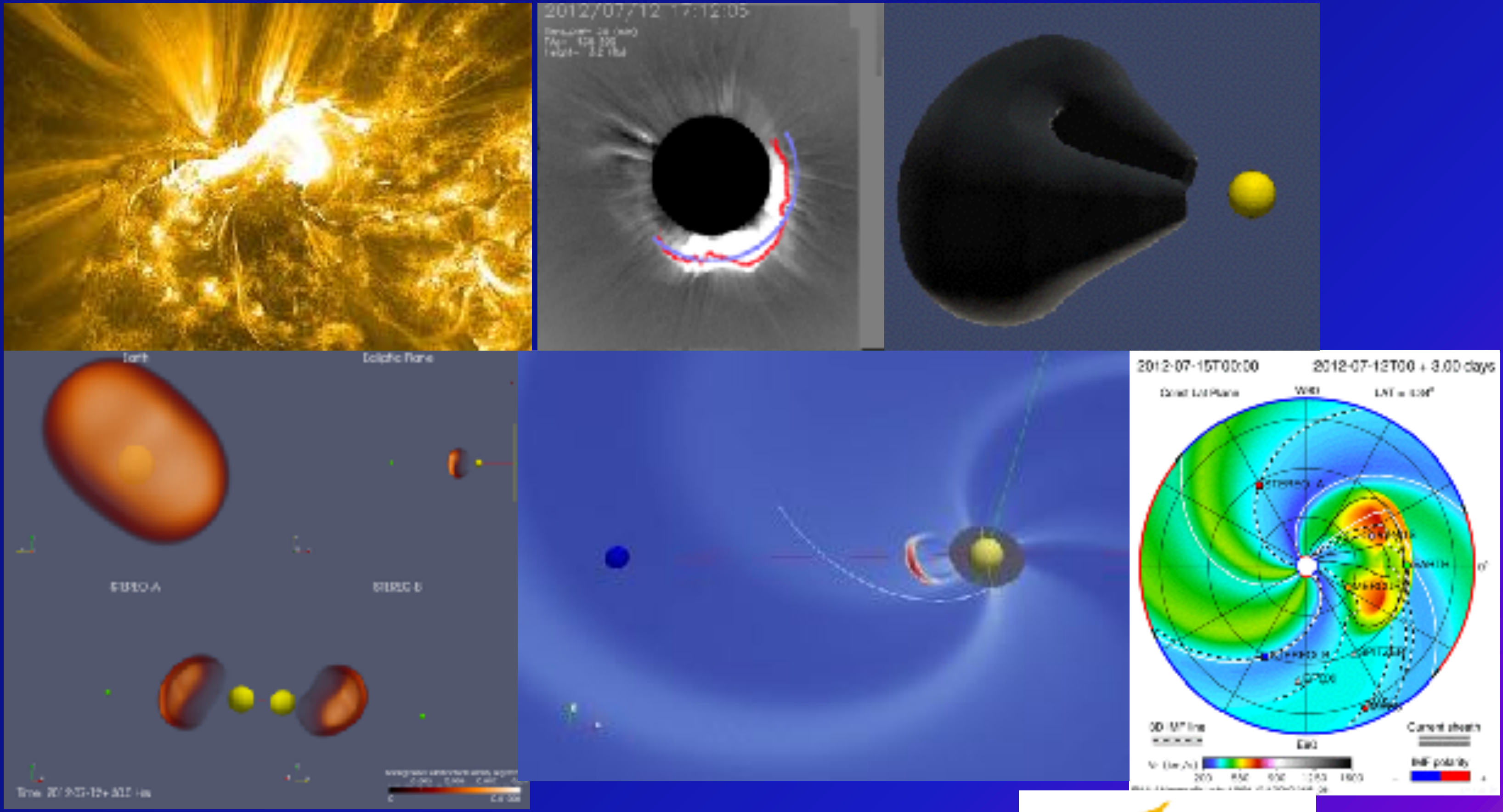
ISEST 2018 Workshop Sep. 24 - 28, 2018 Hvar, Croatia

