HelioSTET: Enhancing Heliospheric Magnetic Field Modeling Using Suprathermal Electrons

David Galarza, Alicia Petersen – SWIFT Lab – University of Florida

Introduction

Current forecasting models like EUHFORIA have the potential to give satellites orbiting Lagrange points or other objects of interest within the inner heliosphere forewarning when dangerous solar activity is imminent.

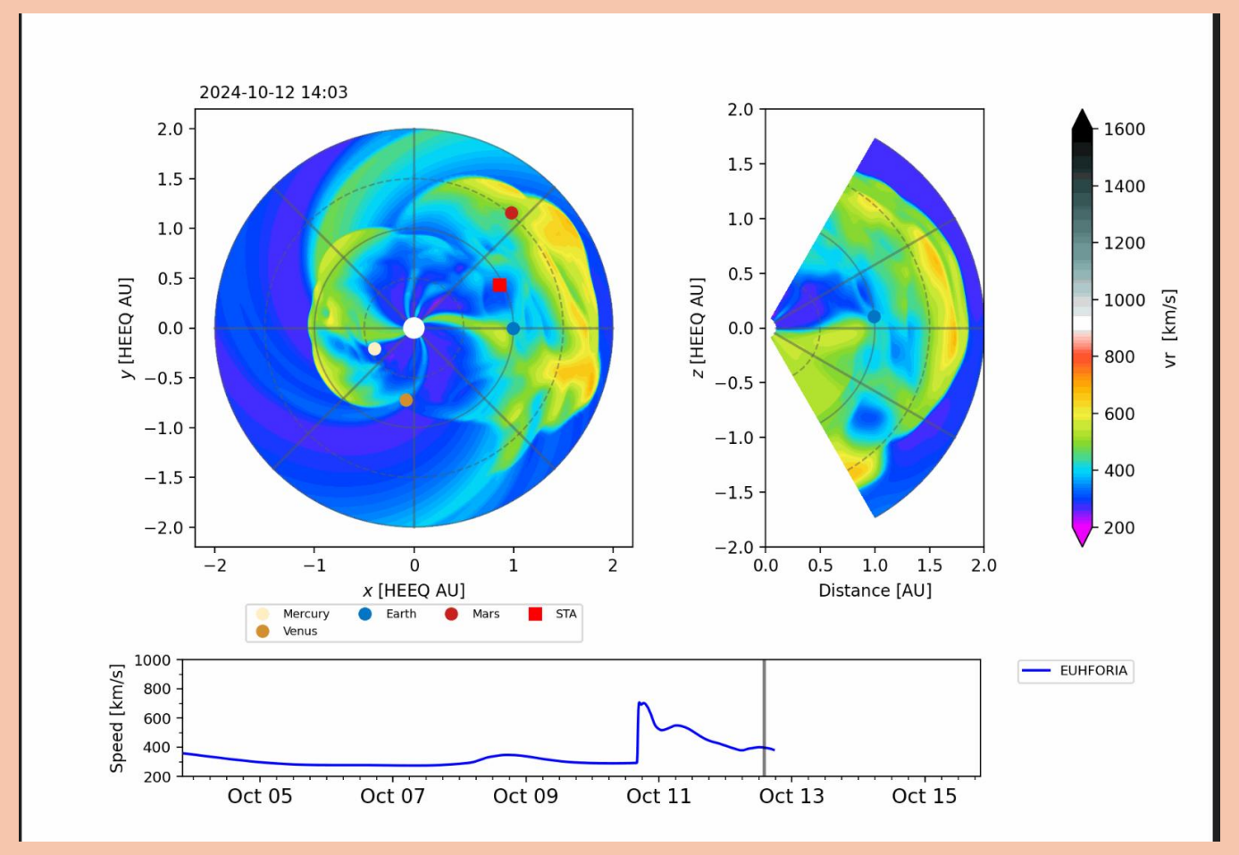


Figure 1: EUHFORIA Heliosphere run of the series of major solar activity on October 10-11 that resulted in major satellite damage

