Predictive Science Inc.

EGU General Assembly 2022

Space Weather Predictions of CMEs and SEPs Through the Inner Heliosphere

Erika Palmerio

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

epalmerio@predsci.com

The Ever-Evolving Space Weather Science

- Space weather research and forecasts traditionally focussed on Earth (for obvious reasons!)
- In recent years, interest in space weather predictions has expanded to include impacts at other planets beyond Earth (such as Mars) as well as spacecraft scattered throughout the heliosphere (such as STEREO, Parker Solar Probe, Solar Orbiter)
- The scope of space weather science now encompasses the whole heliospheric system, and multipoint measurements of solar transients (e.g. coronal mass ejections, CMEs, and solar energetic particles, SEPs) can provide useful insights and validations for prediction models

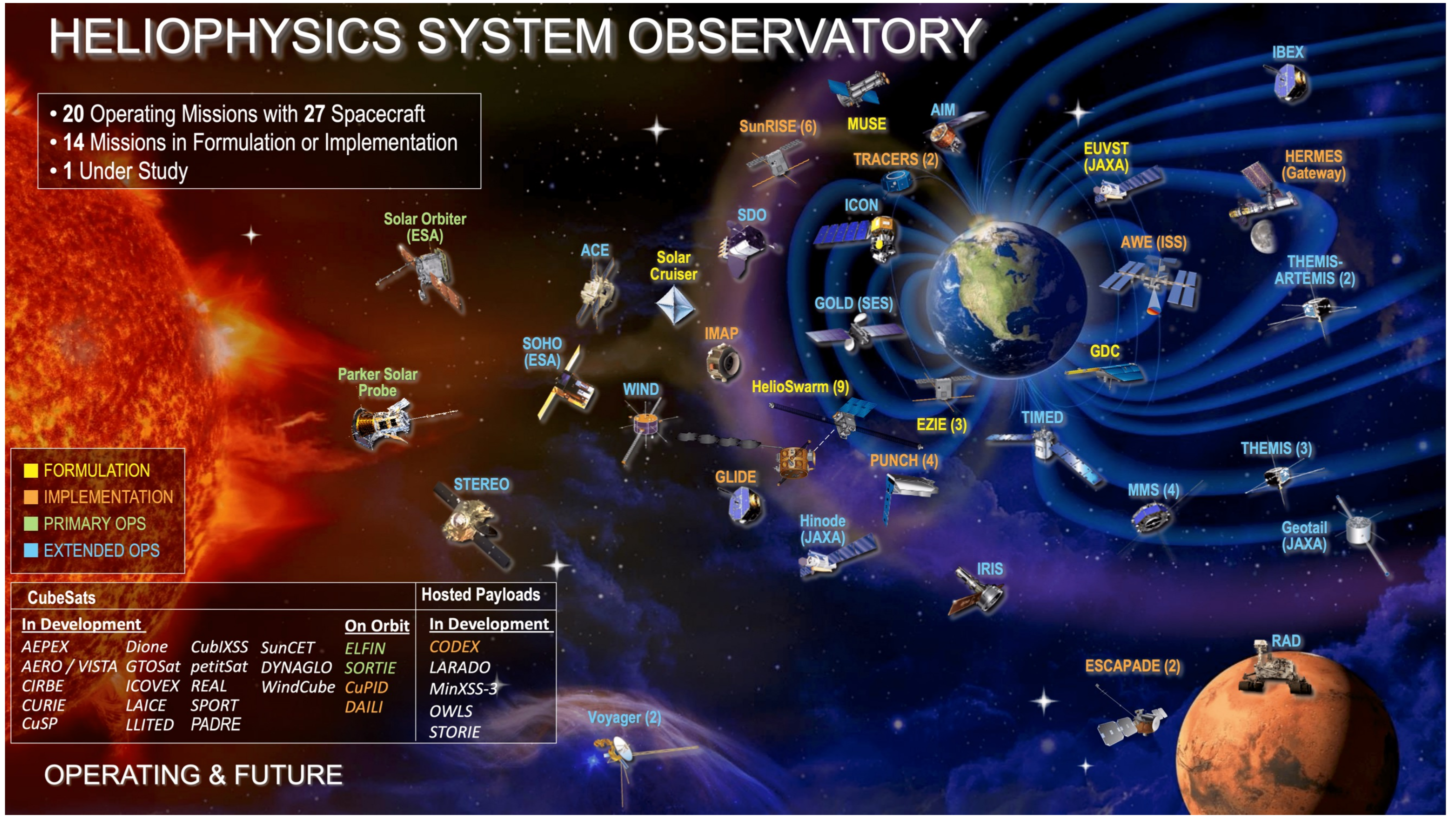


Image credit: NASA

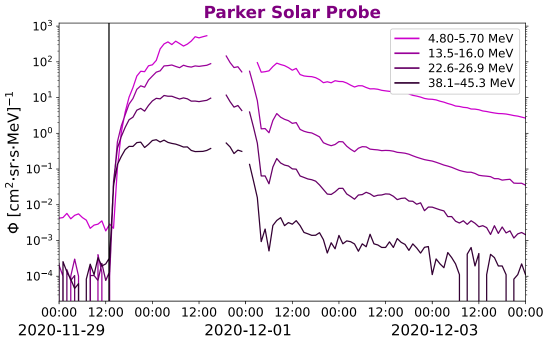
Predictive Science Inc.

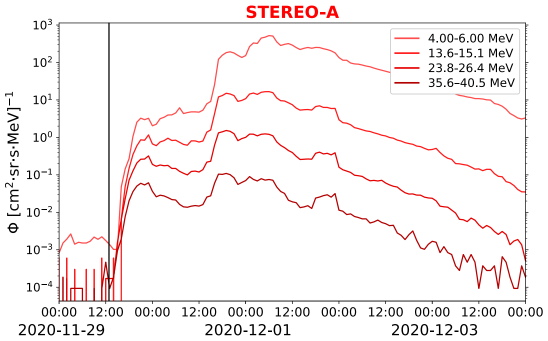
EGU General Assembly

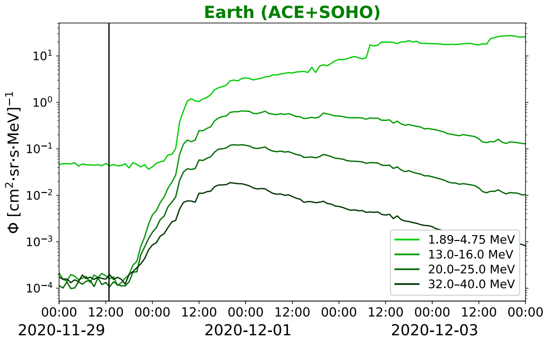
CMEs and SEPs: Forecasting the Whole Inner Heliosphere on 2020-11-29