Global Evolution of CMEs From the Sun to the Earth



Jie Zhang

GEORGE MASON UNIVERSITY

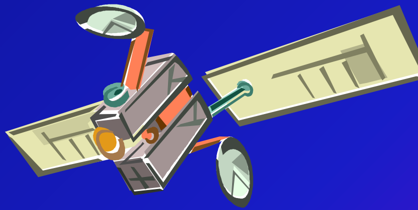
The Sun-Earth Connection

Sun | Interplanetary Space | In-situu

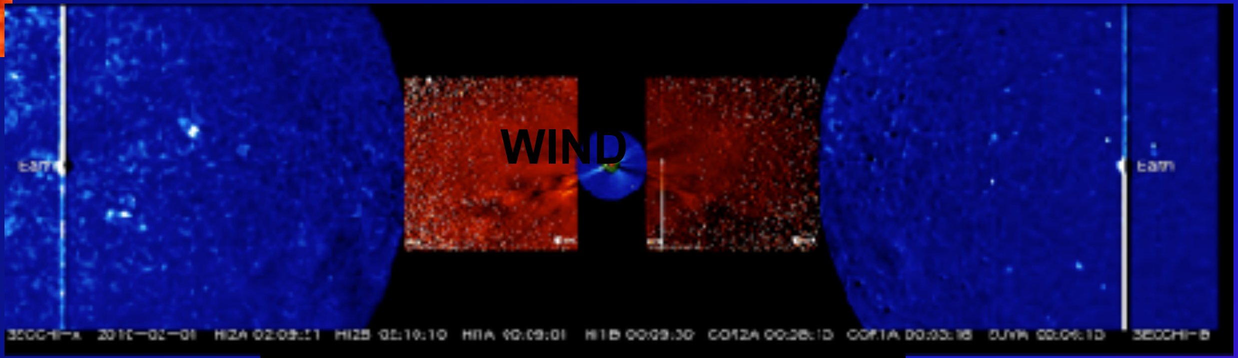
SOHO
SDO
HINODE
…

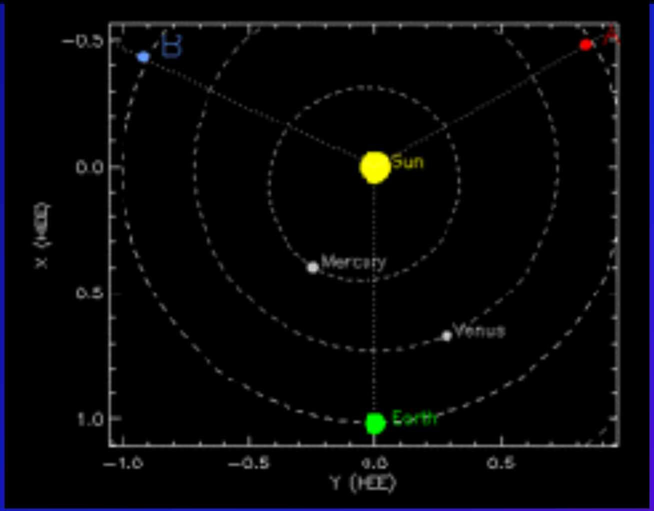
STEREO-A
STEREO-B

PSP



ACE
WIND





+++++++++
Numerical
+++++++++

Outline

1. ISEST project in five years

2. Global evolution of CMEs
    1. Precursor Phase
    2. Impulsive Acceleration Phase
    3. Residual Acceleration Phase
    4. Propagation Phase

