A Minimum and Sufficient L5-L1 Platform for Forecasting CME-Driven Geomagnetic Storms

James Chen

Plasma Physics Division, Naval Research Laboratory

L5 in Tandem with L1: Future Space-Weather Missions Workshop

6–9 March 2017, London, UK

Supported by NRL Base Research Program

OUTLINE

- What new *information from L5* data to predict what?
  - Near-Sun CME trajectory data (Z_{data}) to predict $\mathbf{B}_{CME}$(1 AU) *faster than real time*
  - *Unique advantage of L5 observation*
- Where is **B** field information contained in CME data?
  → In the CME *dynamics* $Z_{data}(t)$
- ***Focus***: accurate and timely forecasting of major (CME-driven) geomagnetic storms
- ***Objective***: use the predicted $\mathbf{B}_{CME}$(1 AU) to calculate global ionospheric dynamics in 3-D (without using indices)

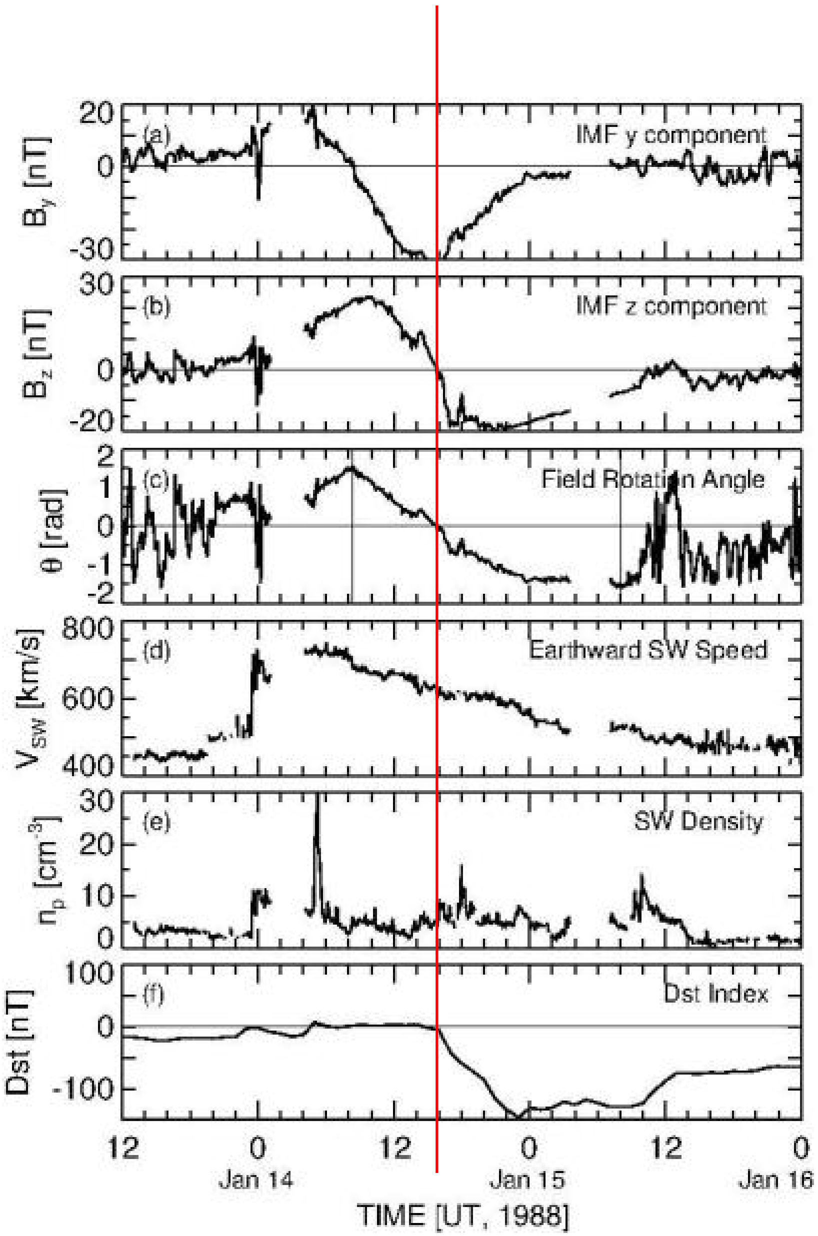
MAJOR GEOMAGNETIC STORMS: *CAUSAL PROCESS*

