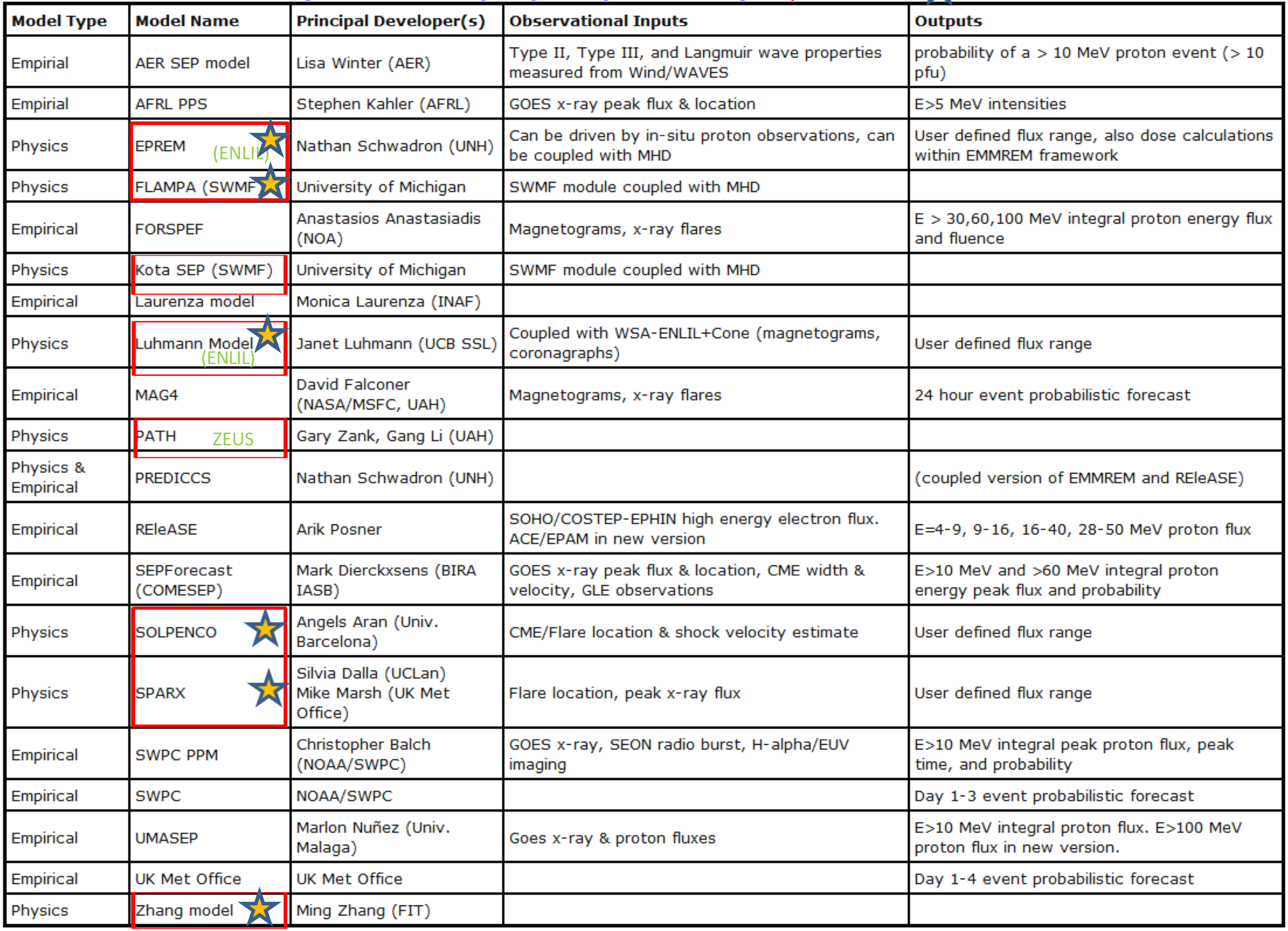
SEP Models in the Community and Literature *(compiled by Mike Marsh)*

Physics-based ★ =uses some empirical results



Model Type	Model Name	Principal Developer(s)	Observational Inputs	Outputs
Empirial	AER SEP model	Lisa Winter (AER)	Type II, Type III, and Langmuir wave properties measured from Wind/WAVES	probability of a > 10 MeV proton event (> 10 pfu)
Empirial	AFRL PPS	Stephen Kahler (AFRL)	GOES x-ray peak flux & location	E>5 MeV intensities
Physics	EPREM (ENLIL) ★	Nathan Schwadron (UNH)	Can be driven by in-situ proton observations, can be coupled with MHD	User defined flux range, also dose calculations within EMMREM framework
Physics	FLAMPA (SWMF) ★	University of Michigan	SWMF module coupled with MHD	
Empirical	FORSPEF	Anastasios Anastasiadis (NOA)	Magnetograms, x-ray flares	E > 30,60,100 MeV integral proton energy flux and fluence
Physics	Kota SEP (SWMF)	University of Michigan	SWMF module coupled with MHD	
Empirical	Laurenza model	Monica Laurenza (INAF)		
Physics	Luhmann Model (ENLIL) ★	Janet Luhmann (UCB SSL)	Coupled with WSA-ENLIL+Cone (magnetograms, coronagraphs)	User defined flux range
Empirical	MAG4	David Falconer (NASA/MSFC, UAH)	Magnetograms, x-ray flares	24 hour event probabilistic forecast
Physics	PATH ZEUS	Gary Zank, Gang Li (UAH)		
Physics & Empirical	PREDICCS	Nathan Schwadron (UNH)		(coupled version of EMMREM and REleASE)
Empirical	REleASE	Arik Posner	SOHO/COSTEP-EPHIN high energy electron flux. ACE/EPAM in new version	E=4-9, 9-16, 16-40, 28-50 MeV proton flux
Empirical	SEPForecast (COMESEP)	Mark Dierckxsens (BIRA IASB)	GOES x-ray peak flux & location, CME width & velocity, GLE observations	E>10 MeV and >60 MeV integral proton energy peak flux and probability
Physics	SOLPENCO ★	Angels Aran (Univ. Barcelona)	CME/Flare location & shock velocity estimate	User defined flux range
Physics	SPARX ★	Silvia Dalla (UCLan) Mike Marsh (UK Met Office)	Flare location, peak x-ray flux	User defined flux range
Empirical	SWPC PPM	Christopher Balch (NOAA/SWPC)	GOES x-ray, SEON radio burst, H-alpha/EUV imaging	E>10 MeV integral peak proton flux, peak time, and probability
Empirical	SWPC	NOAA/SWPC		Day 1-3 event probabilistic forecast
Empirical	UMASEP	Marlon Nuñez (Univ. Malaga)	Goes x-ray & proton fluxes	E>10 MeV integral proton flux. E>100 MeV proton flux in new version.
Empirical	UK Met Office	UK Met Office		Day 1-4 event probabilistic forecast
Physics	Zhang model ★	Ming Zhang (FIT)		

General Types of ‘Physics-based’ SEP modeling methods used:

-> Test particles or dist. functions in PFSS and/or Parker Spiral model fields*
 *Near-Sun source assumed; often target impulsive (early) event phase
 * Solar wind usually uniform radial outflow, may have helio current sheet
 * Field may include fluctuations or ’meandering’ directions
 Examples: Dalla et al., Laitinen et al., Ming Zhang et al.