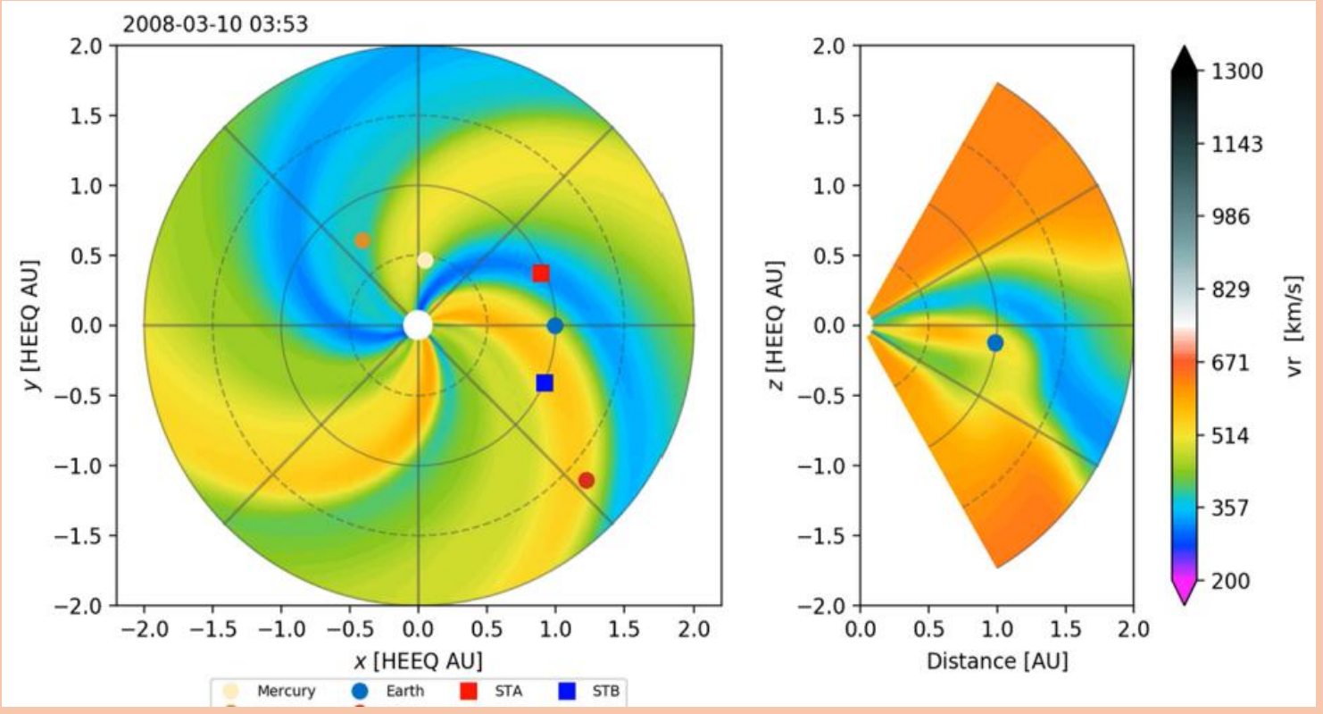


Figure 2: EUHFORIA Heliosphere run of the background solar wind during solar minimum in 2008

Space weather forecasting depends on accurate modeling of the heliospheric magnetic field (HMF), but widely used models like EUHFORIA and SWMF struggle to accurately reproduce HMF variability, especially during solar activity. This impacts predictions of solar energetic particle (SEP) events, coronal mass ejections (CMEs), and geomagnetic storms. Even in quiet solar conditions, significant discrepancies exist in solar wind speed and density predictions. These errors compound during active solar periods, leading to poor forecasting accuracy. To address these limitations, we leverage suprathermal electron (SE) observations to refine HMF structure identification.