Major geomagnetic storms

- Caused by long durations of strong southward IMF on Earth [*Rostoker and Falthammar* 1967; *Hirshberg and Colburn* 1969; *Russell et al*. 1974]
- Driven by CME ejecta magnetic field $\mathbf{B}_{CME}$ — after discovery of CMEs
- *v*. Recurrent storms—sector boundary crossings [*Neupert and Pizzo* 1974]

Forecasting major storms

- Accurately forecast $\mathbf{B}_{CME}$(1 AU) in a timely manner (24—48 hrs) (severity and duration)
- ***But,*** no $\mathbf{B}_{CME}$ data until it reaches 1 AU



NEED INPUT INFORMATION FOR FORECASTING

Modeling magnetic field of evolved CME ejecta

- Most common approach: use *apparent* photosperic magnetic “field” (i.e., uncancelled flux per pixel) to drive numerical models; study CME initiation mechanisms
  - Apparent “fields” and “flows” = sum of all sources; relation to the eruptive structure is ambiguous for forecasting individual events
  - Need an *understanding* of the specific relationship to eruption

INFORMATION CONTENT OF DATA

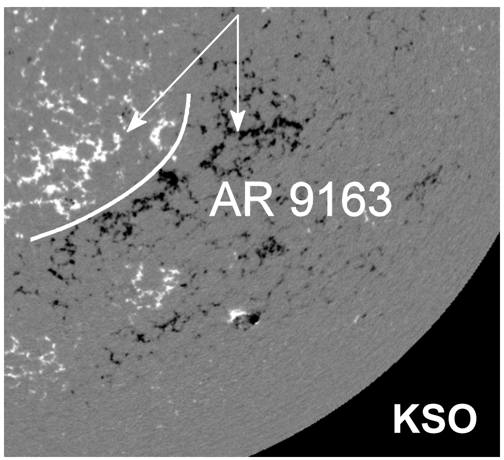
L5+L1 Solar data to predict CME dynamics to 1 AU

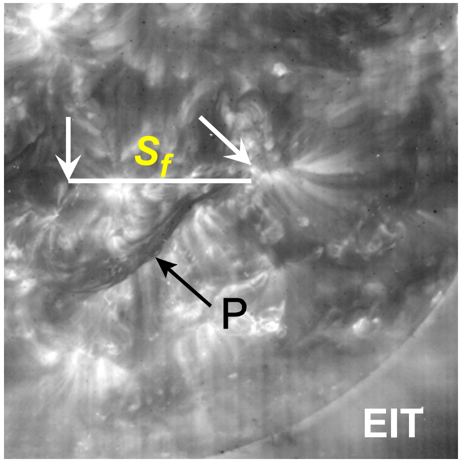
- L5: CME trajectory $Z_{data}(t_i)$ *near* the Sun

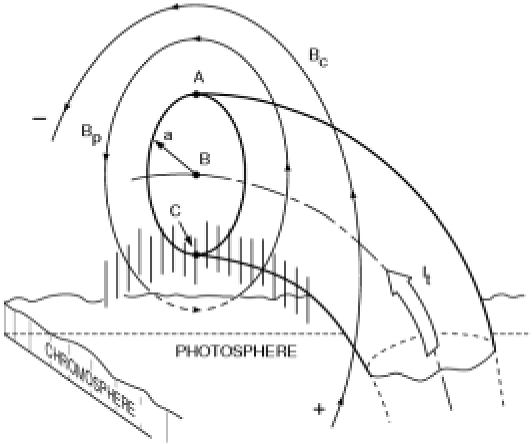
  L1: Magnetograms of source region ⟶ polarity of flux-rope **B**; $\Delta\mathbf{B}_{photo}(t)$

  EUV images to determine source location and direction of eruption; estimate S_f

⟶ **"Minimum and Sufficient"**







Why can one extract $\mathbf{B}_{CME}$(1AU) from near-Sun CME trajectory?