-> ‘Particles’ injected and followed in time-dependent (usually MHD) simulated fields –e.g. WSA-ENLIL-cone, ZEUS
 *Often assumes the shocks describe moving, evolving SEP source region(s)
 *May be kinetic or guiding center treatments or ‘pseudoparticles’
 *May or may not include diffusive transport
 Examples: Aran et al., Li et al., Laitinen et al., Luhmann et al.

-> Solutions for distribution functions (f(x,p,t)) using a transport equation,
 *With self-consistent acceleration folded in based on time-dependent MHD corona/solar wind background fields and flows
 *Incorporate assumptions about diffusion
 *Incorporate assumptions about source population description
 Examples: Schwadron et al. +PSI group, Sokolov et al. SWMF group)

All have many ‘knobs’ to turn: e.g. diffusion coefficients (or scattering parameters), ‘seed’ populations (some include flare plus plasma/shock source ‘injection’, some add suprathermal ions). Each has advantages, disadvantages.

Importance of the background/setting description

Typical uses of background (often MHD) models in physics-based SEP models:

-> For B fields, and convection (E=-VxB) E fields for Lorentz force calculations
-> For field lines for parallel transport contributions
-> For 3D descriptions of background plasma parameters (in case of MHD) for advection, corotation, …
-> For temporally and spatially evolving Shock characteristics
-> In some cases, for information on connections to coronal structure, and solar events (flares, EUV waves, CMEs/shocks)

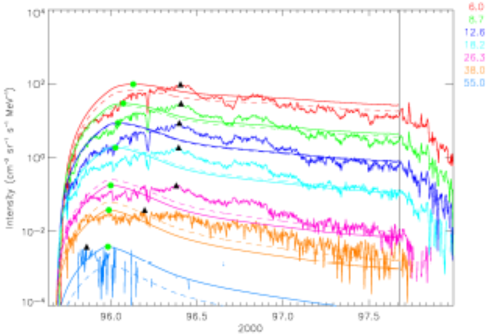
Some background models provide only near-Sun descriptions, others only approximate what happens inside a few 10s of Rs; some include the full sweep of spatial domains and even detailed eruption descriptions

Most models focus on fixed near Sun sources or SEP event upstream of shock. Some incorporate ESP events at shock arrivals. Only a few include the post shock period.

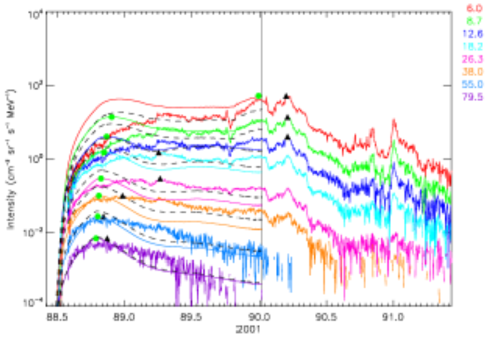
For ‘real’ events these may incorporate realistic corona/solar wind backgrounds based on magnetic synoptic maps – models with their own sets of challenges.

‘Real Event’ simulations are hard to find in the literature. Some examples:

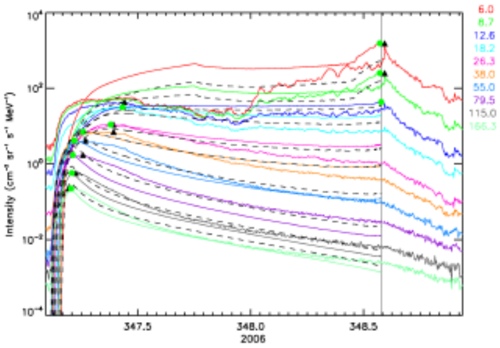
April 4, 2000 SEP event:
Slow Wind, no $E > 66$ MeV, W66



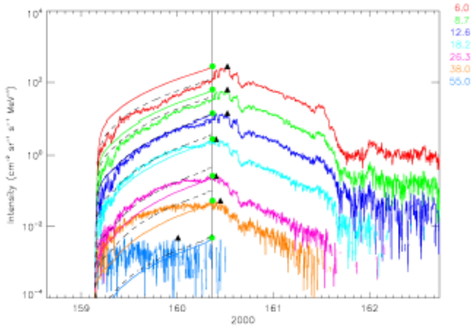
March 29, 2001 SEP event:
Slow Wind, $E > 66$ MeV, W15



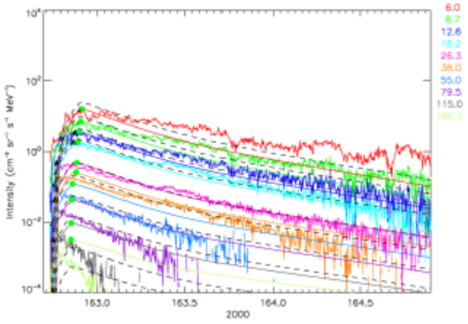
December 13, 2006 SEP event:
Fast Wind, $E > 66$ MeV, W23



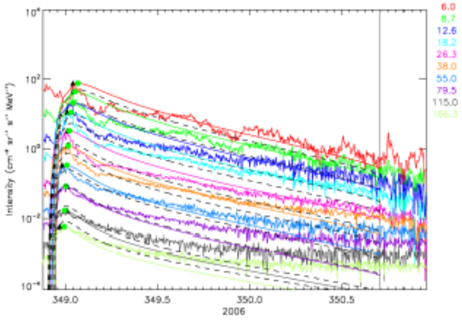
June 6, 2000 SEP event:
Fast Wind, no $E > 66$ MeV, E15



