of solar wind speed and geomagnetic indices with higher accuracy than traditional models. It bridges the gap between research and operations by providing reliable, interpretable forecasts critical for safeguarding technological systems and advancing heliophysics research. This innovative approach demonstrates the potential of combining machine learning with domain expertise to address challenges in heliophysics and beyond.

ABSID: MCH25_041

TITLE

Physics-informed machine learning for the analysis of spectropolarimetric observations (INVITED)

AUTHORS

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AFFILIATION

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ABSTRACT

: In the last decade, machine learning and neural networks have emerged as powerful tools for extracting and analyzing relevant information from huge collections. They have demonstrated their versatility in data preprocessing, automatic segmentation of solar features, image deconvolution and reconstruction, acceleration of spectropolarimetric inversions and prediction of explosive phenomena. Some years after their introduction in solar physics, it is evident that these techniques have not only reached a phase of increased sophistication, but that new approaches are being explored that combine physical constraints, statistical methods and new modeling capabilities with novel and promising solutions. In this contribution, I will review a selection of pioneering applications to various problems in solar physics, describing each methodology, discussing outstanding issues, and offering a perspective for future research.

ABSID: MCH25_002

TITLE

Physics-informed loss functions for vertical total electron content forecast

AUTHORS

Eric Nana Asamoah,
Massimo Cafaro,
Italo Epicoco,
Giorgiana De Franceshi,
Claudio Cesaroni

AFFILIATION

INGV

ABSTRACT

Vertical Total Electron Content (vTEC) is one of the most important parameters in the study of space weather, in particular the ionospheric physcis. vTEC is used to quantify the level of ionisation of the upper atmosphere and its variability, especially under space weather events. During space weather events, the impacts on the earth cannot be overlooked. As a contribution to countermeasures to mitigate the errors introduced by the ionospheric threats, several vTEC forecasting models have been developed using different approaches. In our research study, we leverage the high performance of machine learning models and some constraints, which can be imposed on the loss function, to improve the training process specifically for the associated events of space weather. The vTEC data for the mid-latitude station Tsukuba, Japan (36.06 N, 140.05 E) for a full solar cycle from 2006-2018 is calibrated from 30-second GNSS data drom regional IGS data gathering facilities. Daily, this data is collected in RINEX files and sent to the Crustal Dynamics Data Information System (CDDIS). Since we are building a multivariable machine learning model, other external drivers are required, and these data were downloaded from https://cdaweb.gsfc.nasa.gov. To avoid the influence of multicollinearity and select the most important external drivers to be used for our model, we use the Pearson correlation coefficient of threshold 0.5 to discard some of the external drivers and further use the permutation of feature importance algorithm to select a couple of external drivers that are most important with respect to their forecasting horizons. We designed physics-informed loss functions for forecasting vTEC. This approach of integrating physical constraints into the learning process neural network model adds significant improvement to the performance, which is promising for further development in ML techniques in space weather.

ABSID: MCH25_008

TITLE

Physics Informed Neural Networks Milne Eddington (PINN-ME) inversions

AUTHORS

Momchil Molnar(SwRI, USA),
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Matthias Rempel (HAO, USA)

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ABSTRACT

Spectropolarimetric inversions of solar observations are fundamental for the estimation of the magnetic field in the solar atmosphere. Current approximation necessitated by computation requirements for photospheric spectral lines is that they form under the Milne-Eddington (ME) approximation, where the inferred atmospheric properties are constants. Despite the simplifications in current inversions, observational data typically exhibits noise and instrumental effects, which limits the precision of estimating the solar plasma parameters. We present a novel method for spectropolarimetric inversions of solar data under the ME approximation with a Physics Informed Neural Network (PINN) to estimate the solar magnetic field. Building on synthetic spectral line profiles, we demonstrate that our approach can reliably solve complex configurations in a computationally-efficient way. Our method intrinsically enables spatial and temporal coupled inversions that can overcome limitations of noise, directly provides uncertainty estimates, and is straight-forward to extend to different instrument configurations. Our method also accounts for the instrumental point-spread-function, further informing the spatial coupling, as well as providing uncertainty estimates based on the auto-differentiation properties of the neural network. We apply our method to observations from Hinode SOT/SP and SDO/HMI and compare our results to other state-of-the-art ME inversion codes. We also show how our method seamlessly disambiguates the 180 degree degeneracy of the inferred magnetic field azimuth, which is an outstanding problem for current generation inversions. Our method operates with minimal memory requirements, makes efficient use of spatio-temporal relations, and is adjustable to observations from new instruments. This study provides a first step to utilize PINNs for spectropolarimetric inversions, and demonstrates the potential to address long standing challenges.