– Observed $Z_{data}(t)$ is determined by: $\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B}$

– *Dynamics* contains the information

DRIVING FORCES OF CMEs

- The EFR equations of motion for a flux rope
- The major (R) and minor (a) radial equations (coupled for 3-D expansion)

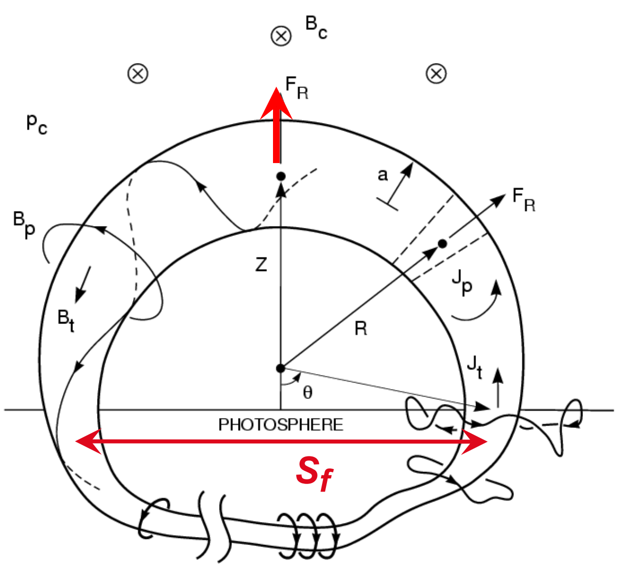
$$M\frac{d^2Z}{dt^2}=\frac{I_t^2(t)}{c^2R}\left[\ln\left(\frac{8R}{a}\right)+\frac{1}{2}\beta_p-\frac{1}{2}\frac{B_t^2}{B_p^2}-2\left(\frac{R}{a}\right)\frac{B_c}{B_p}-1+\frac{\xi_i}{2}\right]+F_g+F_d$$

$$M\frac{d^2a}{dt^2}=\frac{I_t^2}{c^2a}\left(\frac{B_t^2}{B_p^2}-1+\frac{\overline{p}-p_a}{B_p^2/8\pi}\right)$$

- Major radial equation of motion:

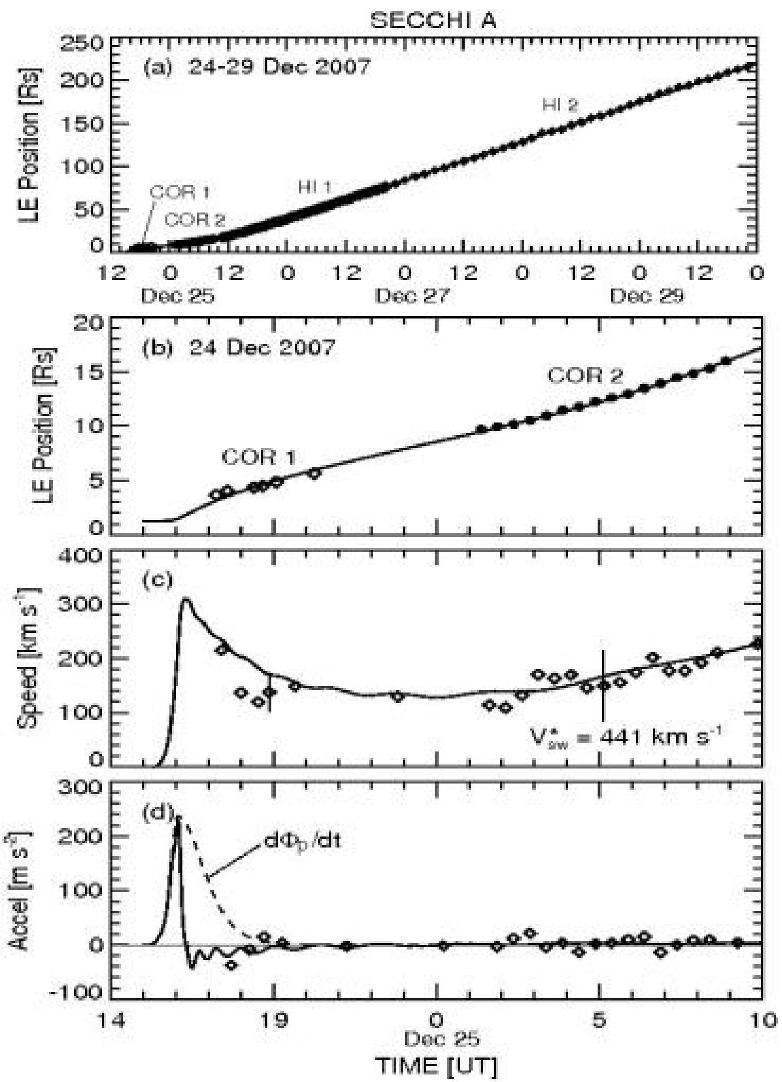
$$\frac{d^2Z}{dt^2}=A\left(\nabla\times\mathbf{B}\times\mathbf{B},\, S_f,\ldots\right)$$