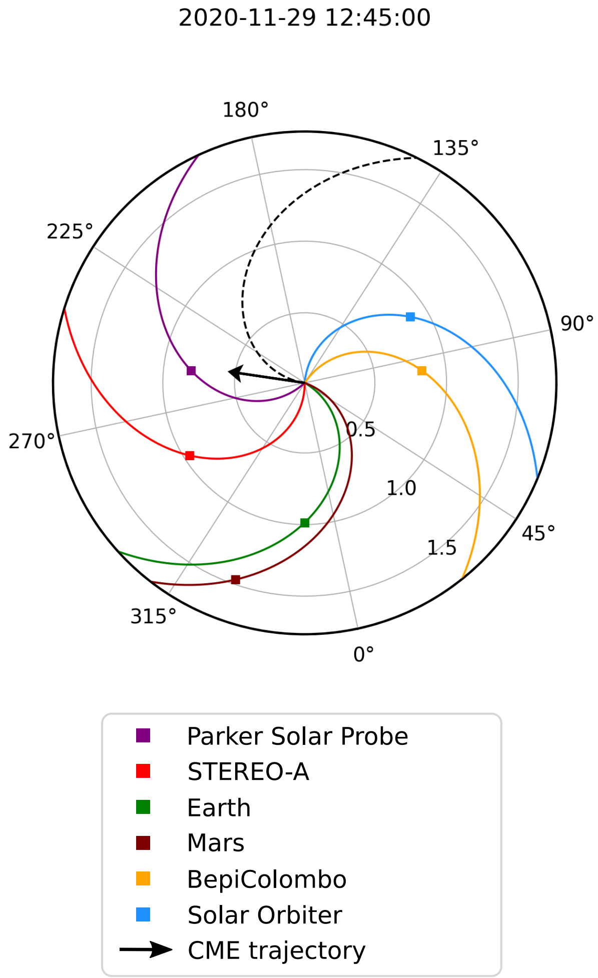
CME eruption just behind the E limb from Earth's viewpoint, associated with an M4.4 flare (likely higher "true" flare class) and directed roughly towards Parker Solar Probe

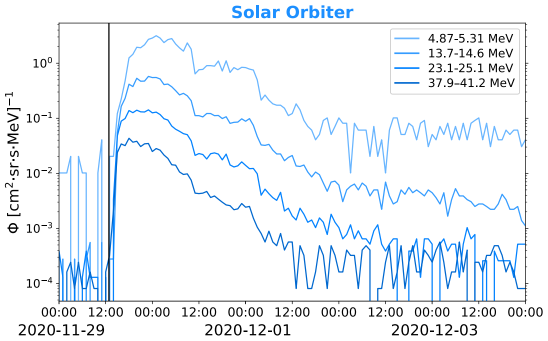
CME encountered in situ at Parker Solar Probe and STEREO-A (see e.g. Möstl et al. 2022, Nieves-Chinchilla et al. 2022)

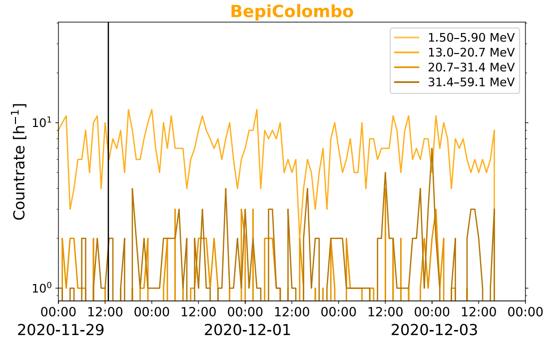


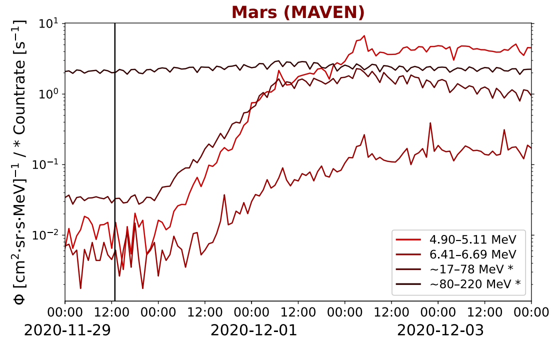










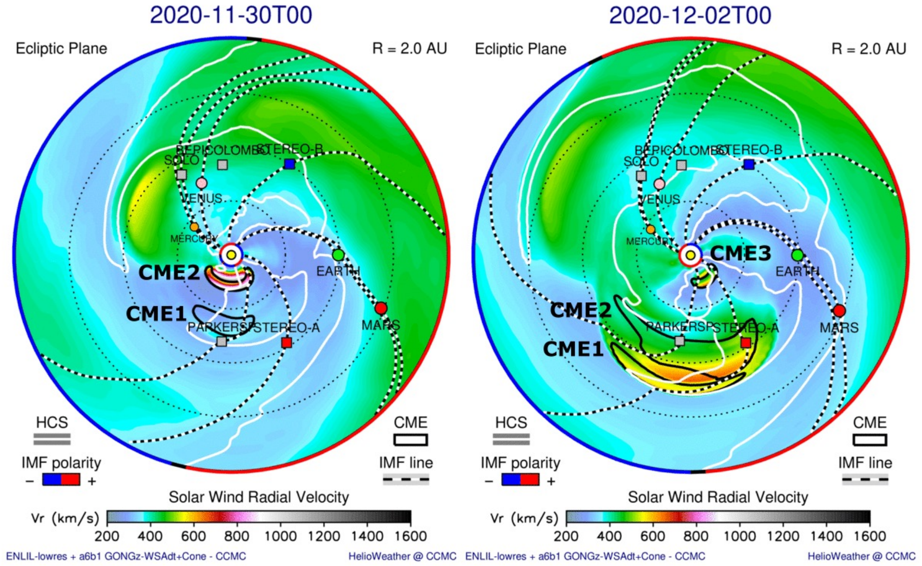


SEPs from the event measured at Parker Solar Probe, STEREO-A, Earth, Mars, and Solar Orbiter (see e.g. Kollhoff et al. 2021, Palmerio et al. 2022)