ABSID: MCH25_018

TITLE

Spectropolarimetric Inversion in Four Dimensions with Deep Learning (SPIn4D): Physics-Informed Machine Learning for 3D Reconstruction of the Solar Photosphere

AUTHORS

Kai E. Yang, Xudong Sun, Jiayi Liu, Peter Sadowski, S. Curt Dodds, Lucas A. Tarr, Matthias Rempel, Sarah A. Jaeggli, Thomas A. Schad, Ian Cunnyngham, Yannik Glaser, Linnea Wolniewicz

AFFILIATION

The University of Hawaii at Manoa

ABSTRACT

We introduce a novel Physics-Informed Machine Learning method to reconstruct the three-dimensional (3D) structure of the lower solar atmosphere, including both the fully disambiguated vector magnetic fields and the geometric height associated with each optical depth. Traditional techniques for resolving the 180 degree azimuth ambiguity in a single layer while disregarding the non-flat nature of a single optical depth (e.g., the Wilson depression in sunspots). In contrast, our approach simultaneously performs the disambiguation and determines the mapping between optical depth and physical height in order to produce the field that most closely adheres to the physically required divergence-free constraint. When tested on magnetohydrodynamic simulations of quiet Sun, plage, and sunspot regions, it reliably resolves the horizontal magnetic field orientation in strongly magnetized pixels. By coupling the disambiguated vector field with inferred layer heights, we achieve self-consistent 3D reconstructions of the vector electric currents in the solar photosphere, paving the way for deeper insights into the magnetic and electric current structures of the lower solar atmosphere.

ABSID: MCH25_027

TITLE

Explainable Machine Learning and Physics-Informed Neural Networks in Heliophysics

AUTHORS

Anchal Aiswariya Dutta

AFFILIATION

IISER BEHRAMPUR

ABSTRACT

The rapid advancements in machine learning (ML) and neural networks have opened new frontiers in heliophysics, enabling more accurate modeling of solar dynamics, space weather prediction, and plasma physics. However, traditional deep learning models often function as black boxes, limiting interpretability and trust in critical applications. This study explores the integration of Explainable Machine Learning (XML) techniques and Physics-Informed Neural Networks (PINNs) to improve both accuracy and interpretability in heliophysical models. PINNs leverage fundamental physical laws, such as Maxwell's equations and magnetohydrodynamics (MHD), as constraints within neural network architectures, allowing models to generalize beyond purely data-driven approaches. By embedding known physics, PINNs ensure compliance with conservation laws, reducing the risk of overfitting and increasing robustness in predicting solar flares, coronal mass ejections, and magnetic field dynamics. Furthermore, explainability methods, such as SHAP (SHapley Additive Explanations), Grad-CAM, and attention mechanisms, provide deeper insights into the decision-making process of ML models, identifying key features and improving trust in AI-driven predictions. This research aims to develop hybrid PINN-based models for heliophysics applications, comparing their performance with traditional ML approaches. The study will assess model generalization, computational efficiency, and explainability in predicting solar wind interactions with Earth's magnetosphere. By combining domain knowledge with AI transparency, this work advances both the scientific understanding of solar phenomena and the reliability of machine learning models in space weather forecasting.

ABSID: MCH25_028

TITLE

Physics-informed AI framework for automated solar wind stream identification and geoeffective-ness prediction

AUTHORS

Sanchita Pal, Thomas Narock, Luiz F. G. dos Santos, Andreas J. Weiss, Simon W. Good, Lan Jian, Teresa Nieves-Chinchilla, Ayris Narock