3. CME prediction
    - Time of arrival (TOA)
    - Hit/Miss
    - Geo-effectiveness and the Bz challenge

4. Conclusions and Discussion

Project ISEST/MiniMax24

International Study of Earth-affecting Solar Transients

J. Zhang[1], M. Temmer[2], and N. Gopalswamy[3]
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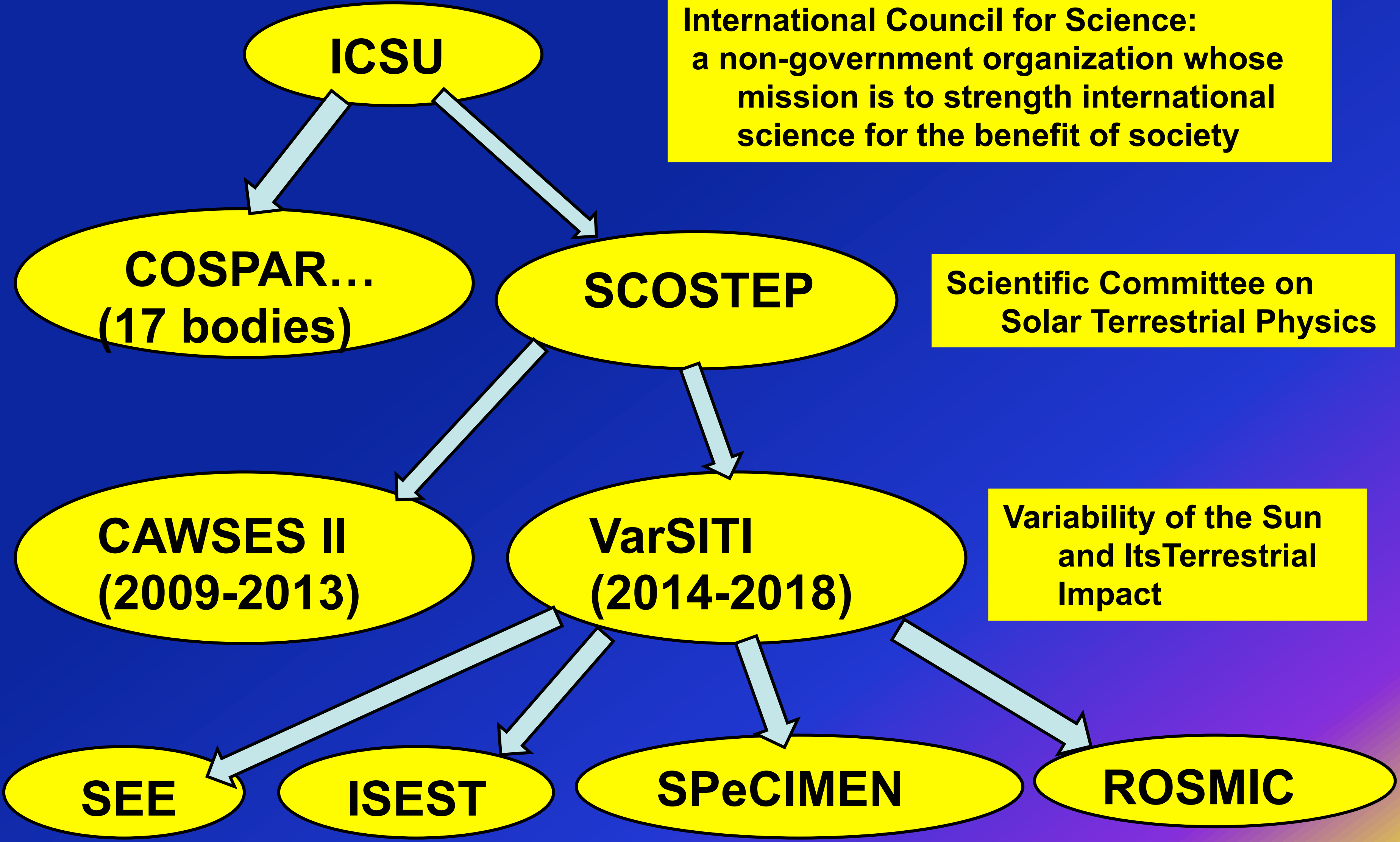
Jie Zhang Manuela Temmer Nat Gopalswamy

Goal of ISEST

Understand the origin, propagation and evolution of solar transients through the space between the Sun and the Earth, and develop the prediction capability of space weather

Organizational Structure



ICSU

International Council for Science:
a non-government organization whose
mission is to strength international
science for the benefit of society

COSPAR…
(17 bodies)

SCOSTEP

Scientific Committee on
Solar Terrestrial Physics

CAWSES II
(2009-2013)

VarSITI
(2014-2018)