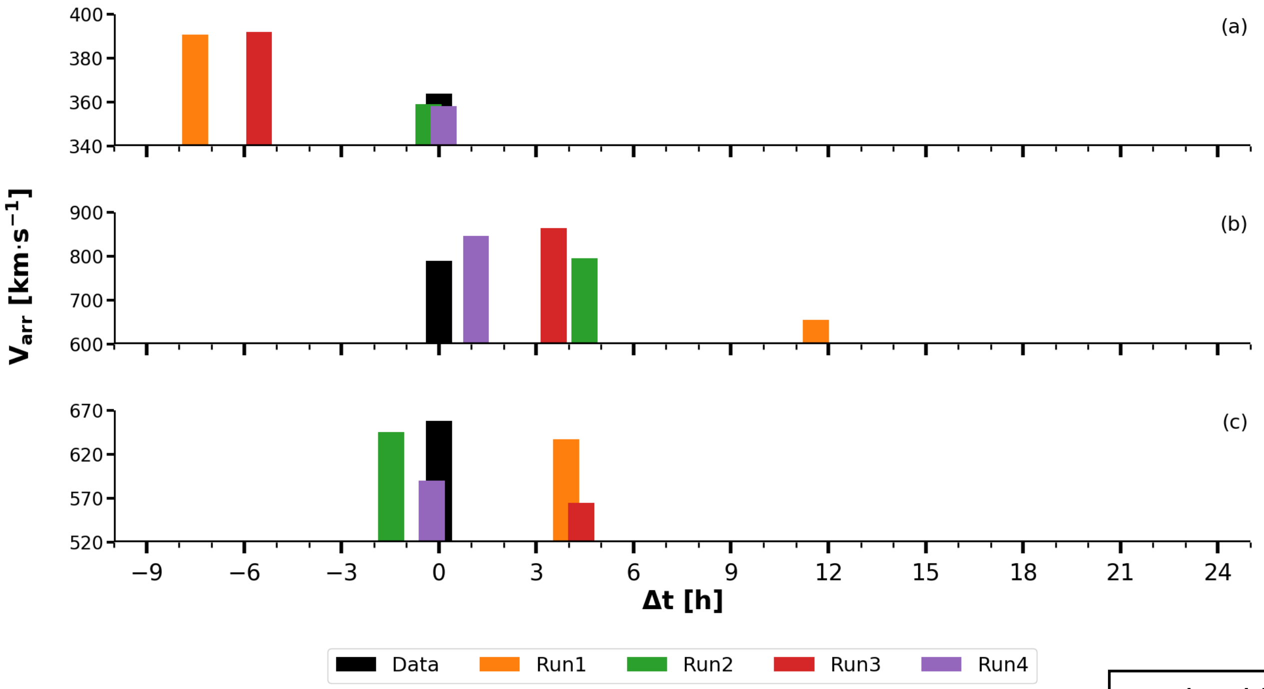
Planet/spacecraft configuration plot made with Solar-MACH (https://solar-mach.github.io)

epalmerio@predsci.com

The 2020-11-29 Event: CME Predictions With WSA–Enlil



CME1: Preceding event 2020-11-26
CME2: 2020-11-29 ``main´´ eruption



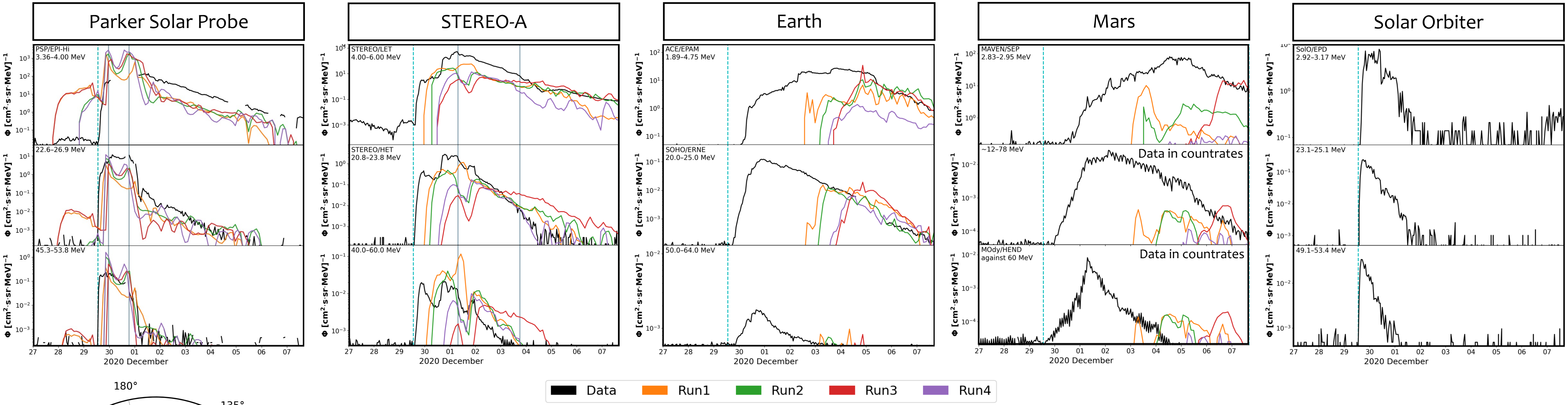
MHD Wang–Sheeley–Arge (WSA; Arge et al. 2004) + Enlil (Odstrcil et al. 2003) ``mini-ensemble´´:

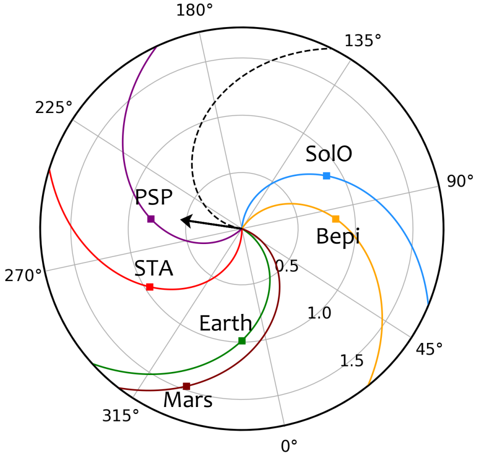
- Run1: real-time forecasts, Run2/Run3: science hindcasts, Run4: post-event analysis
- CMEs inserted at the outer WSA boundary / inner Enlil boundary of 21.5 $R_\odot$ or 0.1 AU
- Arrival times and speeds match the typical uncertainties (order of ~10 hrs for arrival time)
- CME input parameters derived in real time not dramatically worse than the hindcasts ones
- Modelled solar wind background significantly affecting the CME arrival times and speeds

Work published on SpWea, doi:10.1029/2021SW002993 [Palmerio et al. 2022]

epalmerio@predsci.com

The 2020-11-29 Event: SEP Predictions With WSA–Enlil–SEPMOD





Test particle code SEPMOD (Luhmann et al. 2007) run on WSA–Enlil results:

- Requires connectivity to a shock to propagate particles
- Results show that well-connected observers → much better predictions
- SEP event onset delayed even in the best cases (CMEs inserted at 21.5 $R_\odot$)
- Observers that do not connect to the heliospheric shock miss SEP event
- Forecast run performs similarly to hindcasts and post-event analysis runs
- Computationally-efficient model, helpful for real-time applications