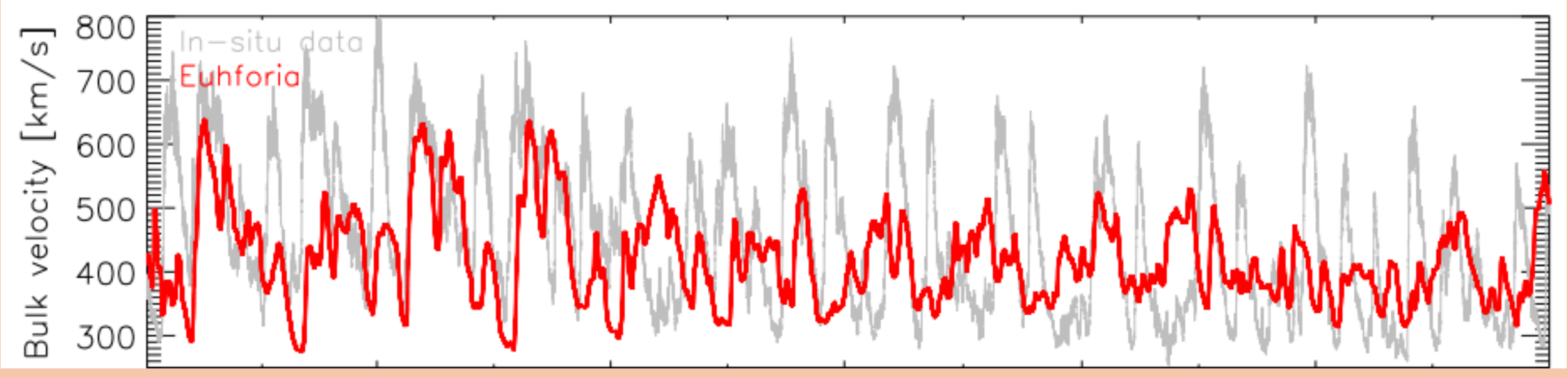


Figure 3: EUHFORIA model output bulk velocity (red) vs in-situ data from ACE plotted over the same time period

Building a Better Model: The Role of Suprathermal Electrons

A more accurate understanding of HMF properties that facilitate the physics behind existing forecasting frameworks, is essential. Suprathermal electrons (SEs) act as natural tracers of the magnetic field, providing critical insight into field topology and turbulence. HelioSTET is designed to use these observations to refine HMF models and improve particle transport predictions. SEs from the solar corona propagate through the HMF in three distinct types - strahl, halo, and superhalo electrons, each offering a glimpse at the magnetic surroundings they navigate through. A key advantage of SE observations is their ability to provide continuous, in-situ measurements of the HMF topology across a range of heliospheric conditions. Unlike other space weather tracers, SE PADs respond dynamically to variations in the field, offering a unique method for identifying regions of enhanced turbulence or magnetic reconnection. By incorporating these insights, HelioSTET refines how we interpret large-scale heliospheric dynamics, bridging a critical gap between theoretical modeling and observational validation. If we can better map the HMF, we can better predict the propagation of solar storms and energetic particles.