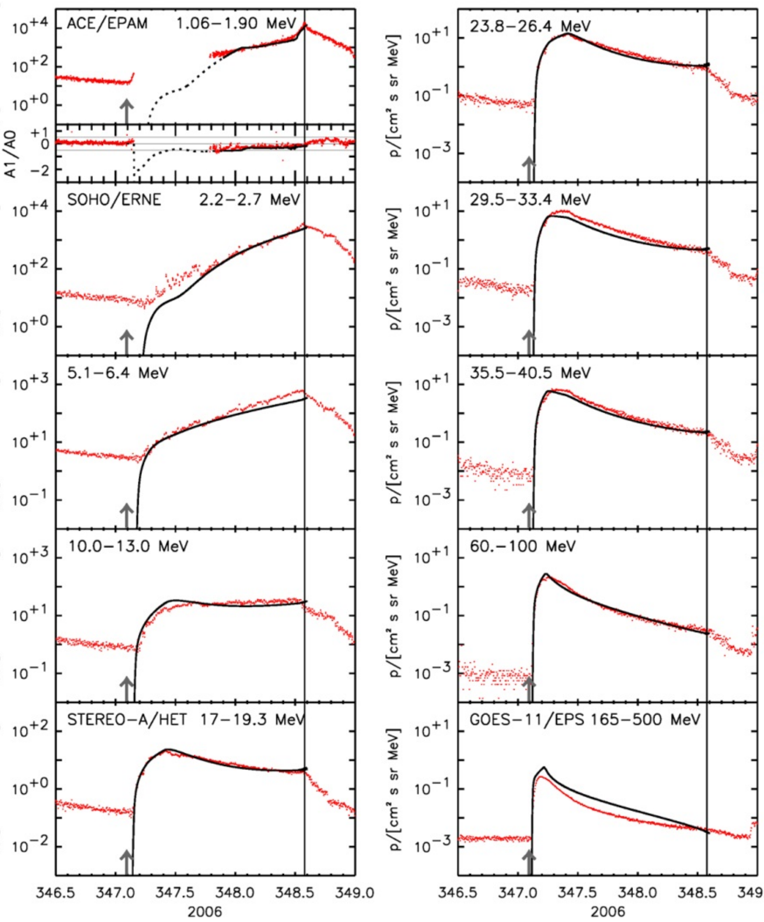
June 10, 2000 SEP event:
Fast Wind, $E > 66$ MeV, W38,
No shock



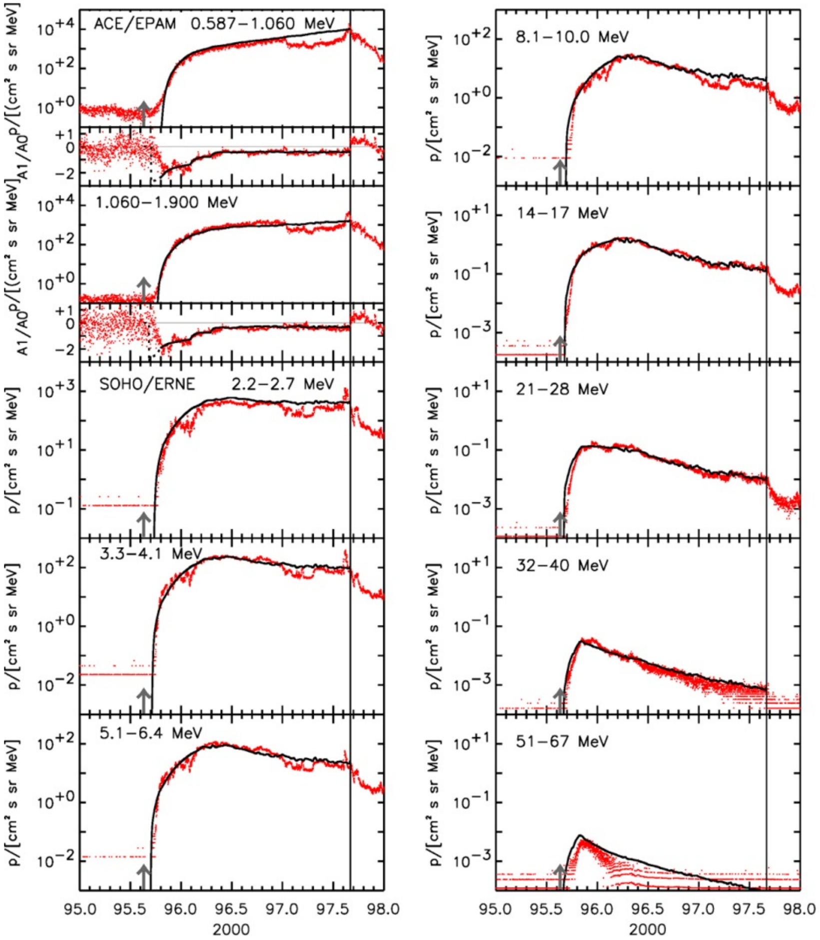
December 14, 2006 SEP event:
Fast Wind, $E > 66$ MeV, W44,
No shock



SOLPENCO applications (Aran et al., 2013 online document)

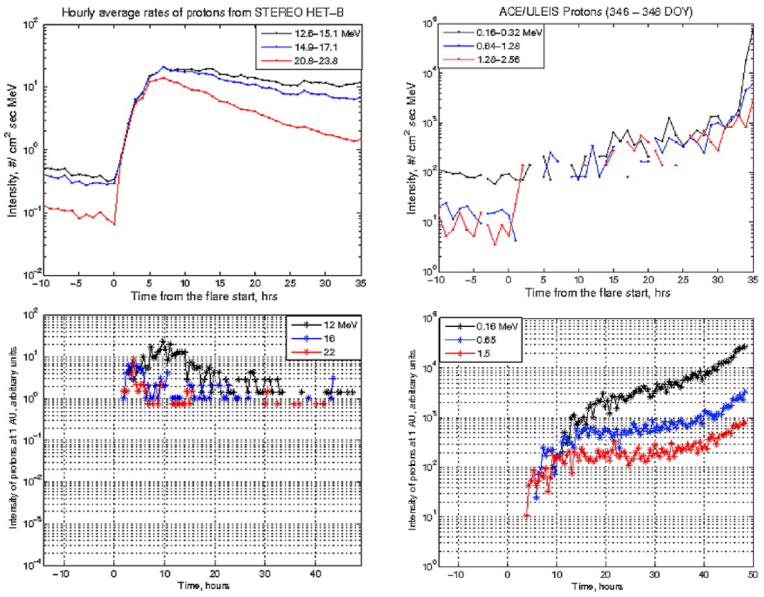


December 2006 event Pomoell et al., JSWC, 2015



April 2000 event Pomoell et al., JSWC, 2015

Examples of modeled ‘real’ events in the literature



Dec 2006 event-PATH Verkhoglyadova et al., JGR 2010

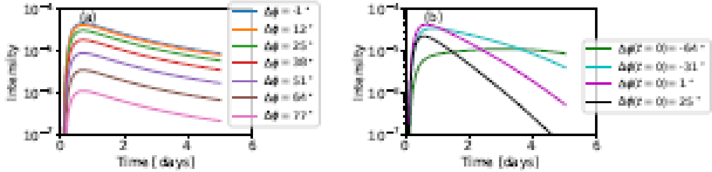


Figure 1. Time-intensity curves for 10 MeV protons given by Eq. (2.1) with $\lambda = 0.03$ AU at $r = 1$ AU. (a): SEP intensities on field lines that corotate with the Sun. (b): SEP intensities observed with spacecraft at 1 AU moving relative to the corotating field lines.