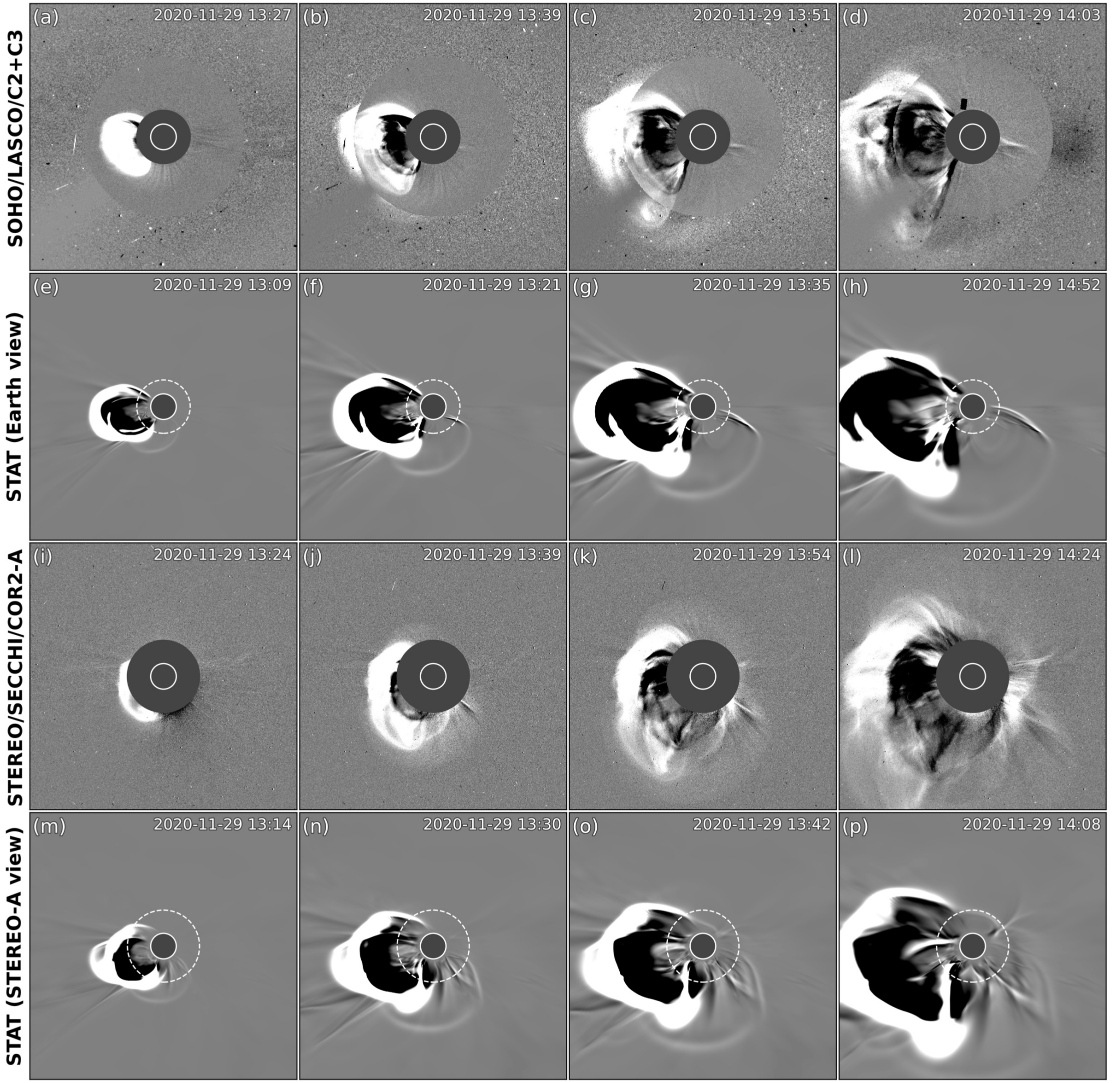
Work published on SpWea,
doi:10.1029/2021SW002993
[Palmerio et al. 2022]

epalmerio@predsci.com

The 2020-11-29 Event: Modelling the CME Eruption & Evolution With STAT

Solar Particle Event (SPE) Threat Assessment Tool (STAT; Linker et al. 2019) = Magnetohydrodynamic Algorithm outside a Sphere (MAS; Mikić et al. 1999) + Energetic Particle Radiation Environment Model (EPREM; Schwadron et al. 2010)

STAT combines MHD with focussed-transport particle modelling, and simulates the low-coronal phase of SEP acceleration (until the CME leaves the outer boundary of the coronal domain at 30 $R_\odot$)



CME eruption modelled from its initiation at the Sun, then compared via synthetic white-light images to coronagraph data from SOHO (near Earth) and STEREO-A (near L5 at the time of this event)

Work performed with Ron Caplan, Jon Linker, Matt Young, Nathan Schwadron, Tibor Török, Cooper Downs, and Christina Cohen [Caplan et al., in preparation]

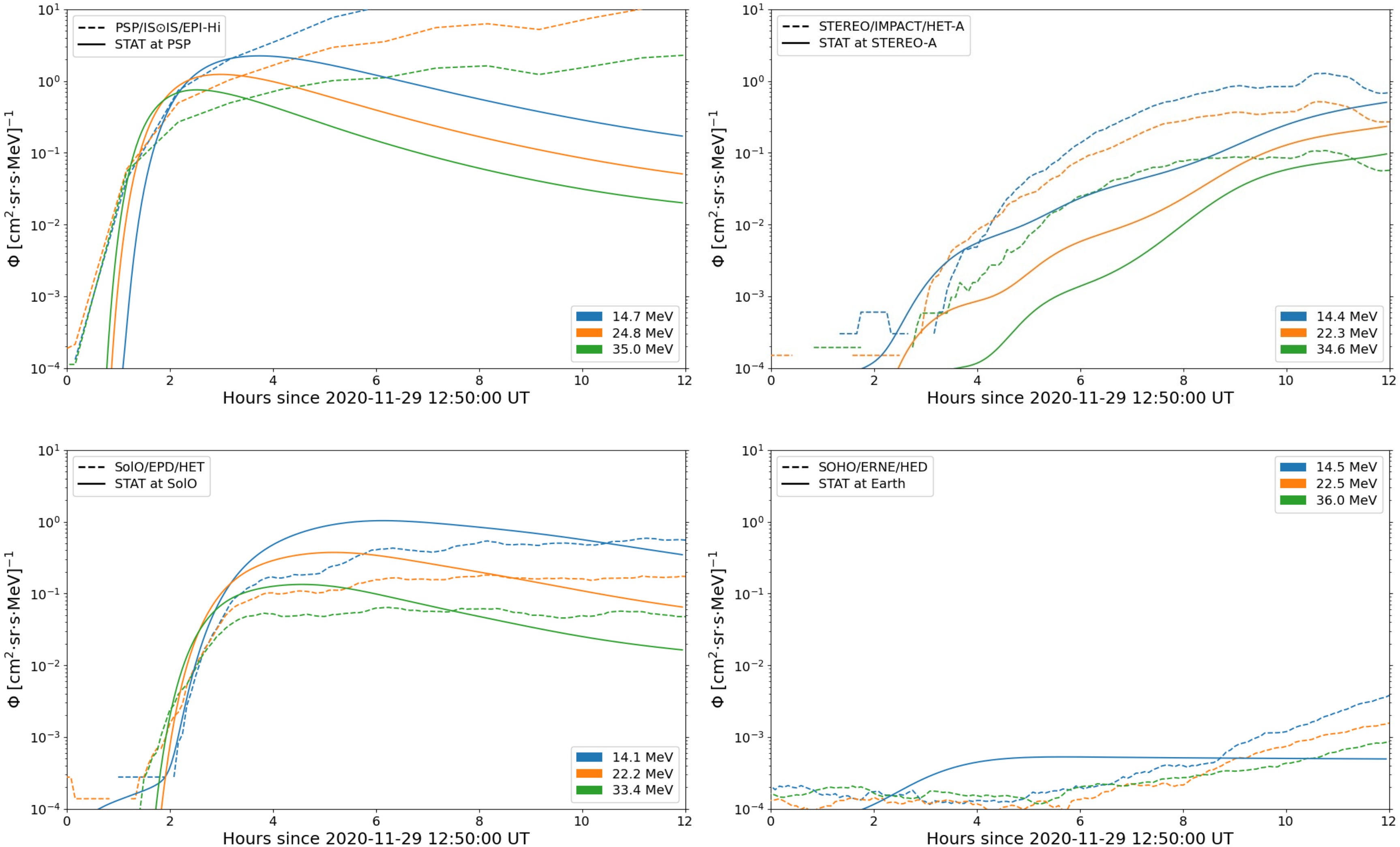
Predictive Science Inc.