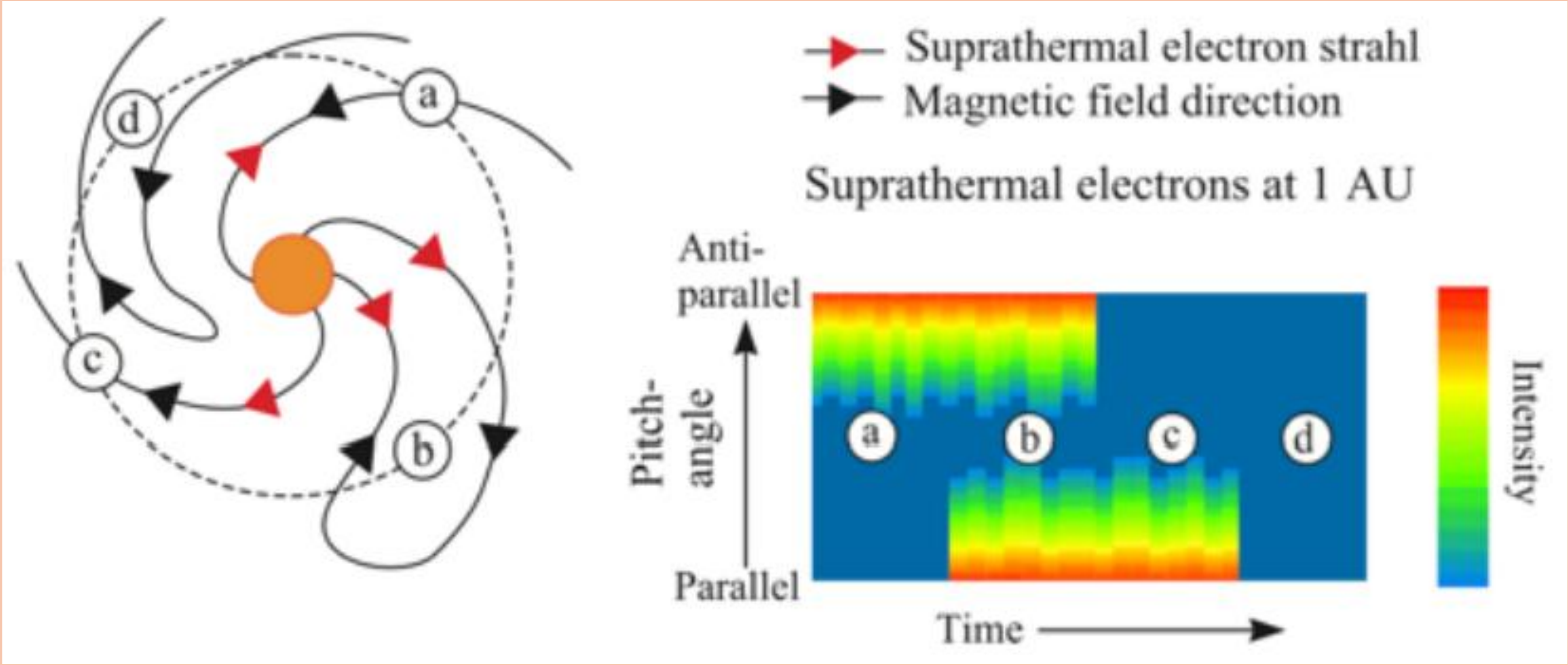
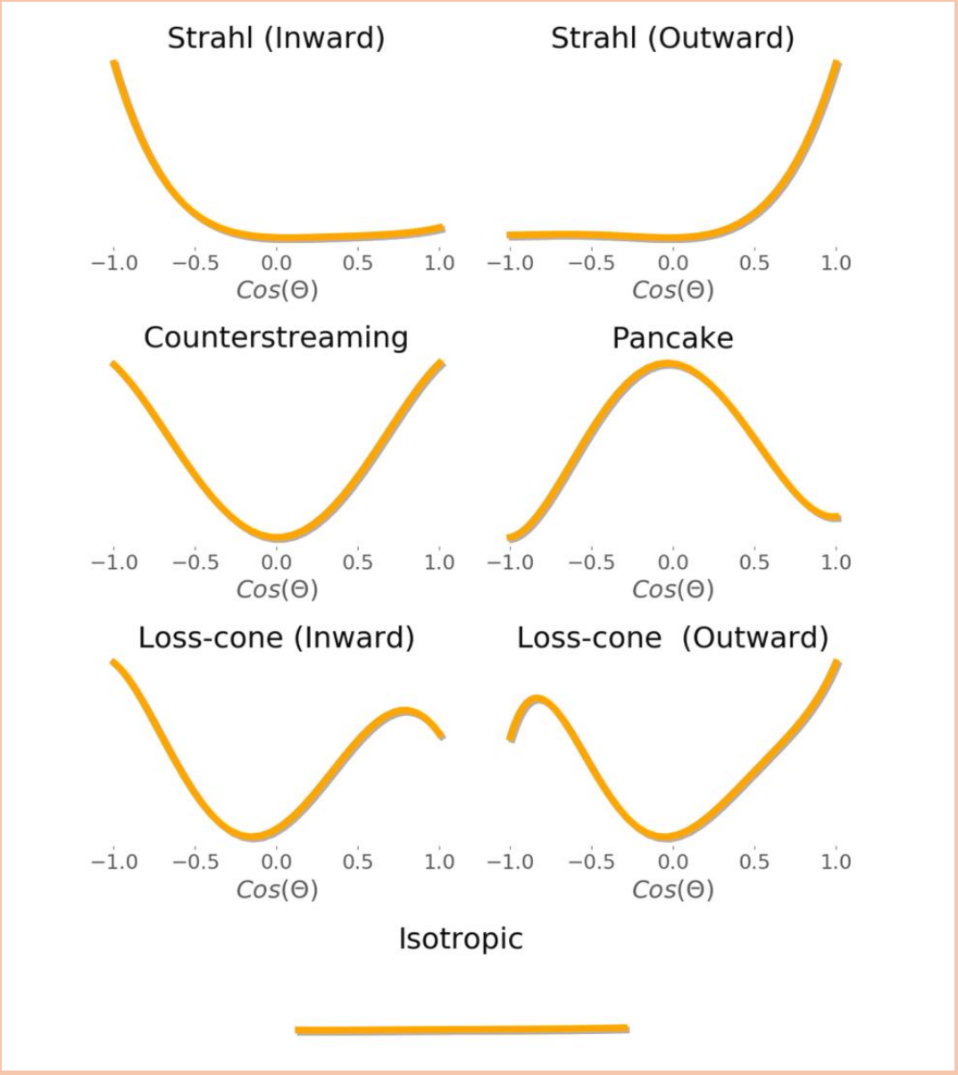