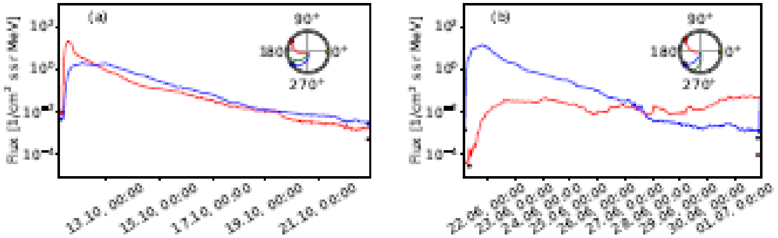


Figure 2. 10 MeV proton intensities on (a) 11 October and (b) 21 June 2013. In the inset, the red and blue circles show the STA and STB locations at the start of the event, respectively, and the red, blue and green spirals show the Parker spirals connected to the STA, STB and the SEP source location.

Oct and June 2013 events-Laitinen et al., proc. IAU 335, 2017

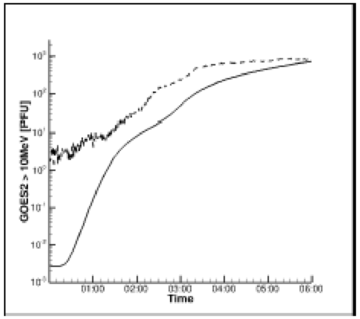
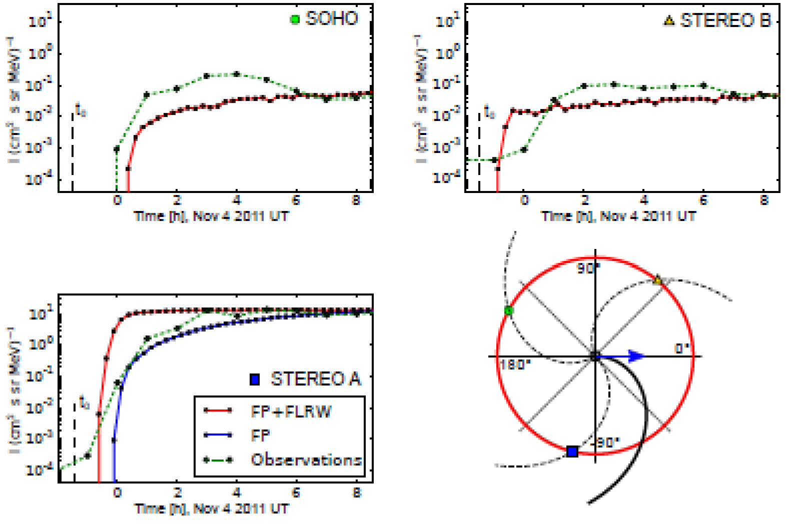


Figure 4. Time evolution of simulated flux of SEP exceeding 10 MeV (GOES channel 2) at 1 AU on a single line (solid black line) compared to GOES measurements (dashed black line). Time is measured from the CME initiation (4:00 on January 23, 2012).

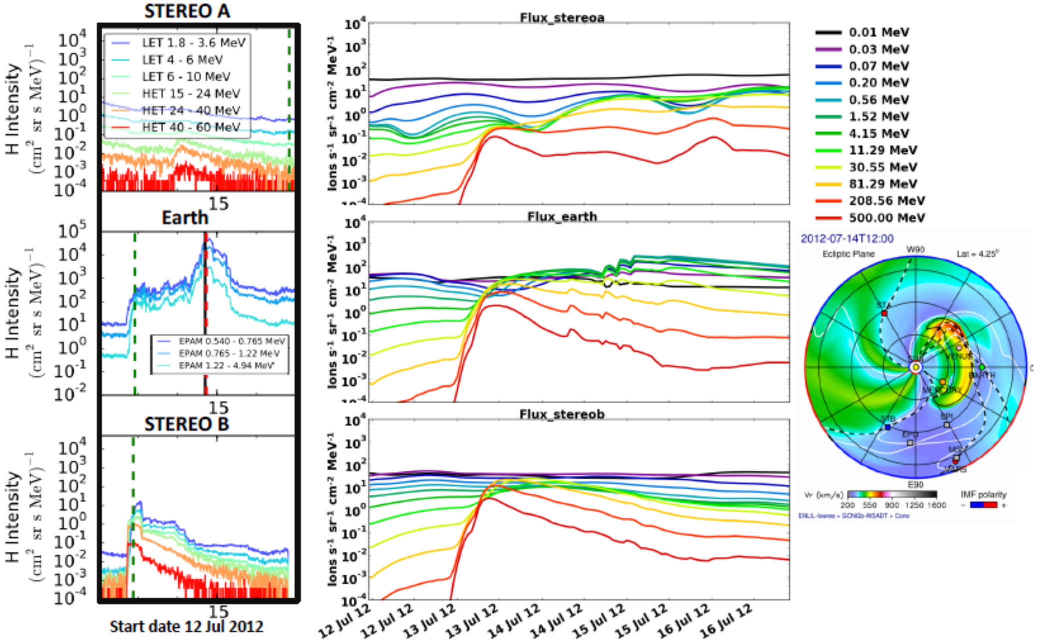
Jan 2012 event FLAMPA Borovikov et al., 2018 preprint



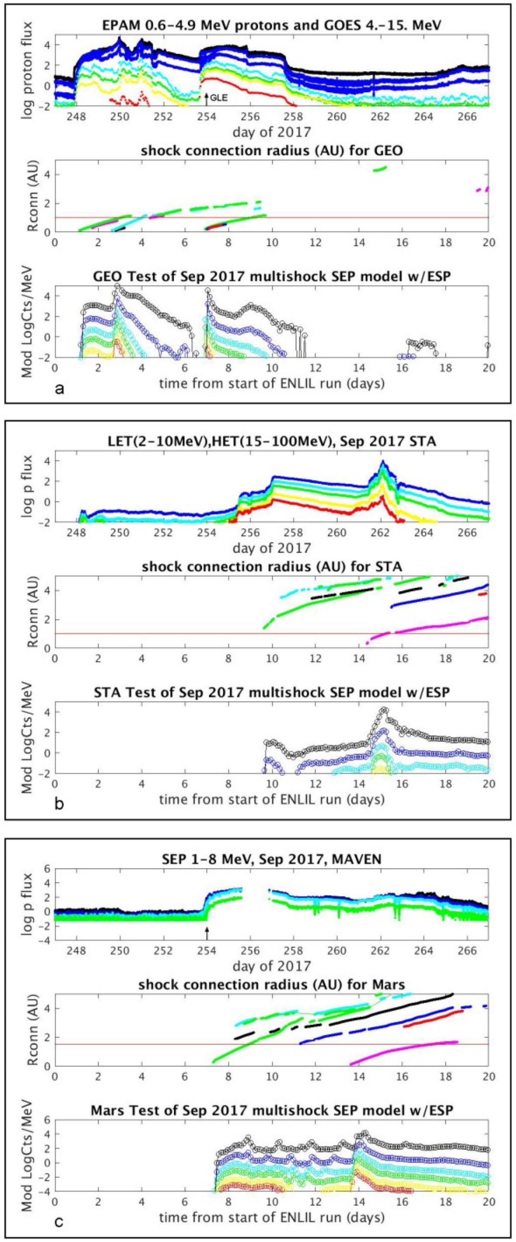
Nov 2011 event-Laitinen et al., A&A, 2015

Examples of modeled ‘real’ events in the literature (cont.)