$$\mathbf{B}_{pred}=F\left[\left(\frac{d^2Z}{dt^2}\right)_{data}\right]$$

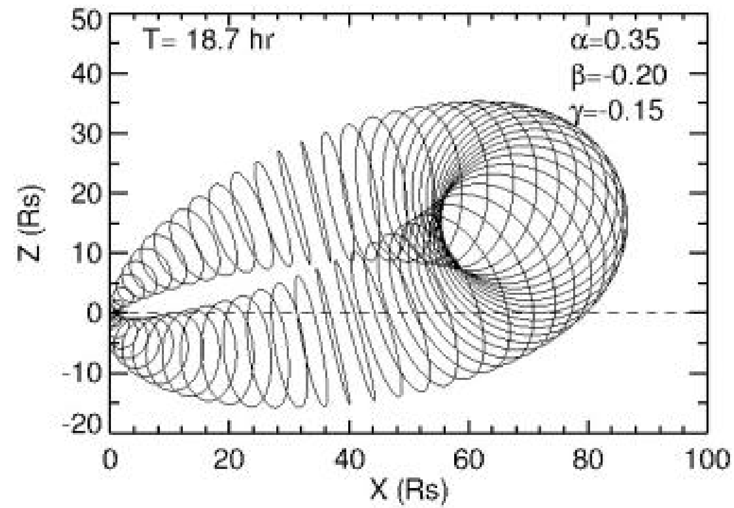


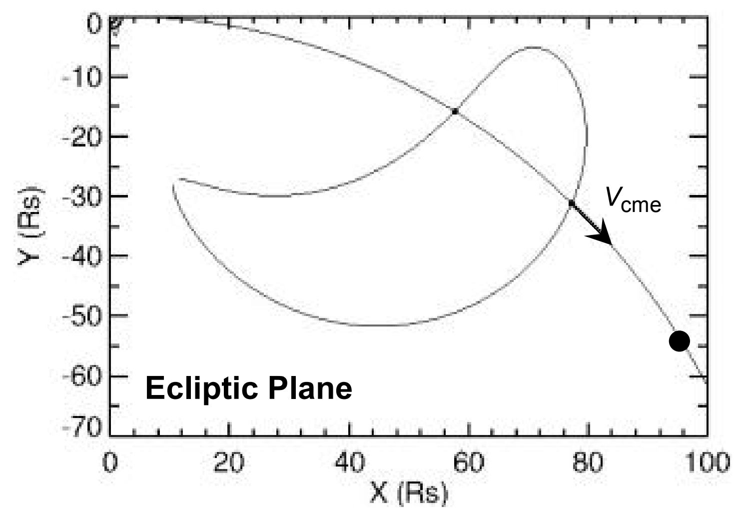
ERUPTING FLUX ROPE (EFR) MODEL OF CMEs

EFR Model CME trajectory
Comparison with STEREO –A data

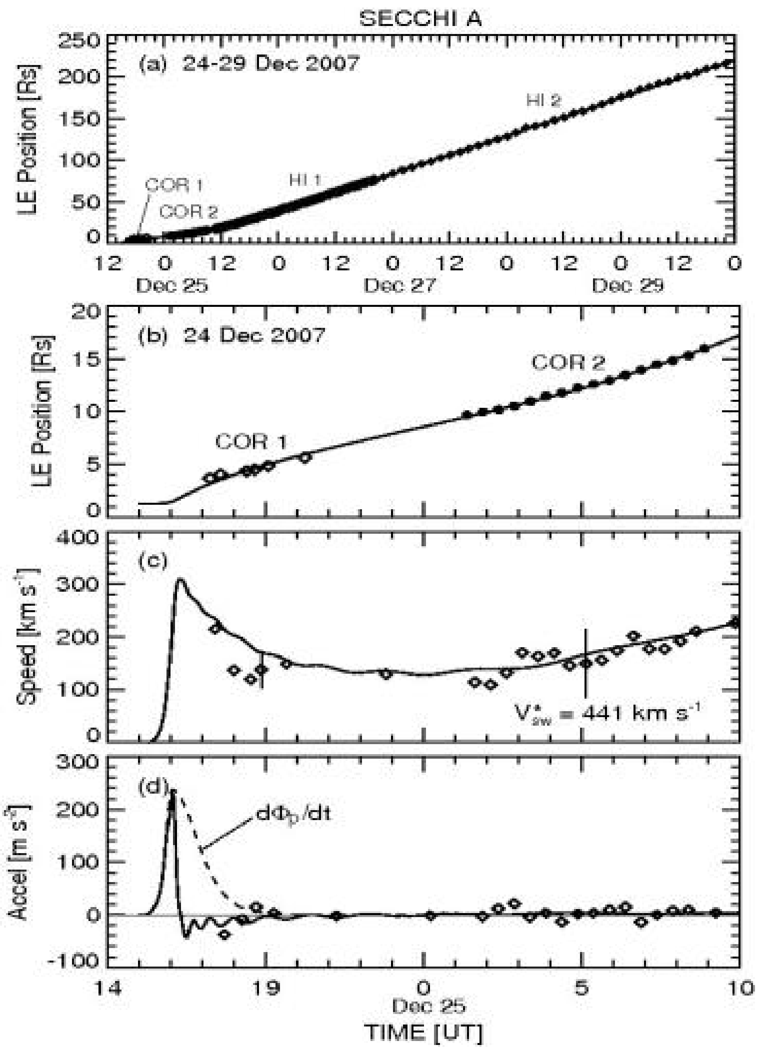