AFFILIATION

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ABSTRACT

Since we live in a rapidly growing space age and planning for several human explorations even in our neighboring planet, growing knowledge and building frameworks potential to reduce risk posed by space weather disturbances has become critical. The solar wind may contain magnetic ejecta and structures of different plasma properties that may cause serious disturbance in space weather. In this work, we introduce techniques that use supervised machine learning models namely convolutional and probabilistic neural networks and support vector machines to classify solar wind based on their magnetic and plasma characteristics. We propose two independent pipelines where the first one is composed of a convolutional neural network and a support vector machine. For training purposes, we use simulated magnetic ejecta that are prepared by combining physics-based model and solar wind fluctuation properties in injection and inertial frequency range during magnetic ejecta and non-ejecta solar wind intervals. The pipeline at first, flags the solar wind stream wherever large-scale magnetic ejecta are present and later detects their geoeffectiveness. The second pipeline contains a probabilistic neural network to auto-classify solar wind streams in different types including magnetic ejecta, high speed and slow speed solar wind with uncertainty. This model is trained using specifically chosen magnetic and plasma characteristics expressing behavior of different solar wind stream types. While validating with real data, the models show promising results. The first pipeline that uses only solar wind magnetic properties as input has an accuracy of 88.6% and the second one has an accuracy of 96%. Both the models can be utilized in real-time solar wind and may offer warnings of disturbed space weather, which may in principle lower possible risks associated with space weather disturbances.

ABSID: MCH25_029

TITLE

Koopman Operator Theory And New Data-Driven Approach to Modeling and Signal Processing Of Spatiotemporal Data

AUTHORS

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AFFILIATION

Dartmouth College

ABSTRACT

We present a method combining ideas from the theory of vector-valued kernels with delay-coordinate embedding techniques in dynamical systems capable of identifying spatiotemporal patterns, without prior knowledge of the state space or the dynamical laws of the system generating the data. The approach is particularly powerful for systems in which characteristic patterns cannot be readily decomposed into temporal and spatial coordinates and are characterized by a wide range of scales, potentially coupled with each other. We show our approach reveals coherent patterns of intermittent character with significantly higher skill than conventional analytical methods based on decomposing signals into separable spatial and temporal patterns. Our approach employs Koopman operator theory and its data-driven approximation with novel machine learning approaches. Extensions of our techniques to nonparametric predictions, including data-assimilation and subgrid-scale modeling, will be presented as well. Applications in time-domain astronomy will be discussed in the end.

ABSID: MMCH25_042

TITLE

Physics-informed neural networks for the next generation of solar magnetic field modeling

AUTHORS

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M. Rempel,
J. K. Thalmann,
A. M. Veronig,
M. Molnar,
T. Podladchikova