Variability of the Sun
and ItsTerrestrial
Impact

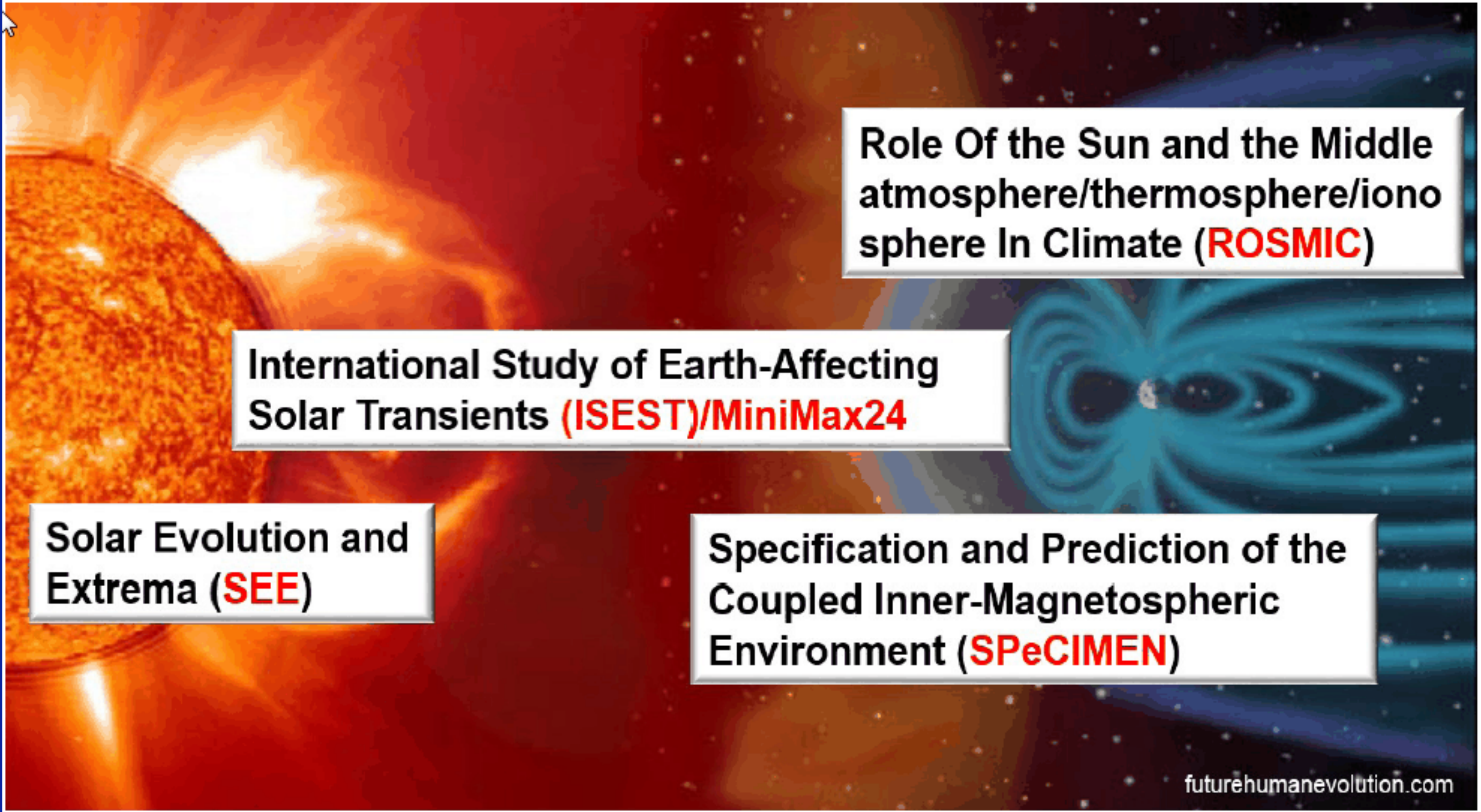
SEE

ISEST

SPeCIMEN

ROSMIC

VarSITI (2014-2018)



Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate (**ROSMIC**)

International Study of Earth-Affecting Solar Transients **(ISEST)/MiniMax24**

Solar Evolution and Extrema (**SEE**)

Specification and Prediction of the Coupled Inner-Magnetospheric Environment (**SPeCIMEN**)