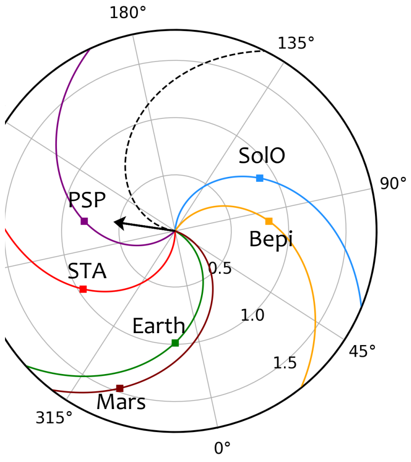
EGU General Assembly

The 2020-11-29 Event: SEP Predictions With STAT

The CME starts leaving the 30 R⊙ coronal domain around t = 3 hrs

The event onset and early profile is well captured at all locations, but fluxes start dropping later on at those locations that are expected to receive large contributions from the CME-driven IP shock





Note:
Initial particle seed population multiplied by 10 in these plots

Work performed with Ron Caplan, Jon Linker, Matt Young, Nathan Schwadron, Tibor Török, Cooper Downs, and Christina Cohen [Caplan et al., in preparation]

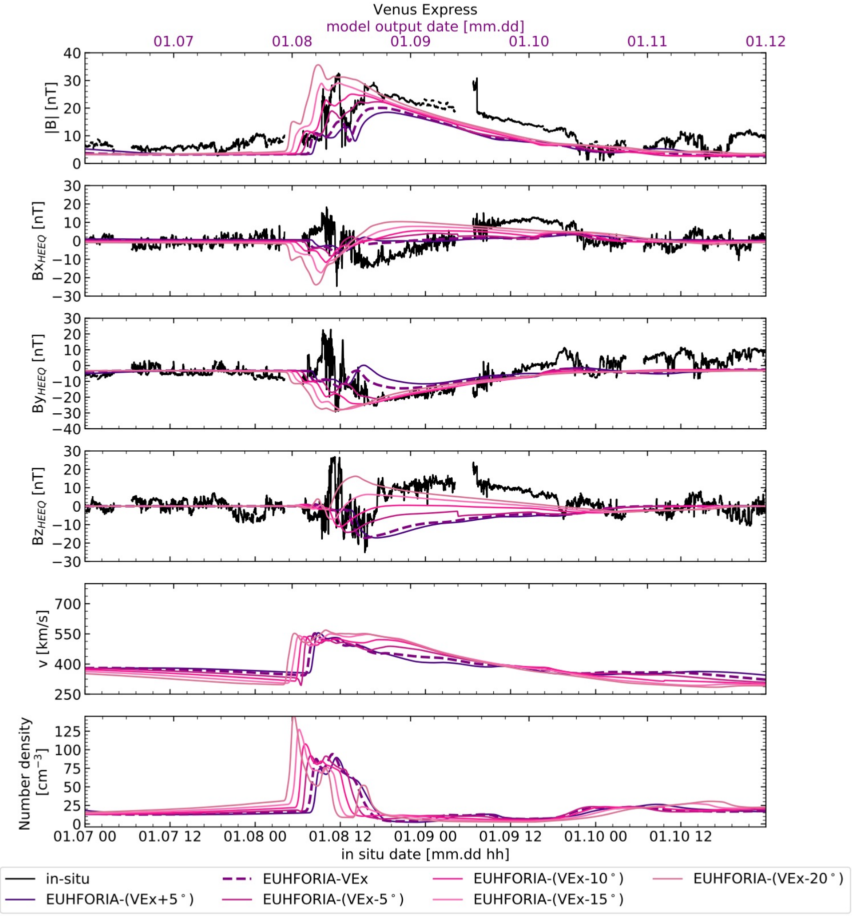
epalmerio@predsci.com

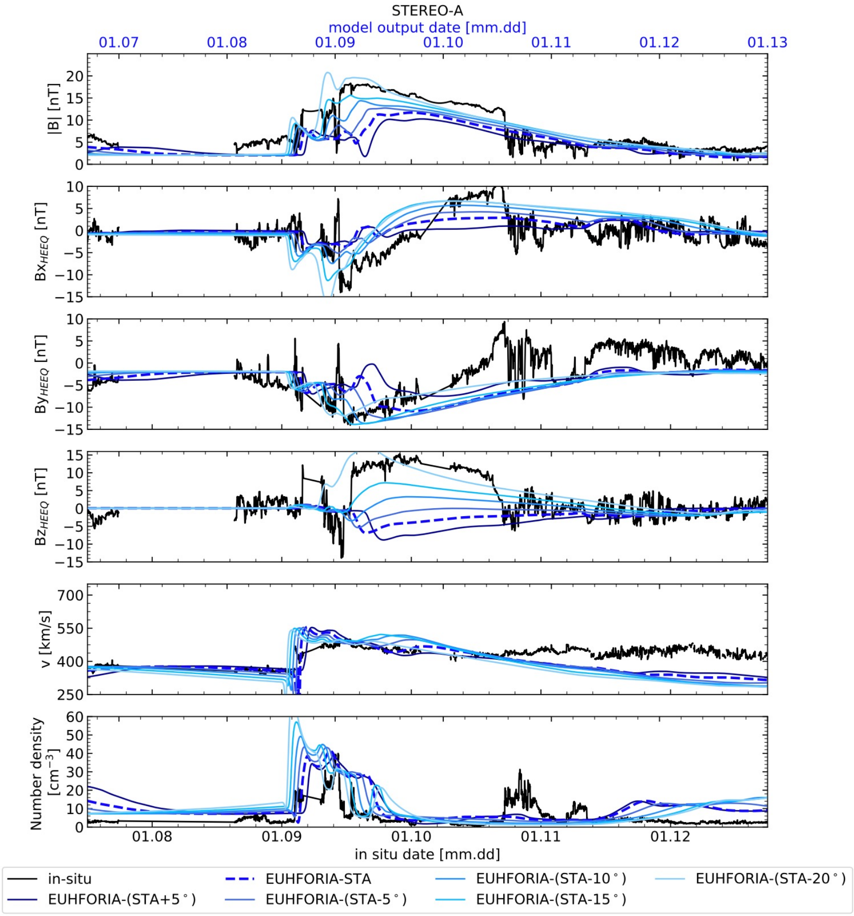
Predictive Science Inc.