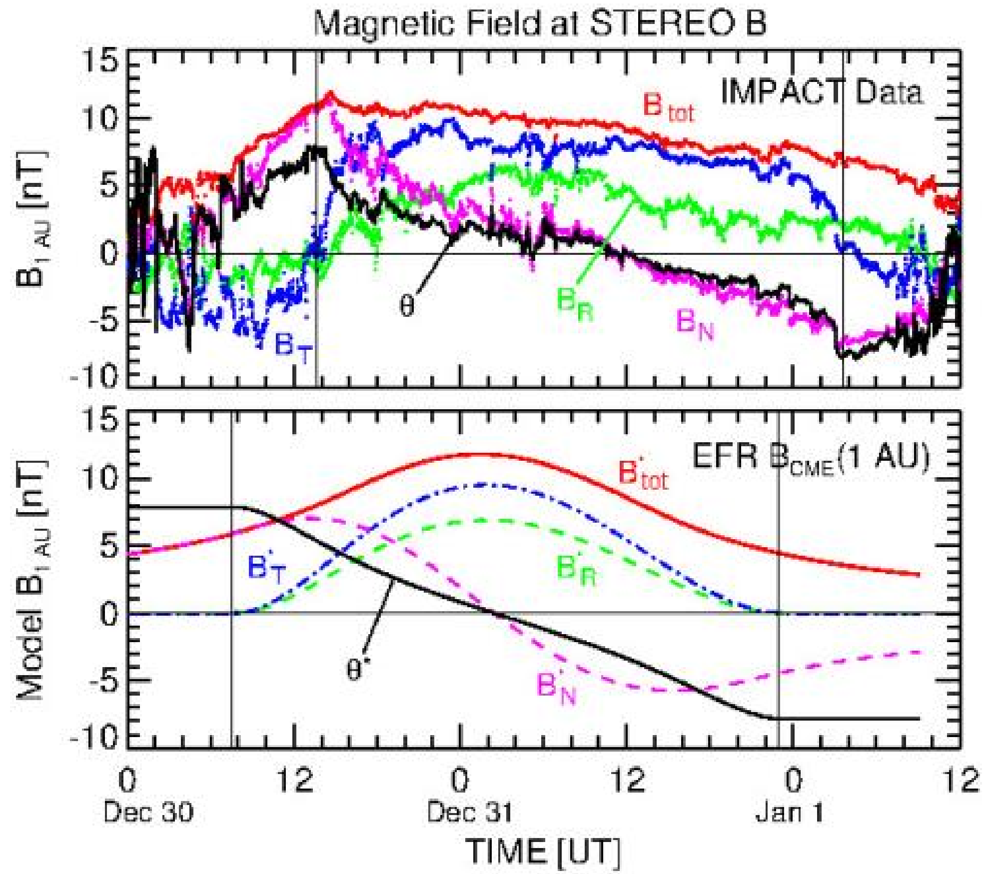
3-D EFR Flux Rope: Magnetic Surfaces





COMPARISON WITH STEREO-B DATA





$B_{max}(data) \approx B_{max}(EFR) \approx 12\ \text{nT}$

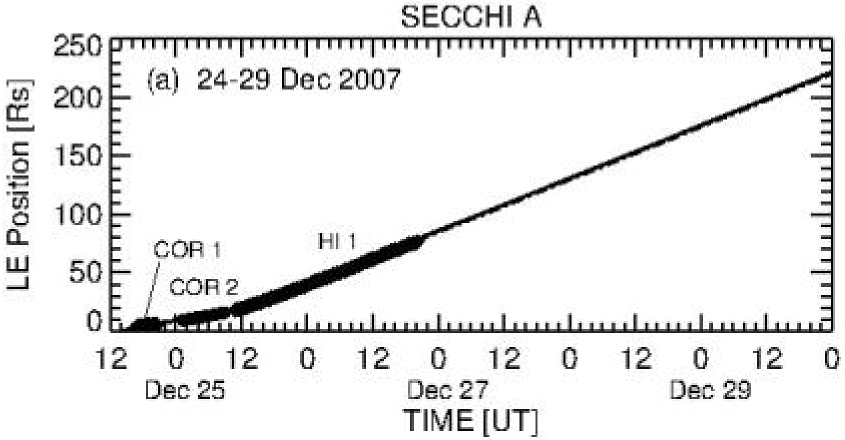
[*Kunkel and Chen* 2010, *ApJL*]

- Solution is within <1% of the height data.