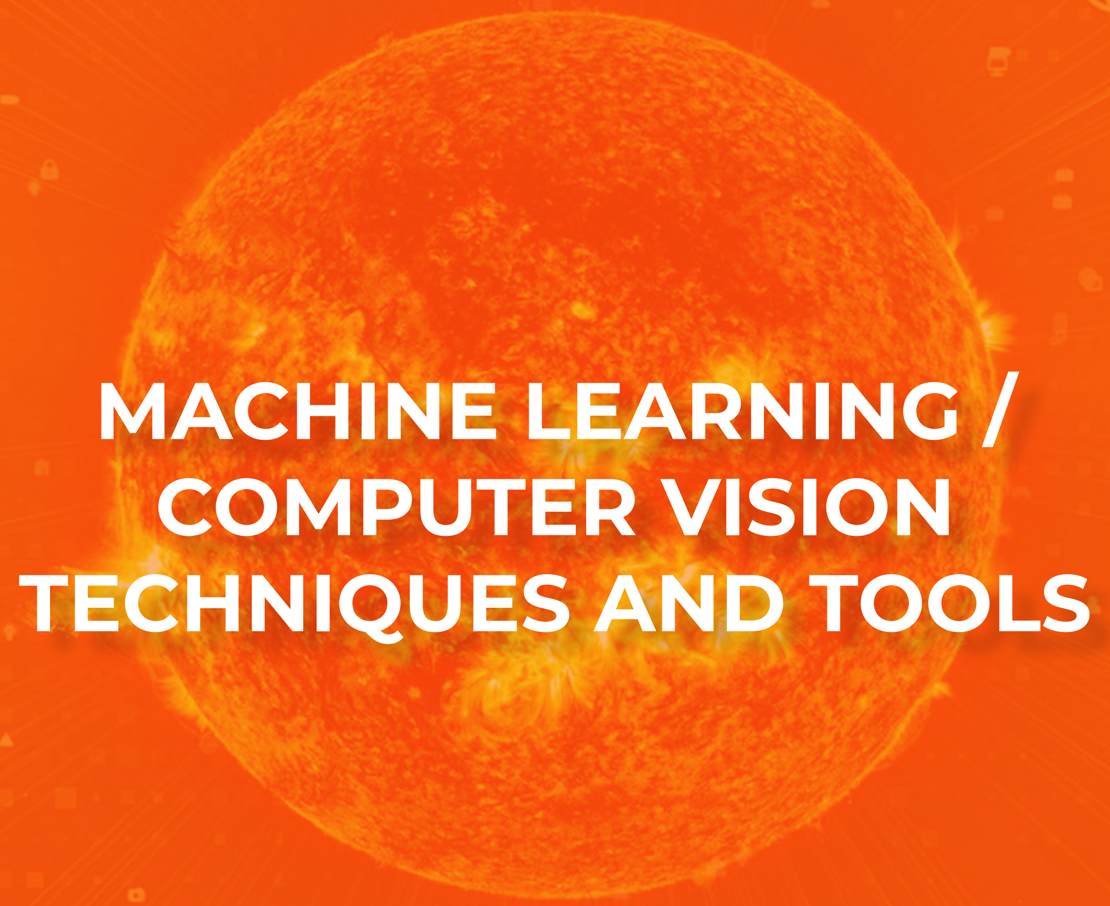
AFFILIATION

High Altitude Observatory, NSF NCAR

ABSTRACT

Physics-informed neural networks (PINNs) provide a novel approach for numerical simulations, tackling challenges of discretization and enabling seamless integration of noisy data and physical models (e.g., partial differential equations). In this presentation, we discuss the results of our recent studies where we apply PINNs for coronal magnetic field simulations of the solar atmosphere, which are essential to understand the genesis and initiation of solar eruptions and to predict the occurrence of high-energy events from our Sun. We utilize our PINN to estimate the 3D coronal magnetic fields based on photospheric vector magnetograms and the force-free physical model. This approach provides state-of-the-art coronal magnetic field estimates in quasi real-time. We simulate the evolution of the active region NOAA 11158 over 5 continuous days, where the derived evolution of the free magnetic energy unambiguously relates to the observed flare activity. We extend this approach by utilizing multi-height magnetic field measurements and combine them in a single simulation. Our evaluation shows that the additional chromospheric field information leads to a more realistic approximation of the solar coronal magnetic field. In addition, our method intrinsically provides an estimate of the corrugation of the observed magnetograms. We provide an outlook on our ongoing work where we use PINNs for global force-free magnetic field extrapolations. This approach enables a novel understanding of the global magnetic topology with a realistic treatment of current carrying fields. In summary, PINNs have the potential to greatly advance the field of numerical simulations, accelerate scientific research, and enable advanced space weather monitoring.

SESSION 3



MACHINE LEARNING / COMPUTER VISION TECHNIQUES AND TOOLS

ABSID: MCH25_043

TITLE

Machine Learning and Eruptive Solar Phenomena: Current Advances, Challenges, and Our Approach (INVITED)

AUTHORS

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AFFILIATION

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ABSTRACT

In recent years Machine Learning (ML) methods have become more frequently applied to specific solar physics problems, as they are well suited to extracting useful information from time series and large multi-wavelength imaging data. Over the past decade researchers have been studying the performance of Convolutional Neural Networks (CNNs), Generative Adversarial Networks (GANs), and Recurrent Neural Networks (RNNs)—particularly Long Short-Term Memory (LSTM) for a wide range of tasks, from image segmentation to predicting solar flare occurrences. Several research groups have demonstrated how Physics-Informed Neural Networks (PINNs) effectively integrate data-driven deep learning with physics-based constraints, ensuring that solutions remain consistent with underlying physical principles. In this report, we discuss how combined application of these approaches can enhance our understanding of the physics behind eruptive solar phenomena. We present an update on our progress in developing hybrid algorithmic and data-driven methods for tracking solar eruptive events using both ground-based and space-based observational data.