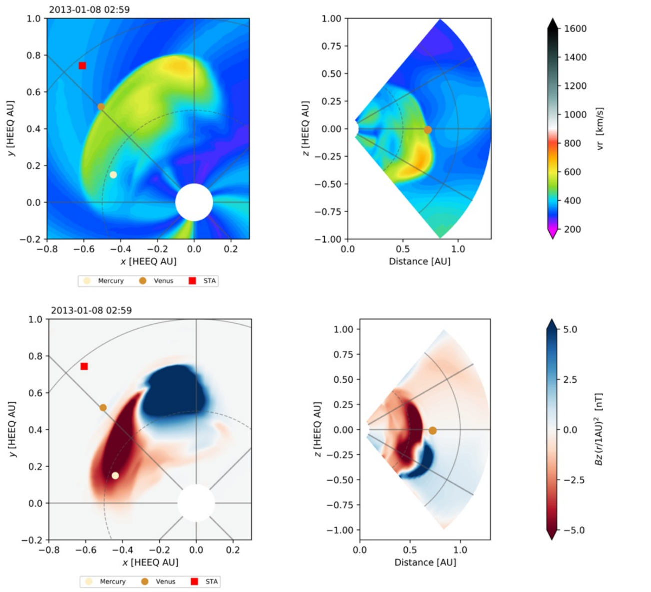
EGU General Assembly

Improving CME Predictions: Including CME Magnetic Fields in MHD Models

Example application: EUHFORIA+Spheromak (Verbeke et al. 2019) employed to model a multi-spacecraft CME encounter (at Venus and STEREO-A) from an eruption on 2013-01-06







Work published on A&A, doi:10.1051/0004-6361/202140315 [Asvestari et al. 2021]

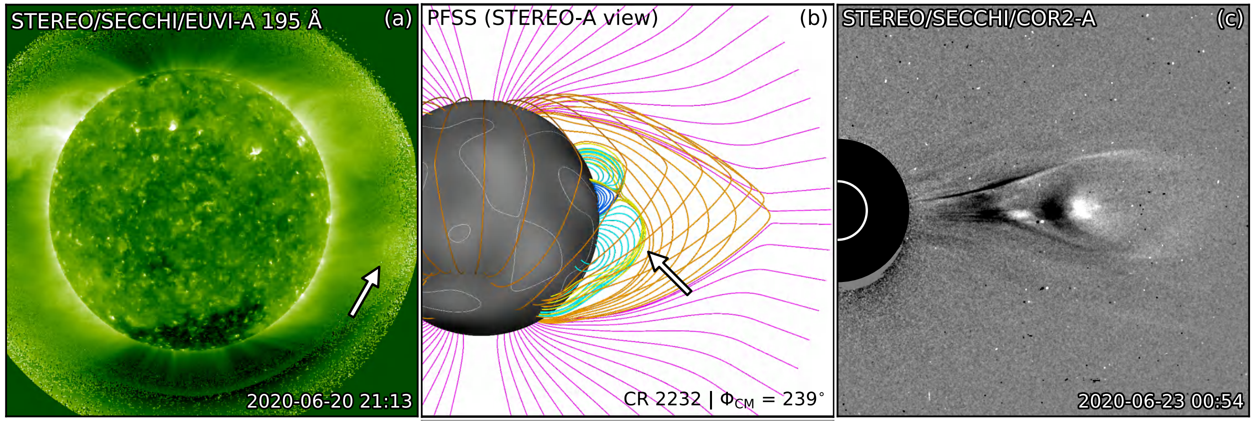
epalmerio@predsci.com

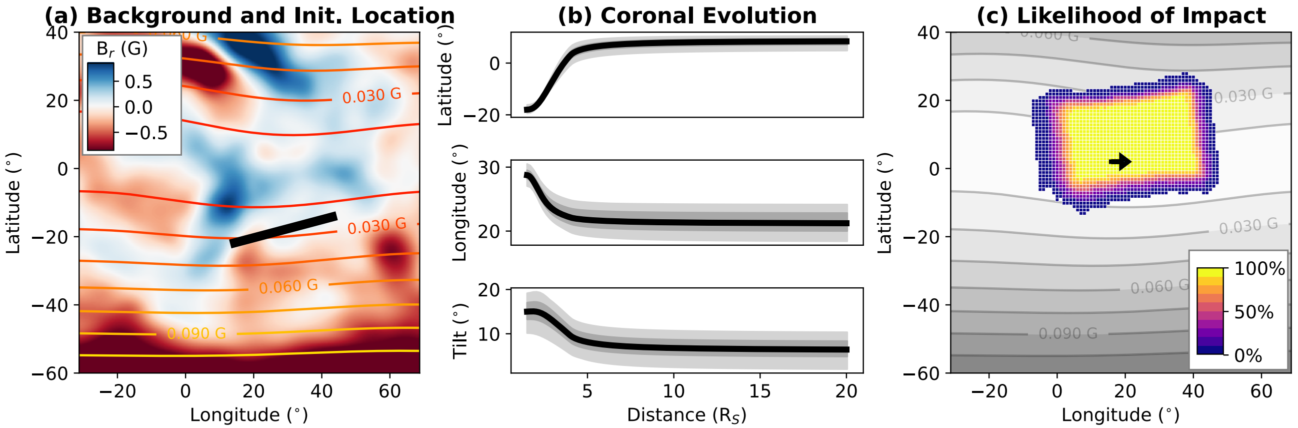
Predictive Science Inc.