12 July 2012 CME
Preliminary ENLIL+EPREM results



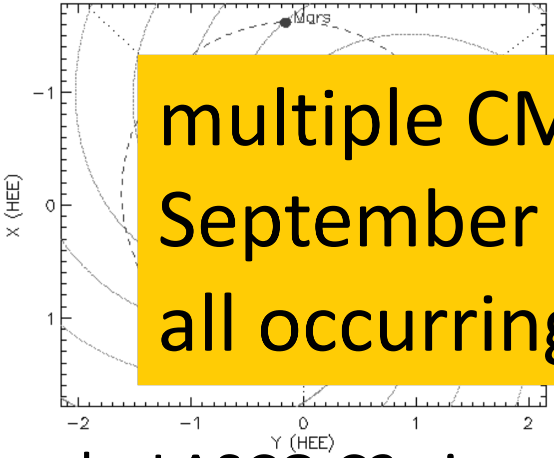
EPREM Schwadron et al., 2016, CCMC Workshop presentation



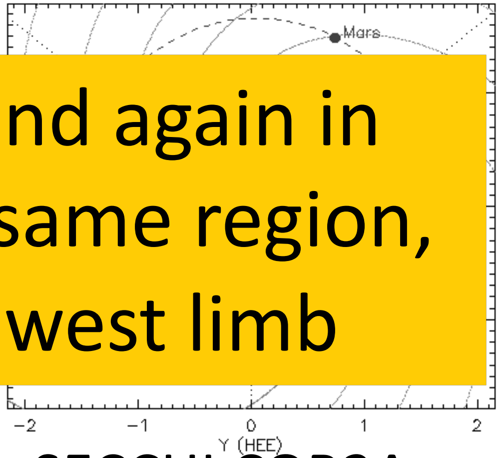
Sep 2017 events SEPMOD
Luhmann et al., Space Weather 2018

The July-September 2017 cases show why real events are hard

July 2017

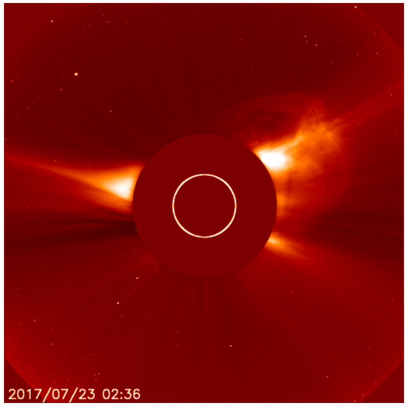


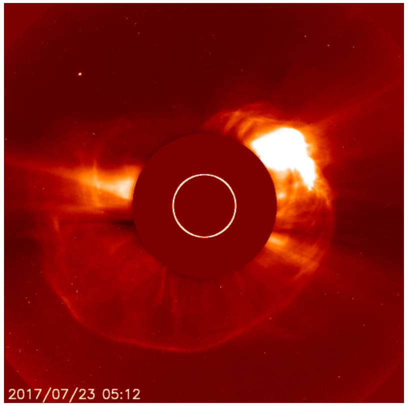
Sept 2017

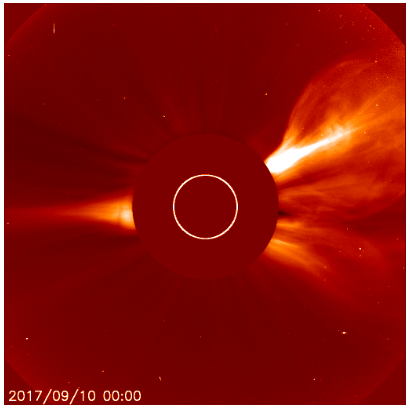


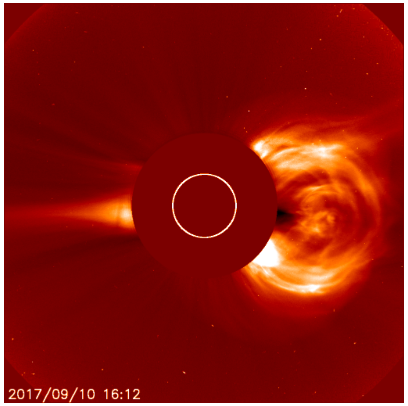
multiple CMEs in July and again in September 2017 from same region, all occurring near with west limb

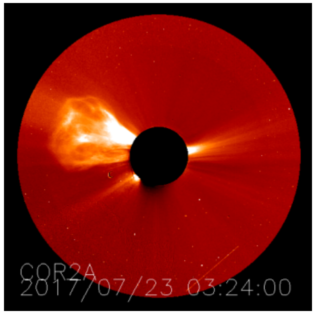
Top panels: LASCO C2 views. Bottom panels SECCHI COR2A