ABSID: MCH25_004

TITLE

Self-supervised machine learning for digitizing historical catalogs of solar observations

AUTHORS

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AFFILIATION

Moscow State University

ABSTRACT

Historical catalogs with solar disk drawings and handwritten records contain significant amounts of information about solar activity in the past. However, in order to utilize this information and make it available for wider research, a laborious process of digitizing the data is required. Once the data is spread over thousands of pages, manual processing becomes hardly possible. It turns out that even the standard supervised computer vision methods become imprecise due to the high variability of the records. In such cases, the self-supervised machine learning approach can be helpful. In short, we implemented a procedure in which the text recognition neural network model is continuously and automatically fine-tuned on each new document, based on relations between the recorded data and plausibility conditions, in order to improve the accuracy despite changing handwriting styles or variable background conditions. Using this approach we were able to digitize more than 10,000 pages of the tabular catalogs of Zurich Observatory from 1887-1920 with a much better accuracy than with the pre-trained models. In the presentation, we will discuss implementation details, which may be useful in broader applications, and the results obtained.

ABSID: MCH25_013

TITLE

Reinforcement Learning for Accelerating Radiative Transfer Simulations in Solar Physics

AUTHORS

Brandon Panos

AFFILIATION

FHNW

ABSTRACT

The computational complexity of radiative transfer (RT) within the solar chromosphere presents a fundamental challenge, limiting our ability to extract physical properties from remote sensing observations. We propose a novel machine learning approach to accelerate RT simulations by reframing the problem as a game in which a reinforcement learning (RL) agent can find optimal radiation propagation strategies. Using Soft Actor-Critic (SAC) and Generative Adversarial Imitation Learning (GAIL), our method interacts with a physics-based RT engine to learn efficient policies from reward-based feedback. Early results indicate a twofold increase in efficiency.

ABSID: MCH25_016

TITLE

Forecasting geomagnetic local indices using neural networks

AUTHORS

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AFFILIATION

University of Alcalá

ABSTRACT

The accurate forecasting of geomagnetic disturbances is essential for mitigating the impact of space weather on critical infrastructure. While global indices such as SYM-H or the Dst provide a broad representation of geomagnetic activity, local disturbances can exhibit significant deviations depending on the station's geographic location and the Magnetic Local Time (MLT) at which the storm reaches Earth. In this study, we explore the comparison and relationship between local geomagnetic indices, particularly the Local Disturbance Index (LDi), and global ones and we use machine learning to forecast the local index. The LDi represents the local geomagnetic disturbance at a specific observatory. It is calculated by subtracting the magnetic field disturbance from the quiet baseline at a specific station. We have trained a Deep Neural Network (DNN) to predict local disturbances using solar wind and interplanetary magnetic field (IMF) data from the ACE spacecraft, alongside historical values of the index two hours ahead. Our model considers multiple stations, capturing the spatial variability of geomagnetic activity and the influence of MLT on the disturbances. By integrating local indices into forecasting models, we aim to improve real-time space weather monitoring and provide region-specific predictions, which are crucial for industries vulnerable to geomagnetic disturbances. This study highlights the importance of localized forecasts in space weather applications and demonstrates the feasibility of using global solar wind measurements to predict station-specific geomagnetic activity. We also apply the trained model to stations that the model has not seen during training with reasonable success.

ABSID: MCH25_026

TITLE

A Global and Spatiotemporal Time-Distributed Multivariate Deep Learning with Multi-Loss Regularisation for Solar Flare Forecasting

AUTHORS

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Daniel Gass

AFFILIATION

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ABSTRACT

Given the dynamic nature and potential terrestrial impacts of X-class solar flares, it is important yet challenging to construct a flare forecast model. This is especially true when flare characterizations from NASA's Solar Dynamic Observatory's (SDO) extreme ultraviolet instrument (the Atmospheric Imaging Assembly (AIA)) have not been fully understood or investigated. Previous attempts using deep learning do not fully take into consideration during the learning phase the impact of different flare characterizations, instrumental capability and past observational data sequences. The proposed approach adopts CNN and Bidirectional Gated Recurrent Network with multi-loss regularisation to learn the characteristics of global, spatial and temporal features from multiple observational channels (171, 193, 211, 335 Angstroms) of flaring active regions. In particular, entropy, cosine similarity and mean square error are employed to minimise the loss associated with disorderliness, displacement and line intensity changes related to flare eruptions. The training images are constructed as a multivariate temporal sequence of flare or no-flare observations by considering dynamically the prior period up to the peak of each X-flare EUV emission across the four filters. We show that forecasting of future event observations can be improved using the proposed approach. Ten test observational samples with a cadence 12 seconds per active region image are employed between February 2023 to August 2024 which are outside the time period of the training data. The result shows a performance of up to 82% Precision, 81% ACC, 0.63 TSS, and 81% F1 Score for an 8 minute future forecast corresponding to 40 observations, and decreases with 16 and 32 minutes extension. Further independent evaluation is undertaken on ten X-flare variants samples from February 2024 to July 2024 including the May 2024 event to demonstrate the robustness of the model, approach and predictor power.