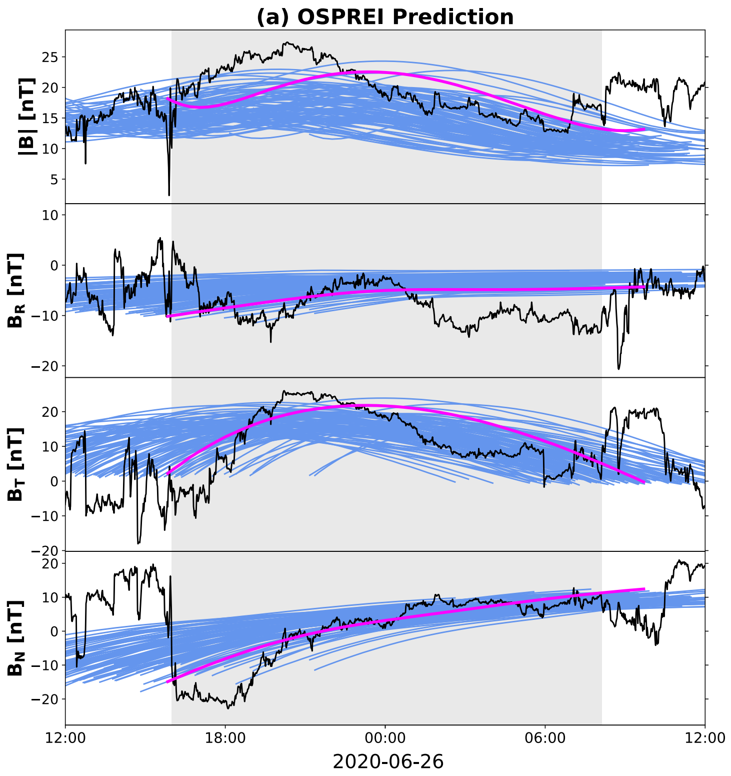
EGU General Assembly

Improving CME Predictions: Including CME Magnetic Fields in Analytical Models

Example application: OSPREI (Kay et al. 2022) employed to model a stealth CME encounter (at Parker Solar Probe at 0.5 AU) from an eruption on 2020-06-21







Next step: Obtain CME magnetic field predictions with OSPREI for a multi-spacecraft CME encounter

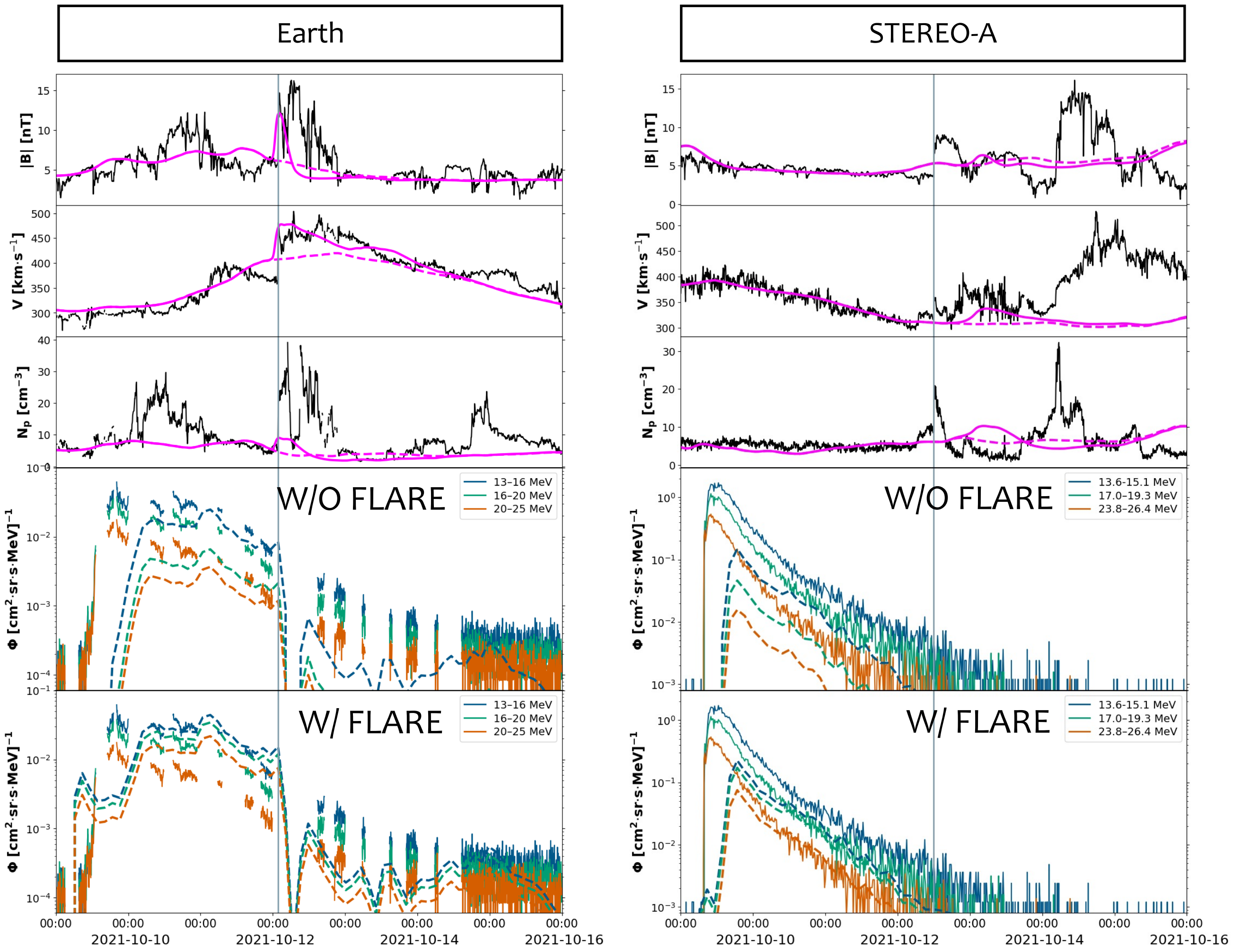
Work published on ApJ, doi:10.3847/1538-4357/ac25f4 [Palmerio et al. 2021]

epalmerio@predsci.com

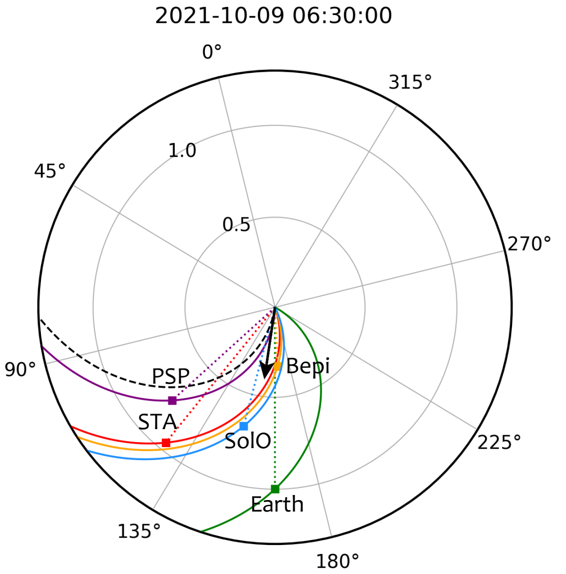
Predictive Science Inc.