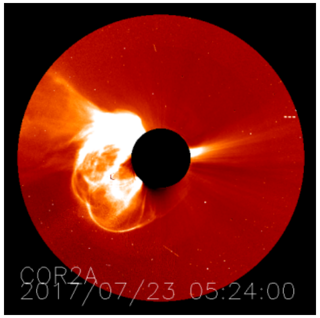


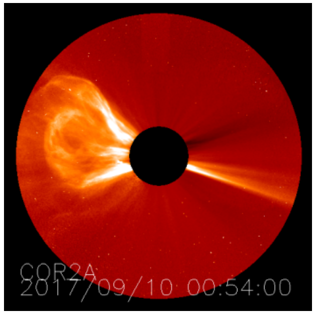


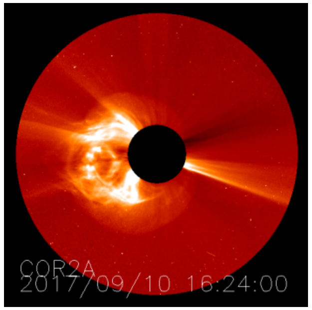




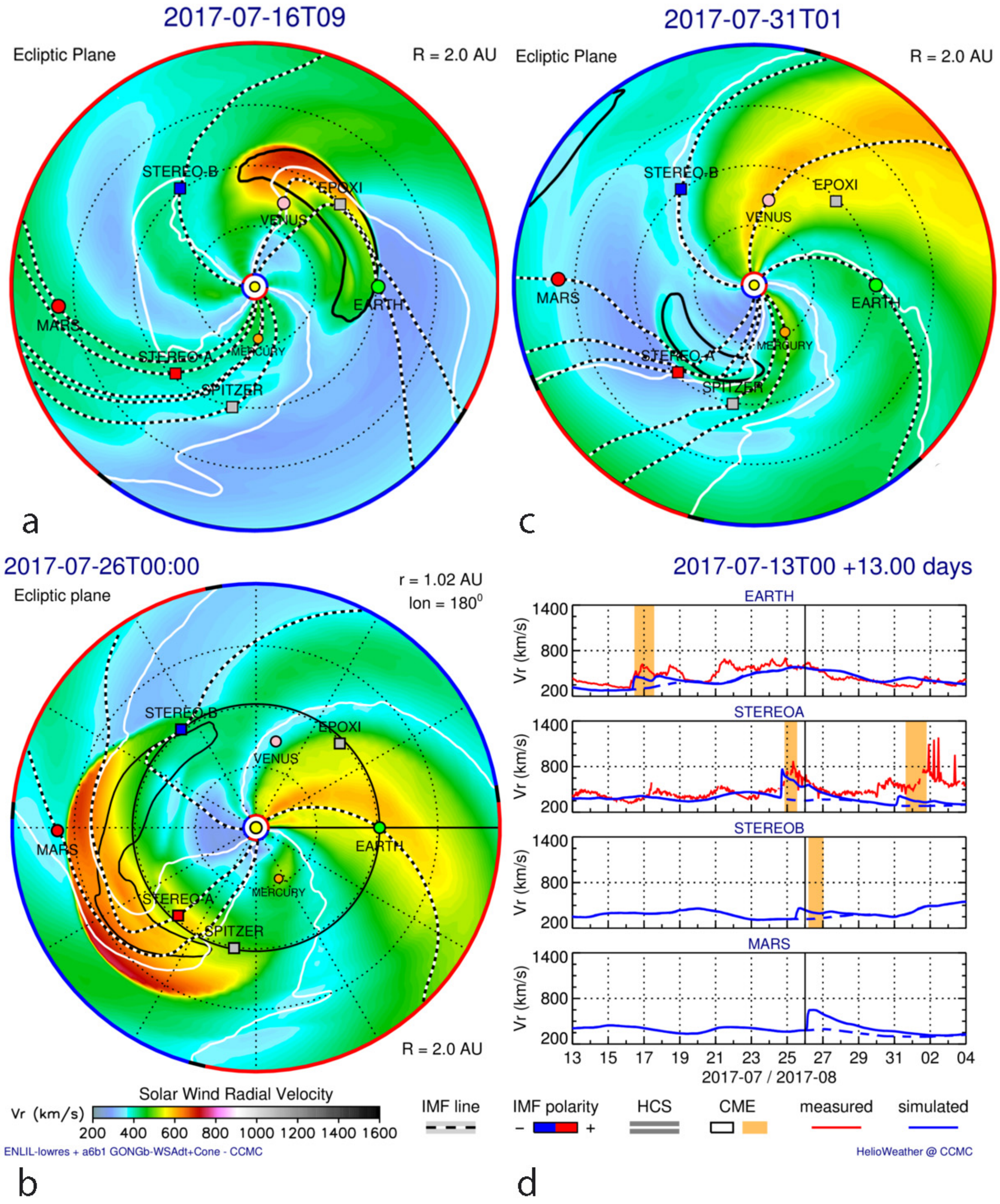








ENLIL modeling for the July case achieved good agreement with in-situ shock arrivals (the commonly used ENLIL ‘validation’)

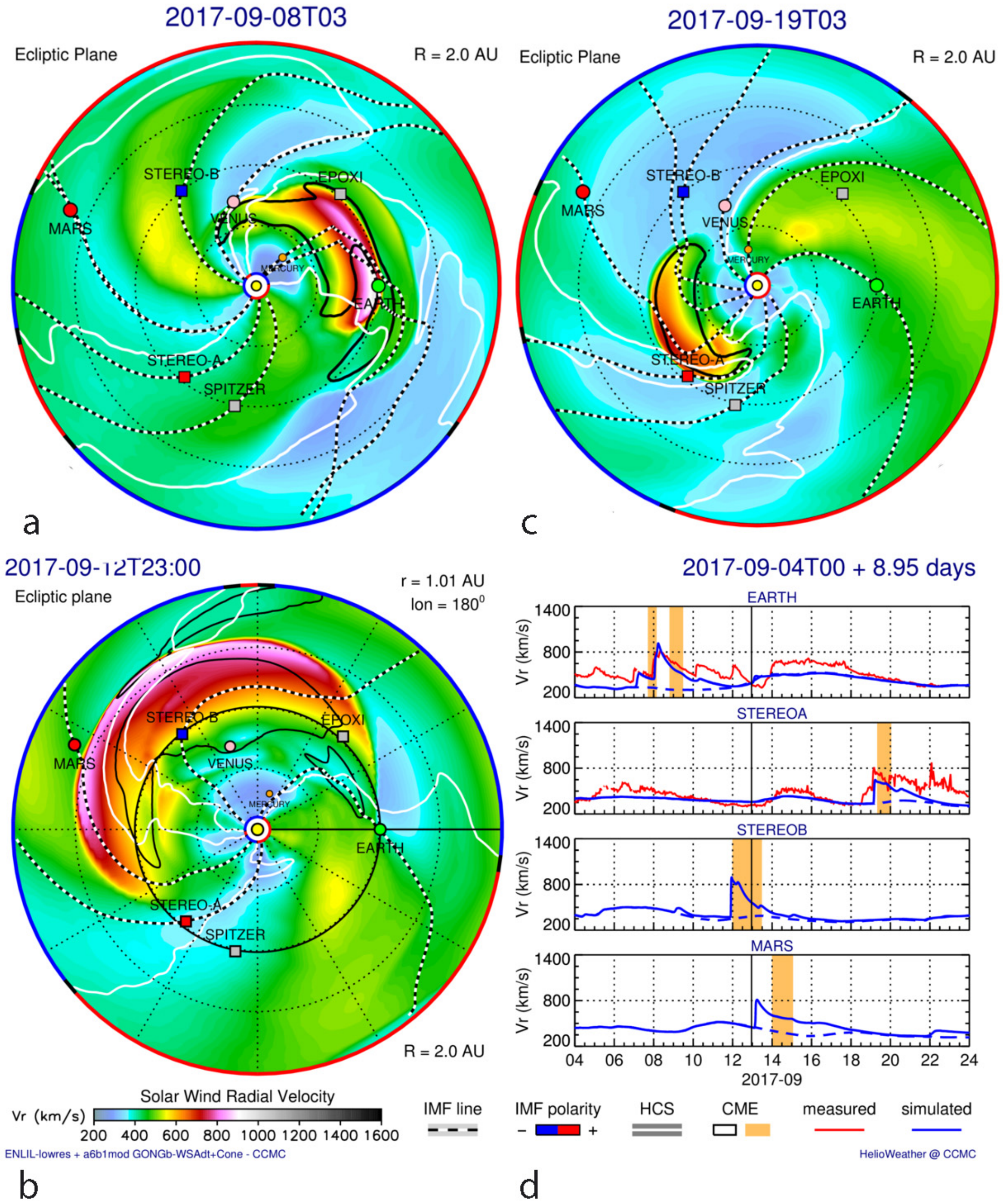


ENLIL-lowres + a6b1 GONGb-WSAdt+Cone - CCMC

HelioWeather @ CCMC

Also ENLIL modeling results for Sept.