Figure 4: Visual of the heliospheric magnetic field on the left, followed by electron flux intensity as a function of pitch angle. Both open and closed field lines are pictured with flux activity happening only in closed line cases (Owens and Forsyth, 2013)

As SEs traverse along field lines, the weakening magnetic field induces higher flux intensities at narrower pitch angles (strahl), due to the preservation of the first adiabatic invariant. These SEs at narrower pitch angle tend to follow field lines extremely closely. However, deviations from this idealized behavior can reveal important physical processes in the heliosphere, such as turbulence, wave-particle interactions, and large-scale magnetic field structures.



By examining Pitch Angle Distributions (PADs) of suprathermal electrons, we can infer key properties of the local HMF environment. Figure 5 illustrates four commonly observed PAD structures and their corresponding physical interpretations (Carcaboso):

Strahl: A narrow beam of electrons aligned with the IMF direction, typically observed in regions of weak scattering.

Counterstreaming Electrons: Two distinct beams traveling in opposite directions along the field line, often indicative of closed magnetic field structures or transient solar wind events.

Isotropic Flux: A nearly uniform distribution of electrons across all pitch angles, suggestive of strong scattering processes or magnetic disconnection events.

Bidirectional Suprathermal Electrons (BDEs): Beams propagating in both field-aligned directions, commonly observed within Interplanetary Coronal Mass Ejections (ICMEs), indicating prolonged Sun connectivity.

These distinct PAD structures provide critical insight into the nature of particle transport and the evolution of the interplanetary magnetic field, allowing for improved space weather modeling and interpretation. The model implements the following governing equation:

$$\frac{\beta}{\sqrt{E}}\frac{\partial\Phi}{\partial t}+\mu\frac{\partial\Phi}{\partial s}-\frac{1-\mu^2}{2}\left(\frac{1}{B}\frac{\partial B}{\partial s}-\frac{F}{E}\right)\frac{\partial\Phi}{\partial\mu}+EF\mu\frac{\partial\Phi}{\partial E}=\langle S_e\rangle+\langle q_e\rangle, \qquad (2.5.1)$$

The suprathermal electron transport equation governs how SE distributions evolve along the heliospheric magnetic field, incorporating effects like pitch-angle scattering, adiabatic focusing, and large-scale field variations. Each term in the equation represents a physical mechanism shaping SE trajectories. The first term describes advection along the field, the second captures pitch-angle diffusion due to wave-particle interactions, and the final term accounts for additional energy diffusion effects. To verify HelioSTET's accuracy, we will first apply it to simplified solar wind conditions to test how well it reproduces known electron behaviors in the absence of turbulence. Once validated, we extend the model to more complex heliospheric environments.

