Solar Transients From The Sun to Earth: Coronal Bright Fronts, Radio Bursts, and Energetic Protons

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(Summary of Ph.D. Dissertation; Thesis language: English
Ph.D. awarded 2024 by the Institute of Astronomy and NAO
of the Bulgarian Academy of Science)

Solar activity profoundly influences our space environment through powerful eruptions and emissions. When the Sun releases intense bursts of energy through solar flares and coronal mass ejections (CMEs), it launches electromagnetic radiation and energetic particles that can severely impact Earth's technological systems. This dissertation addresses critical knowledge gaps in these transient phenomena by examining their origins and dynamics, ultimately supporting the development of more robust forecasting models to protect our essential infrastructure.

The dissertation focuses on three key aspects of solar activity: Coronal Bright Fronts (CBFs), solar type III radio bursts, and Solar Energetic Proton (SEP) events. It aims to analyze CBF kinematics and their interactions with the coronal plasma, investigate the origins and dynamics of type III radio bursts, and develop machine learning models for forecasting SEP fluxes. These studies aim to improve the understanding of solar dynamics and enhance space weather prediction capabilities.

The structure of the dissertation is outlined as follows: Chapter 1 gives a short overview of solar activity and introduces the key solar transient phenomena under study. Chapter 2 examines CBFs, detailing their kinematics and relationships with plasma properties using observations and modeling. Chapter 3 focuses on type III radio bursts, analyzing their sources and trajectories to understand the associated coronal conditions. Chapter 4 presents the development and validation of SEP forecasting models using deep learning techniques. Finally, Chapter 5 summarizes the key findings and implications of the research.

In Chapter 2, we characterize 26 CME-driven CBFs in the low solar corona [Nedal et al., 2024], observed in the extreme ultraviolet (EUV) 193 Åband by the Solar Dynamic Observatory-Atmospheric Imaging Assembly (SDO/AIA) instrument. Using the Solar Particle Radiation Environment Analysis and Forecasting—Acceleration and Scattering Transport (SPREAdFAST) framework, the research combined physics-based and data-driven models to analyze coronal magnetic fields, shock wave dynamics, and Solar Energetic Particle (SEP) propagation. Key kinematic parameters, including shock speed, acceleration, intensity, and thickness, were derived from base-difference images, annulus plots, and J-maps. The integration of the Large Angle and Spectrometric Coronagraph (LASCO) measurements further enhanced SEP spectral characterization and understanding of CBF dynamics.

The study also employed geometric modeling to capture the evolution of shock surfaces and explored parametrized relationships between plasma properties [Miteva et al., 2023]. Findings revealed complex interactions between shocks and plasma parameters, offering valuable insights into coronal shock evolution. The development and application of the Wavetrack tool, which automates the tracking of large-scale solar features, facilitated the detailed mapping of CBF dynamics and their drivers [Stepanyuk et al., 2022]. Future research will refine these methodologies to improve the accuracy of shock and plasma parameter characterizations, advancing our understanding of solar phenomena and their space weather implications.

In Chapter 3, we analyze a series of type III radio bursts observed on April 3, 2019, during a coordinated campaign involving the PSP/FIELDS instrument and LOFAR telescope [Nedal et al., 2023b]. Sixteen weak bursts were detected over 20 minutes during a quiet solar period, with the solar disk dominated by a central active region (AR12737). A semi-automated pipeline aligned and preprocessed data from PSP and LOFAR, enabling precise tracing of burst frequency drifts and electron beam speeds. The bursts shared a common source region off the Sun's southeast limb, with potential origins linked to nanoflares, plasma upflows, or magnetic reconnection.

Imaging revealed consistent burst locations in the middle corona, but discrepancies arose when comparing observations to density models. The Newkirk model overestimated source heights relative to the MAS model, suggesting scattering and propagation effects influence perceived burst locations. These findings align with the hypothesis that changes in coronal topology, such as a stealth CME, could explain density deviations. Future work will refine these models, incorporate Solar Orbiter data, and utilize the TDoA technique to improve source localization. This study highlights LOFAR's value for analyzing faint solar radio bursts and their implications for space weather.

In Chapter 4, we present a comprehensive investigation of SEP dynamics and forecasting, combining simulations and machine learning models to enhance space weather prediction. Using the SPREAdFAST framework, 62 eruptive events with EUV CBFs and 1 AU proton flux enhancements were analyzed [Kozarev et al., 2022]. The study highlights the role of coronal conditions in diffusive shock acceleration and examines interplanetary SEP transport using Solar and Heliospheric Observatory/Energetic and Relativistic Nuclei and Electron (SOHO/ERNE) observations. While the model predictions aligned well with observations, discrepancies at higher energies underscore the need for refining input spectra and incorporating three-dimensional transport effects for improved accuracy.

Additionally, a Bi-directional Long-short term memory (BiLSTM) neural network was developed to predict daily-averaged SEP integral fluxes at 1-, 2-, and 3-day horizons for multiple energy bands [Nedal et al., 2023a]. Leveraging OMNIWeb data from four solar cycles, the model demonstrated strong performance, with high correlations between predictions and observations. However, challenges included reduced accuracy over longer forecasting windows and higher false-negative rates, particularly in the >30 MeV energy band. Future work will address these limitations by incorporating hourly-averaged data, additional solar activity features, and advanced model architectures to improve short-term predictions and enhance real-time forecasting capabilities.

This research underscores the potential of integrating physics-based models and deep learning techniques for SEP forecasting. By advancing understanding of SEP acceleration and transport, these efforts contribute to safeguarding satellites, spacecraft, and astronauts from solar storm impacts while paving the way for more accurate and timely space weather predictions.

Future work will expand datasets for EUV waves and type III radio bursts, integrating high-resolution, multi-wavelength observations from instruments like LOFAR, PSP, and Solar Orbiter. Refining models to account for scattering and propagation effects will improve accuracy, while advanced deep learning architectures and additional solar activity features will enhance SEP forecasting. These efforts aim to develop real-time tools for space weather prediction, providing early warnings to protect satellites, spacecraft, and ground-based systems, advancing heliophysics and space weather research.

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