EGU General Assembly

Improving SEP Predictions: Capturing the SEP Event Onset for Real-Time Applications



Use of the ``fixed-flare-source´´ option in SEPMOD, which assumes the presence of a source at the Enlil inner boundary that is able to inject particles through the heliospheric domain, and that can be timed with the onset of a flare and scaled according to its X-ray classification



Plot from Solar-MACH

Initial tests on the 2021-10-09 eruption

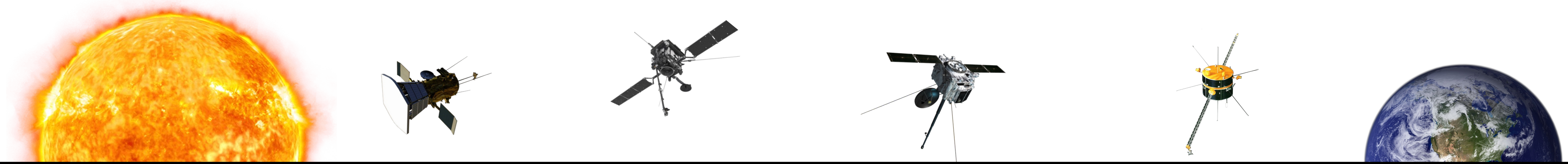
- CME + M1.6 flare from N18E08 (1 $R_\odot$)
- Source mapped to N00E19 (21.5 $R_\odot$)
- The fixed-flare-source particles are tracked *in addition* to the nominal moving-shock-source particles
- This approach improves SEP onset times, simulating flare-accelerated particles and/or a low-coronal shock

Work performed with Janet Luhmann, Christina Lee, Ron Caplan, Beatriz Sánchez-Cano, David Lario, Leila Mays, and Yan Li [Palmerio et al., in preparation]

epalmerio@predsci.com

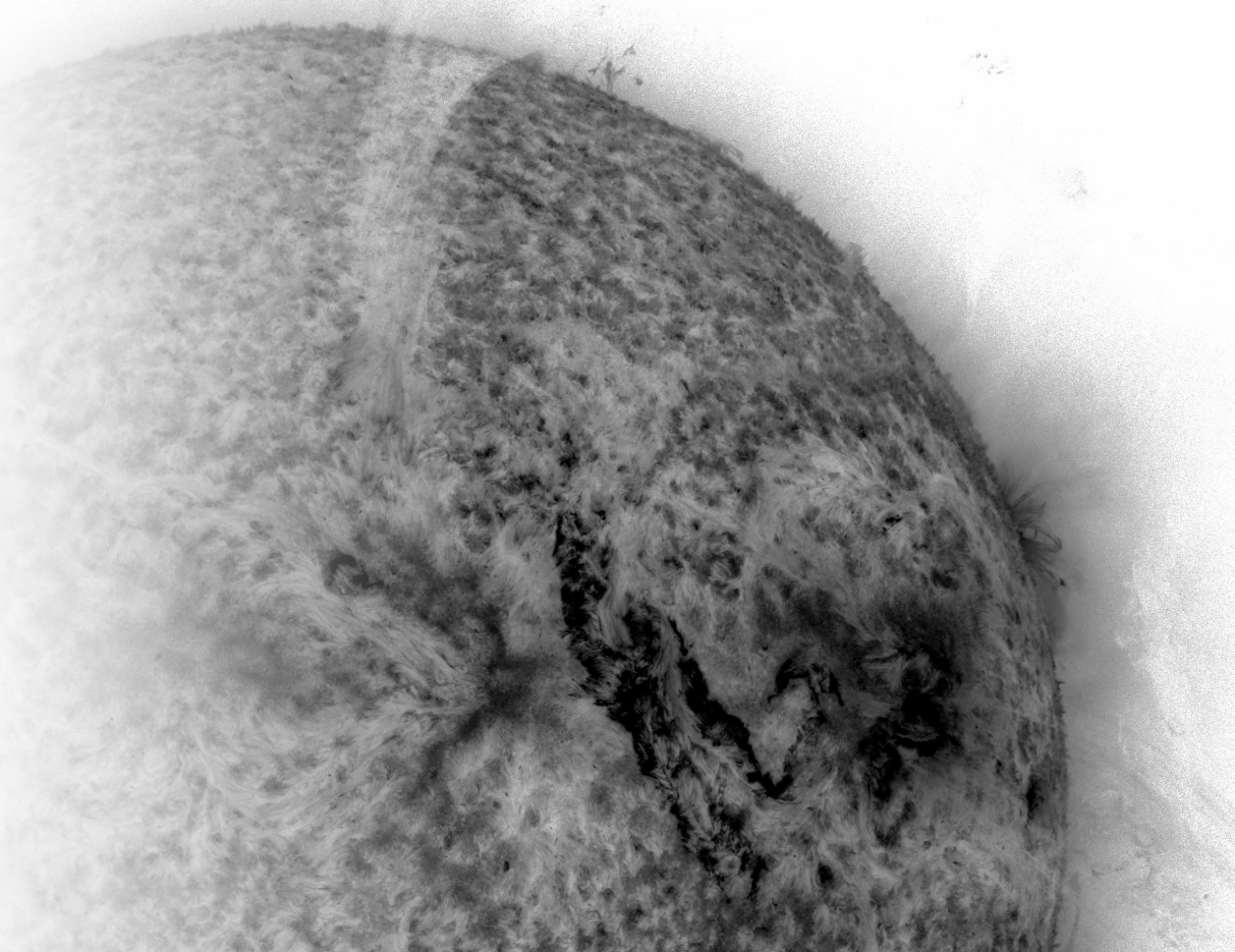
Summary

- Multiple measurements from the available set of spacecraft scattered throughout the heliosphere can provide significant constraints and validation opportunities for space weather forecasts (different results for a single event)
- Many models to test and validate for forecasts! Each model has its strengths, and analysing solar eruptions with a diversified pool of models can provide a more complete understanding of the event as a whole
- Important to think about improvements to our CME and/or SEP models with two main (but separate) goals in mind:
  - Science: More complex, computationally expensive, with more accurate physics (to advance our understanding)
  - Operations: Simpler, but way quicker models, with real-time applications (to improve our current forecasts)
- Examples of aspects of space weather research that have gained momentum recently:
  - Modelling and forecasting CME magnetic fields
  - Modelling and forecasting the onset, duration, and fluxes of SEP events
- Not mentioned enough throughout this talk, but improvements to modelling the solar wind background are of paramount importance in order to accurately forecast the propagation of CMEs and transport of SEPs



epalmerio@predsci.com

Thank you for your attention!



The WSA–Enlil–SEPMOD simulations shown here have been performed at the NASA GSFC Community Coordinated Modeling Center (CCMC) via their public Runs on Request system (http://ccmc.gsfc.nasa.gov)

The STAT simulations shown here have been performed at the Extreme Science and Engineering Discovery Environment (XSEDE) Expanse System at the San Diego Super Computer Center through allocation TG-MCA03S014

Erika Palmerio acknowledges NASA's O2R (no. 80NSSC20K0285), PSP-GI (no. 80NSSC22K0349), and HTMS (no. 80NSSC20K1274) programmes