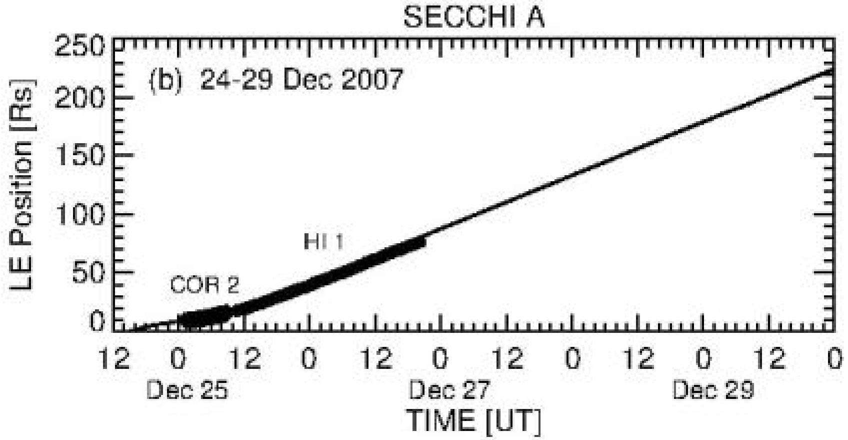
  Calculated *B* field and *plasma* data are consistent with STEREO-B data at 1 AU

MINIMUM AND SUFFICIENT INFORMATION

- Artificially removed HI2 data and obtained the EFR solution
  - Virtually unchanged, $\mathcal{D} = 1.23\%$
  - Magnetic field is unchanged, in good agreement