Future Applications: Research to Operations

Upon verification and validation of simpler cases, future refinements of HelioSTET will focus on extending the model to dynamic heliospheric conditions. Analyzing SE transport in regions dominated by switchbacks—rapid IMF polarity reversals observed by Parker Solar Probe—can provide insight into their large-scale structure and influence on particle propagation. Similarly, Whistler waves, known to scatter SEs and disrupt strahl formation, will be incorporated to evaluate their role in suprathermal electron evolution. By iteratively adjusting HelioSTET to capture these effects, we aim to improve the accuracy of particle propagation modeling across diverse space weather scenarios. While HelioSTET will be designed to improve particle transport modeling for research applications, its insights also carry direct operational implications. By refining our ability to diagnose heliospheric magnetic structures, we provide a critical missing link between scientific models and space weather hazard assessment.

Space weather models need to be interpretable and actionable for users like satellite operators. HelioSTET's improvements in particle propagation modeling can directly feed into an intuitive stoplight system for operational decision-making. Operators will be able to make real-time decisions based on space weather risks. The figures below show the enhanced readability of space weather predictions beyond research communities. These are magnetic field strength plots made using EUHFORIA that display magnetic parameters during a CME.

- Green 🟢 = **Safe conditions**
- Yellow 🟡 = **Increased caution required**
- Red 🔴 = **High risk, consider shutting down sensitive systems**