ABSID: MCH25_033

TITLE

Instrument-to-Instrument translation: An AI tool to intercalibrate and enhance space-based solar observations

AUTHORS

Christoph Schirninger,
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Anna Jungbluth,
Véronique Delouille,
Laurent Dolla,
J. Emmanuel Johnson,
Lilli Freischem,
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ABSTRACT

The Sun is continuously monitored by space-based and ground-based solar telescopes. However, with the rapid improvement in technology, different mission requirements and atmospheric influences the data products are subject to constant change. For combined studies, such as solar variability or multi-instrument investigations, uniform data series are required. In order to address these needs, we further developed the Instrument-to-Instrument (ITI) translation tool (Jarolim et al. 2023). This tool is built on unpaired image-to-image translation, which enables the translation between data sets without the need of a spatial or temporal overlap, enabling a wide range of applications. To achieve instrument intercalibration and to enhance space-based solar observations, we applied the ITI tool to data from the Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter (SolO), and the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) mission. With the combined data of SolO/EUI and SDO/AIA, ITI can be used to provide uniform and calibrated data series to study the Sun simultaneously from multiple vantage points. The results we present show that ITI achieves a closer resemblance in the Fréchet Inception distance (FID) quality metric compared to the baseline calibrated EUI observations. In addition, the light curve evaluation demonstrates that ITI can provide uniform data series that outperform a standard baseline calibration. The ITI tool is available as open-source software for the research community, and can be adapted to novel datasets and research applications.
This research outcome is supported by NASA award 22-MDRAIT22-0018 (No. 80NSSC23K1045) and managed by Trillium Technologies, Inc.

ABSID: MCH25_038

TITLE

Efficient Segmentation, Detection and Clustering of Solar Coronal Structures: A Comparison of U-Net, YOLO and Classical Computer Vision Techniques Using SDO Data

AUTHORS

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AFFILIATION

Centre for mathematical Plasma Astrophysics (CmPA), KULeuven

ABSTRACT

Segmentation and characterization of solar coronal structures are essential for advancing our understanding of the solar atmosphere and accurately identifying key regions such as active regions and coronal holes which are precursors to phenomena like solar flares and coronal mass ejections (CMEs). In this study, we investigate three complementary approaches to automate this process. First, we employ a previously presented deep learning-based U-Net architecture tailored for segmenting and characterizing solar coronal structures. Second, we develop a lightweight algorithm aimed at optimizing resource efficiency, consisting of classical computer vision techniques which include thresholding and morphological filtering. Lastly, to develop an ultra-light deep learning-based algorithm, we reformulate our segmentation problem as a detection task, focusing on identifying a bounding box around the target region. This approach has the potential to significantly reduce the number of training parameters. To achieve this, we explore YOLO (You Only Look Once), a widely used detection algorithm in computer vision, leading to a 95% drop in trainable parameters. The performance is thoroughly evaluated using metrics such as Dice score and Intersection over Union (IoU), with comparisons made against state-of-the-art methods. The framework that best balances segmentation and detection performance with computational efficiency will be selected for integration into a prototype designed to support future space exploration missions. Finally, to characterize the segmented regions, we propose a set of carefully designed hand-crafted features to represent and characterize the resulting segmentations. These representations are analyzed using unsupervised clustering techniques, such as K-means and t-SNE distinguish solar coronal structures, including active regions, coronal holes and bright points. This work is part of the EU project AutomaticS in spAce exPloration “ASAP” (GA no.101082633).