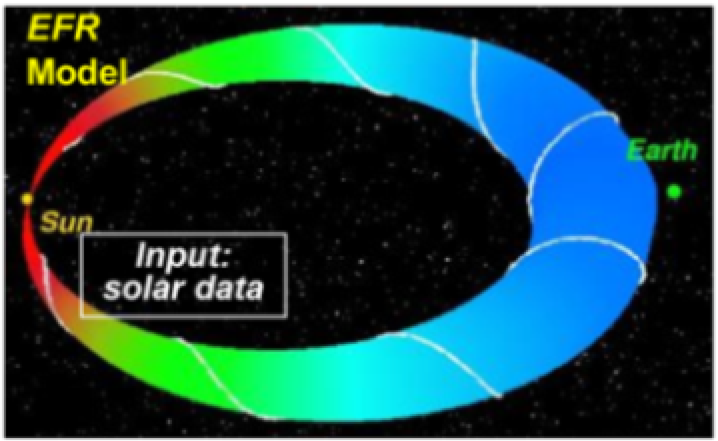
- Further removed COR1 data and constrained the solution with *only* COR2 and HI1data
  - Again virtually unchanged, $\mathcal{D} = 0.55\%$
  - Magnetic field is virtually unchanged

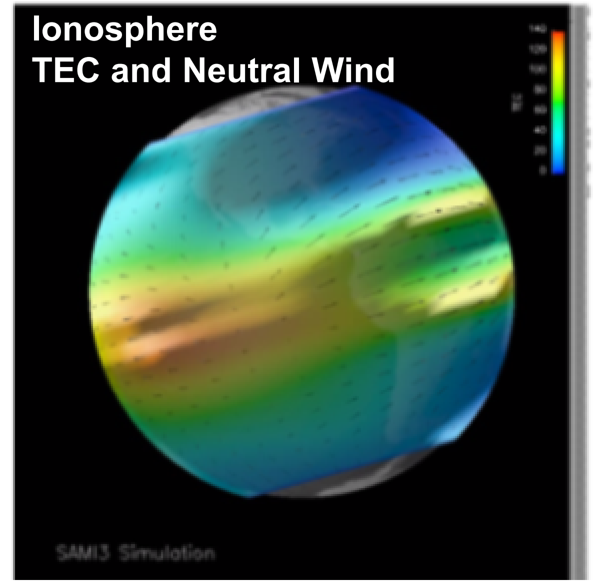


For this event, the warning time is >72 hrs

FORCASTING CME-DRIVEN GEOMAGNETIC STORMS

Sun-Earth System





Physical processes to model faster than real time

- CME dynamics to 1 AU (Earth) *after* eruption ⟶ ***EFR***

  $\mathbf{B}_{CME}(t)$ — $\mathbf{V}_{CME}$, dimension, and 3-D geometry of ejecta (arrival time and duration)

  Polarity and strength of $\mathbf{B}_{CME}$ (1AU)

- Ionospheric dynamics $TEC(\mathbf{x},t)$ in 3-D driven by $\mathbf{B}_{CME}(t)$ ⟶ ***SAMI3*** [Huba]

SUMMARY

Minimum and sufficient data

- CME dynamics and $\mathbf{B}_{CME}(t)$: $\mathbf{B}_{CME}$(1AU) can be extracted from $Z_{data}(t)$ data alone
  - Promise of a true forecasting capability with 24—48 hrs of advance warning time
- Small system for accurately predicting CME-driven geomagnetic storms
  - L5: Coronagraphs to observe CMEs out to 1/3 to 1/2 AU
  - L1: EUV imager to determine the source location
  - L1 enhancements: $\Delta\mathbf{B}_{photo}(t)$, halo CME, I_{SXR}(t), $I_{EUV}(t)$—actionable input information in the event of L5 data outages
  - SAMI3+GCM: combined with SAMI3/RCM, prediction of ionospheric dynamics in 3-D
- L1 IMF data (e.g., ACE/DSCOVR) can yield closely validation with a warning time of several hours (< 10 – 15 hrs) [*Chen et al*. 1997*; Arge et al.* 2002; *Chen et al.* 2012]
- Future refinements: (1) self-consistent 3-D expansion (*Kunkel*, PhD, 2012); (2) further test and refine EFR and SAMI3/RCM