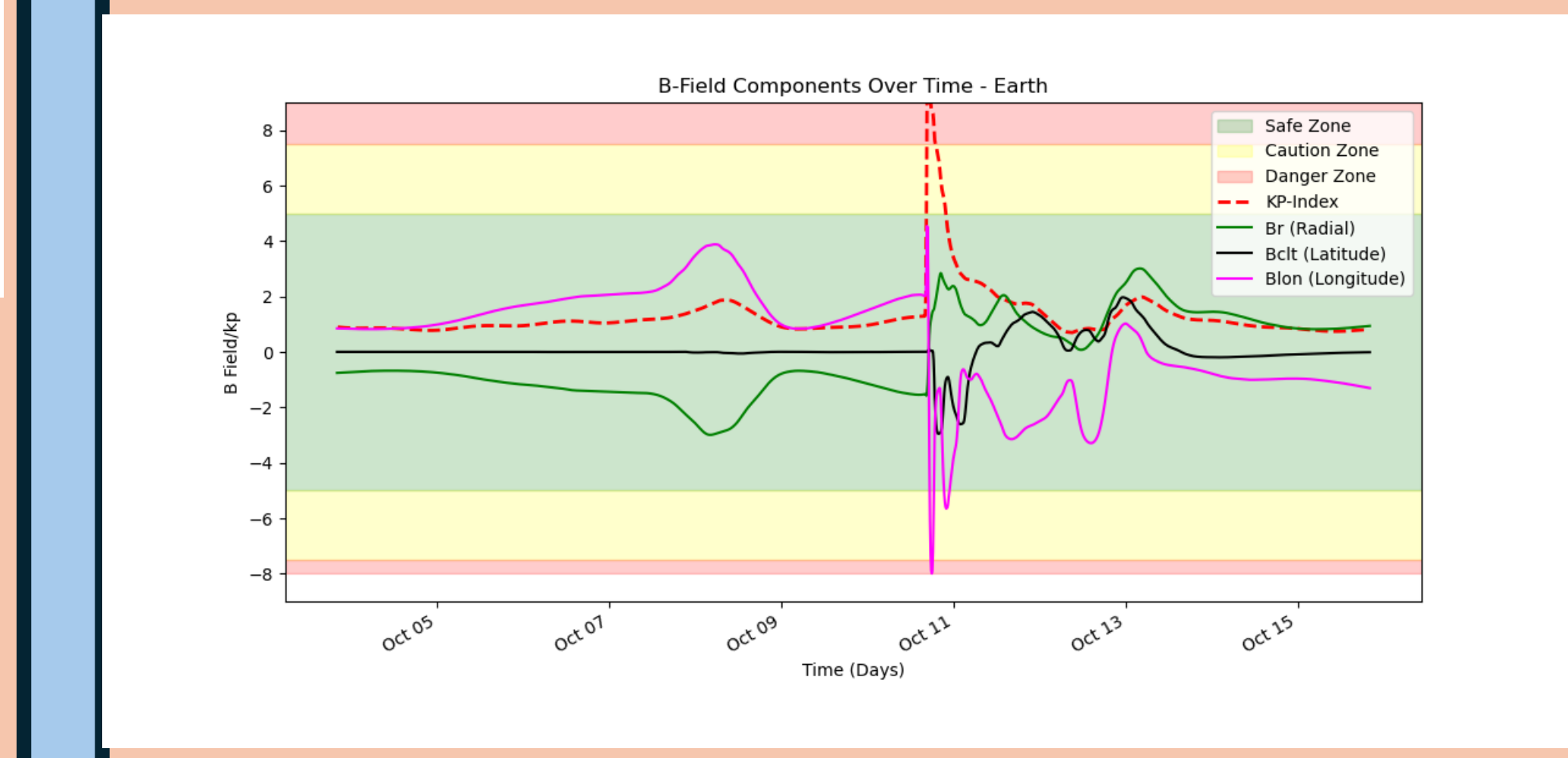


Figure 6: EUHFORIA Output of magnetic field parameters at Earth with Kp-Index during the October 10-11 event with a stoplight map overlayed.

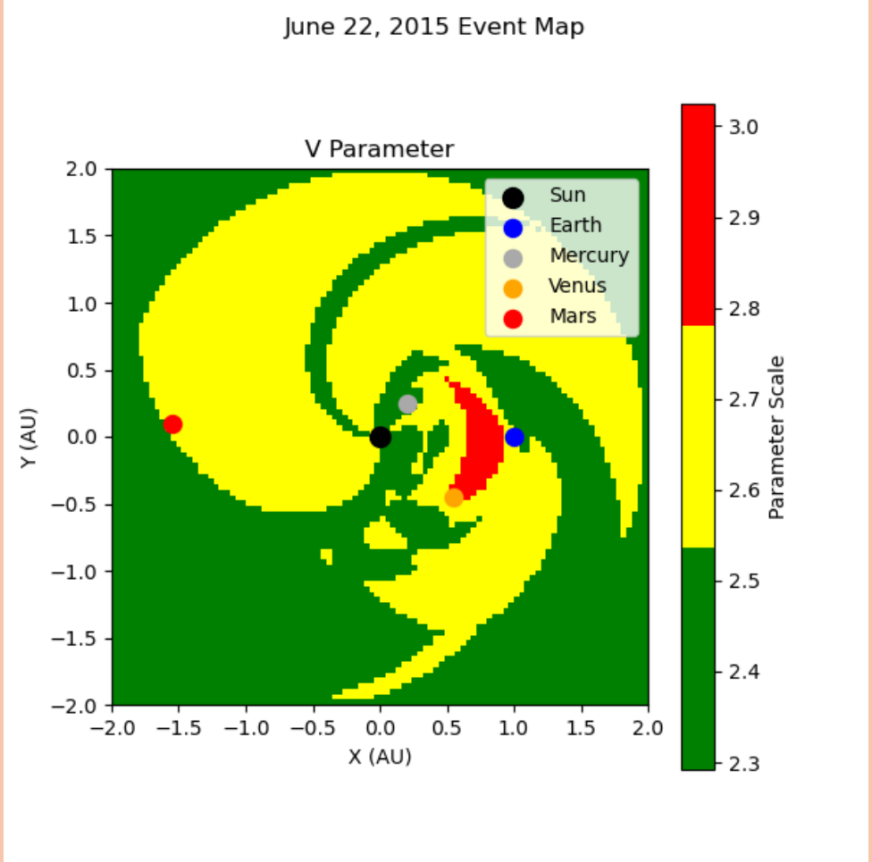


Figure 7: Stoplight map example of how we would like to make model runs for interpretable for spacecrafts

The categorization of space weather hazards using the stoplight system is directly informed by HelioSTET's improvements in particle propagation modeling. By refining our ability to identify regions of enhanced turbulence and connectivity disruptions, we provide an intuitive framework for satellite operators to anticipate and mitigate space weather risks.

Acknowledgments

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