But these initially missed some observed shock arrivals, suggesting that the ENLIL cone CME parameters, together with the length of time the simulation covered, needed alterations.



Things adjusted from ENLIL run to ENLIL run:

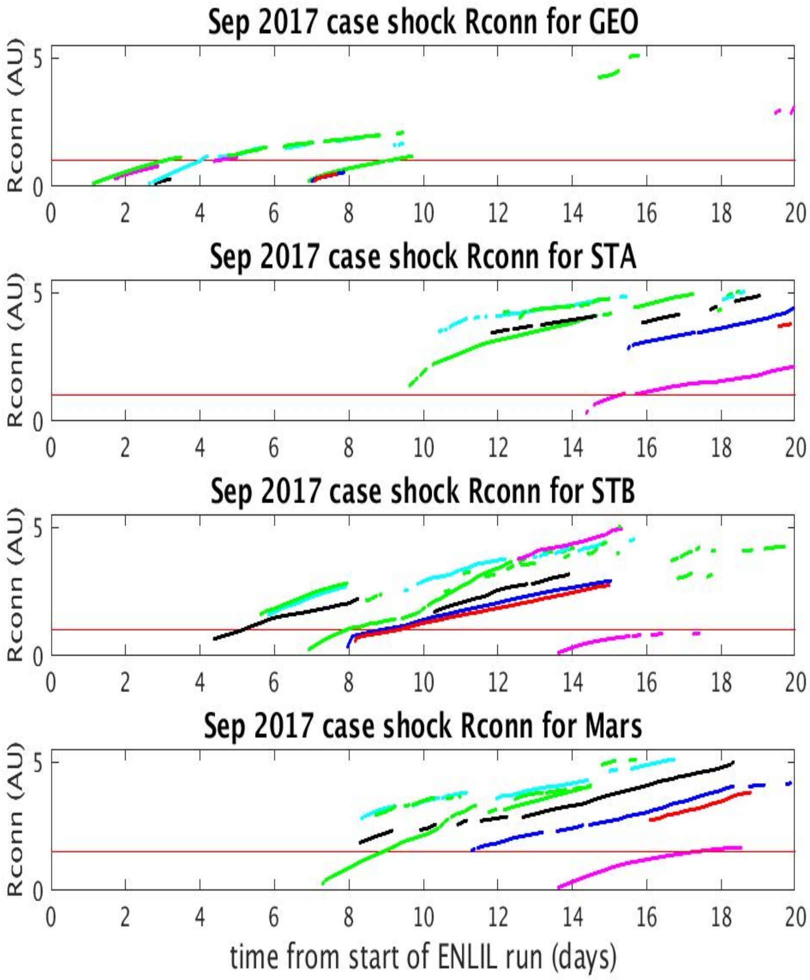
https://ccmc.gsfc.nasa.gov/database_SH/Leila_Mays_092017_SH_1.php
9/4 CMEs, 9/6 CMEs, 9/10 CME half width=58; default parameters
2017-09-10T17:18 lat=-12 lon=80 rad=58 vel=2650 #2017-09-10T16:09:00-CME-001

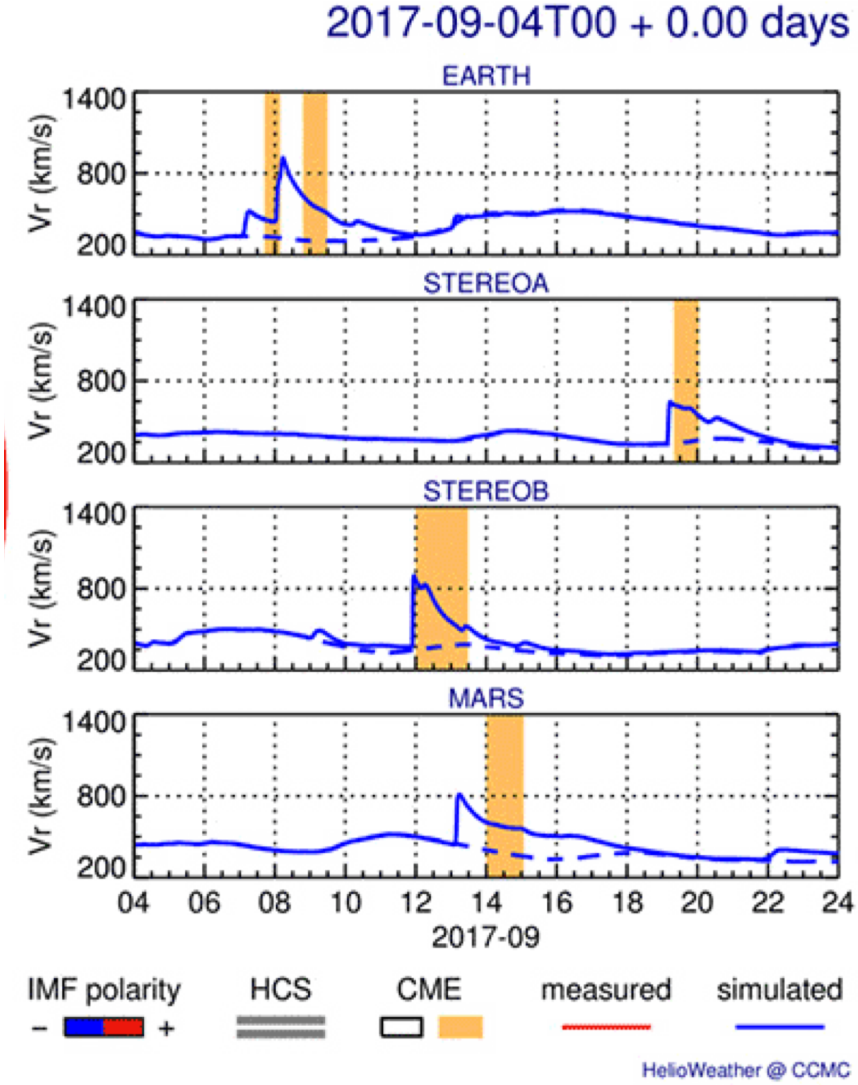
https://ccmc.gsfc.nasa.gov/database_SH/Leila_Mays_101017_SH_4.php
2017-09-10T17:12 lat=-10 lon=92 rad=70 vel=2800 #2017-09-10T16:09:00-CME-001
9/4 CMEs, 9/6 CMEs, added 9/9 CMEs, 9/10 CME half width=70 dcld=2.5