ABSID: MCH25_030

TITLE

FSpectropolarimetric inversions applying Deep Learning Techniques

AUTHORS

Juan Esteban Agudelo Ortiz, Germain Nicolas Morales, Santiago Vargas Domínguez, Sergiy Shelyag

AFFILIATION

Universidad Nacional de Colombia

ABSTRACT

We have entered a new age of advanced instrumentation and improved algorithms that provide us with better quality data to analyze the Sun’s atmosphere. These recent advances in these fields have led to the creation of instruments with high spectral and spatial resolution, such as DKIST and the GREGOR instrument of the European Solar Telescope, among others. Also, in terms of algorithms, codes with less physical constraints have been developed, such as NICOLE or SNAPI, leading to more general interpretations that are able to include non local thermodynamic equilibrium (NLTE) effects. All these developments, together with instruments that have been collecting data from the Sun for some years now, such as HINODE, lead us to greater processing requirements than science can afford in terms of research time and feasible scientific projects. Due to this problem, it has become urgent to search for new fast data processing methods that are able to deal with large amounts of data in a reduced time lapse, allowing as to make conclusions faster but also keeping the physical sense within the analysis of the generated quantities. With the recent popularity of machine learning algorithms, there have been some approaches towards developing radiative transfer equation (RTE) inversion codes that use neural network models trained on data from synthetic and/or from real observations. Following this trend, we propose our own inversion code based on a one-dimensional neural network model trained on simulated data from the MHD code MURaM on the photospheric quiet-sun region with corresponding spectropolarimetric profiles generated by the RTE NLTE code NICOLE. The trained model achieves train loss values of ~10^{-3} and is able to recover the temperature, density, magnetic field LOS component, and velocity LOS component for the center of the disk.

ABSID: MCH25_003

TITLE

: Implementing a Fully Connected Neural Network for Detecting Quasi-Periodic Pulsations in Solar and Stellar Flares

AUTHORS

Sergey Belov, Dmitrii Kolotkov, Valery Nakariakov, Anne-Marie Broomhall

AFFILIATION

University of Warwick

ABSTRACT

Quasi-periodic pulsations (QPP) are frequently observed in solar and stellar flare lightcurves and provide valuable insights into fundamental plasma dynamics, as they are not explained by the standard flare model. Detecting QPP signals, however, is challenging due to their non-stationary nature, noise contamination, and the growing number of flare observations. To address these challenges, we implemented a Fully Convolutional Network (FCN) to classify flare lightcurve time series based on the presence of exponentially decaying harmonic QPP. The FCN was trained using 90,000 synthetic flare lightcurves, both with and without QPP, achieving an accuracy of 87.2% on synthetic test data without overfitting. For validation, the FCN was applied to real stellar flare lightcurves from Kepler, previously identified to contain QPP using other methods. Subsequently, the FCN analysed a larger Kepler flare catalogue of 2274 events, yielding a QPP detection rate of 7% with a probability above 95%. Implemented in Python, the FCN is available via a browser application featuring a user-friendly graphical interface and a detailed installation and usage guide. Our results demonstrate that the FCN is an effective tool for detecting exponentially decaying harmonic QPP in real flare data, making it suitable for preliminary sifting of QPP events in future large-scale observational surveys.

ABSID: MCH25_007

TITLE

An explainable machine learning model for Large-Scale Travelling Ionospheric Disturbances forecasting

AUTHORS

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AFFILIATION

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ABSTRACT

Travelling Ionospheric Disturbances (TIDs) are wave-like plasma density fluctuations that ripple through the ionosphere and play a critical role in Space Weather dynamics. Large-Scale TIDs (LSTIDs), in particular, typically originate from energy injection in polar regions due to geospace forcing. They affect global navigation satellite systems (GNSS) and radio communications, especially at mid-latitudes; hence forecasting their occurrence is crucial. Since there are no physical or empirical models to forecast LSTIDs, the EU-funded T-FORS project (GA-101081835) aims to develop a machine learning model to forecast their occurrence up to 3 hours before its onset. The model, based on CatBoost and trained on a manually inspected HF-based LSTID catalogue, uses a diverse set of physical drivers, spanning 9 years and ranging from geomagnetic indices, and solar wind and activity data, to ionosonde measurements. It results in three distinct operating modes, tailored for scenarios with varying relative costs of false positives and false negatives. In high-risk settings it is crucial to enable decision-makers to understand and trust the predictions made by the model. In our case, explainability is ensured through the SHAP formalism, a game theoretic approach to explaining model output. The model validation phase – involving a global evaluation and interpretation step, followed by an event-level validation against independent detection methods – highlights the model's predictive robustness, suggesting its interesting potential for real-time Space Weather forecasting. We also discuss probabilistic forecasting approaches from a cost-sensitive learning perspective and, through the lens of the conformal prediction framework, we comment on model calibration for end-user risk management. Despite the imbalanced nature of the problem and the complex coupling triggering the phenomenon, our time-series classification approach demonstrates promising performance.