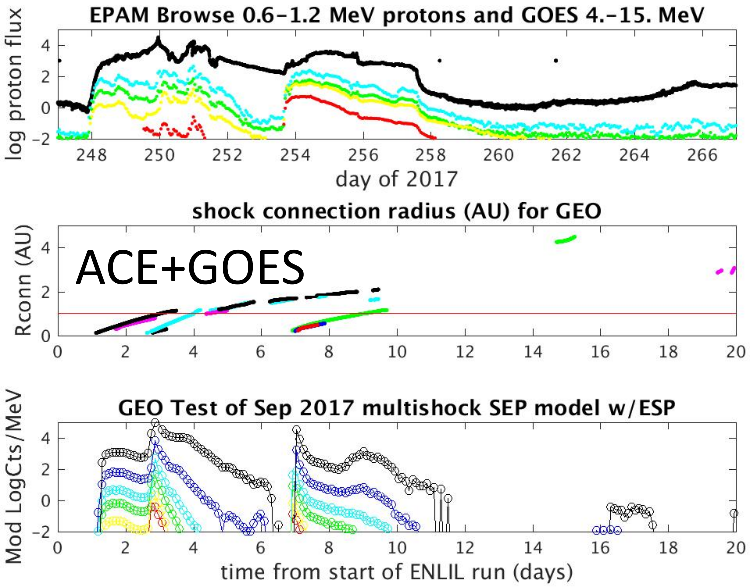
https://ccmc.gsfc.nasa.gov/database_SH/Leila_Mays_120817_SH_9.php
2017-09-10T17:15 lat=-9 lon=108 rad=90 vel=2500 #2017-09-10T16:09:00-CME-001
9/4 CMEs, 9/6 CMEs, 9/9 CMEs, 9/10 CME half width=90 dcld=2, added 9/17 CME

These were made using a combination of revisiting the coronagraph observations and numerical experimentation to get the in-situ shock arrivals at the widespread 'observers' (reflecting challenges for 'real-time' runs)

The September 2017 activity involves multiple shock connections , overlapping in time, for all observers





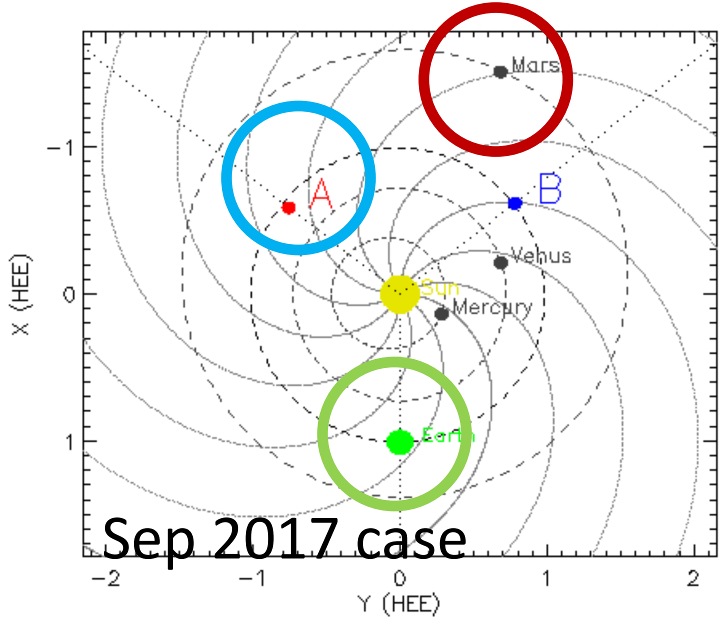

EPAM Browse 0.6–1.2 MeV protons and GOES 4.–15. MeV

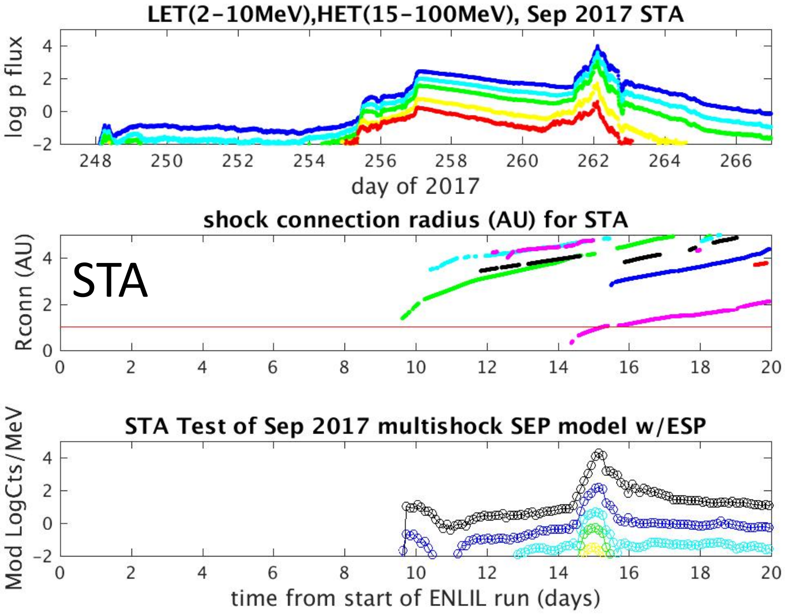
shock connection radius (AU) for GEO

ACE+GOES

GEO Test of Sep 2017 multishock SEP model w/ESP

Observer ‘layout’ (from SSC)

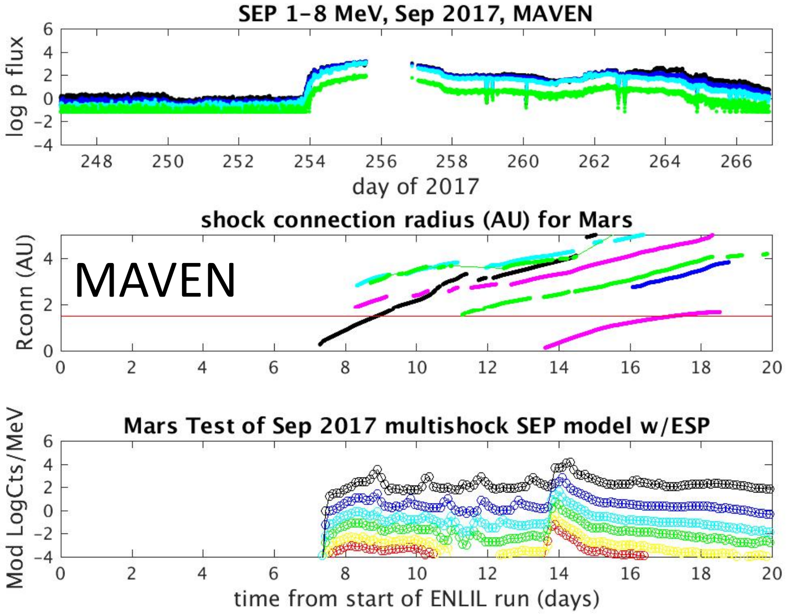

Sep 2017 case


LET(2–10MeV),HET(15–100MeV), Sep 2017 STA

shock connection radius (AU) for STA

STA

STA Test of Sep 2017 multishock SEP model w/ESP


SEP 1–8 MeV, Sep 2017, MAVEN

shock connection radius (AU) for Mars

MAVEN

Mars Test of Sep 2017 multishock SEP model w/ESP

But these produced about the right timing for all the SEP observers.

The July September 2017 Cases are complicated, but most major SEP event periods are similarly so. Physics-based modelers seeking to simulate real events will need to meet these challenges.