ABSID: MCH25_044

TITLE

Early and Actionable Flare Alerts for Large Solar Flare Observation Campaigns

AUTHORS

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AFFILIATION

SSL - UC Berkeley

ABSTRACT

Solar flares rank among the most energetic events in our Solar System, emitting bursts of radiation across the electromagnetic spectrum that can disrupt space weather—triggering phenomena like radio blackouts and increased satellite drag. Traditionally, operational flare products have focused on long-term probabilistic forecasts (estimating the likelihood of a flare of a specific magnitude occurring within a given period) and reactive flare alerts (signaling when flare intensity has already escalated), leaving a critical gap in short-term prediction capabilities. For both scientific research and practical space weather management, there is a clear need for predictions that are more actionable than probabilistic forecasts and that offer earlier warning than current alerts. Early detection of significant flares not only benefits space weather mitigation but also enables prompt, targeted observations of intriguing solar events. In response to this need, we are developing a real-time early solar flare alert system designed to use early flare onset signatures to forecast the magnitude and duration of subsequent eruptive events. In this contribution, we outline the concept behind this system and detail its first implementation, which successfully supported an unprecedented solar-flare-triggered sounding rocket mission on April 17, 2024 that captured observations of a large flare using advanced solar instrumentation. We also highlight the observational advancements required to further enhance the capabilities of this alert system in the future.

ABSID: MCH25_010

TITLE

Bridging Physics and Artificial Intelligence: A Comprehensive Framework for Solar Activity Analysis and Forecasting

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ABSTRACT

This research presents an advanced framework for predicting solar activity, such as solar flares, coronal mass ejections (CMEs), and solar wind variability, which impact space weather and technology. The framework combines Machine Learning (ML) and Computer Vision (CV) to analyze solar images and magnetograms, extracting key features related to magnetic fields, plasma flows, and emissions. Convolutional neural networks (CNNs) process high-resolution images, while recurrent neural networks (RNNs) and transformers model temporal changes, predicting solar events. To ensure predictions align with physical principles like magnetohydrodynamics (MHD) and radiative transfer, the framework uses Physics-Informed Neural Networks (PINNs). The framework also incorporates Explainable AI (XAI) techniques, such as saliency maps and attention mechanisms, to make the model's predictions more interpretable, allowing scientists to validate both the accuracy and physical relevance of the results. This approach is tested using data from missions like the Solar Dynamics Observatory (SDO), demonstrating improved accuracy compared to traditional models. Applications include forecasting solar flares, CMEs, and solar wind parameters, which are essential for space weather predictions. Real-time predictions can help protect infrastructure, such as power grids, by enabling early warning systems for geomagnetic storms. Built using Python-based tools like TensorFlow and OpenCV, the framework fosters collaboration between machine learning and heliophysics researchers. This work contributes to MCH25's goal of advancing predictive frameworks and enhancing our understanding of the Sun-Earth connection. It represents a significant step toward integrating ML with solar science to improve space weather forecasting and infrastructure resilience.

ABSID: MCH25_022

TITLE

SpacePhyML: Enabling Access to Space Physics Data for Machine Learning Applications

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ABSTRACT

Machine Learning (ML) and Neural Networks (NN) are powerful data analysis tools, enabling efficient processing of large quantities of data and providing new insights. ML tools have long played an important role in Space Physics research and with the rise of NN, this importance has only increased. While data, labels and models are often made publicly available, this is frequently done without ease of usage in mind. Thereby creating a high entry barrier for access and stifling innovation. pacePhyML aims to change that by creating a framework for making space physics datasets and models accessible through an easy-to-use interface. SpacePhyML is built on top of PyTorch and installable using the Package Installer for Python (pip), enabling easy installation, usage and integration with existing DNN and ML frameworks. Extensive documentation on the data, labels and models, backs this up by providing a guide for new users to understand the data and create innovative new algorithms. Currently, SpacePhyML contains datasets and models for plasma region classification based on data from the Magnetospheric Multiscale (MMS) Mission. Supporting tools also enable the creation of new datasets, either unlabeled or using existing labels. The models have partially been developed as part of the Automatics in SpAce exPloration (ASAP) project and are optimized for execution onboard spacecraft, making them small and efficient while retaining accuracy. ASAP has received funding from the EU's HORIZON Research and Innovation Action (GA no.101082633).

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