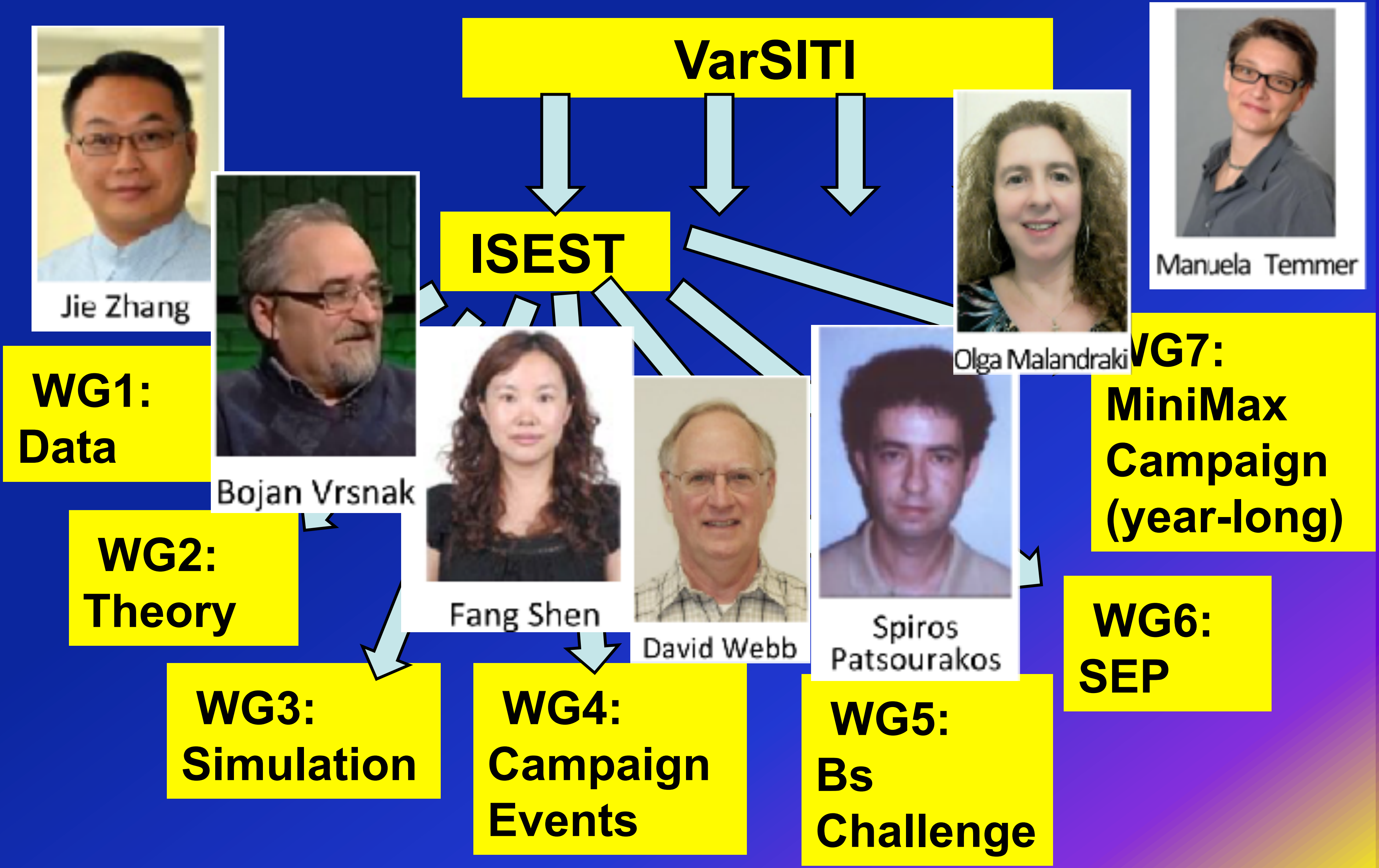
futurehumanevolution.com

http://www.varsiti.org

Scientific Organization Committee (SOC)

Ayumi Asai	Kyoto University (Japan)
Mario M. Bisi	RAL (UK)
Kyungsuk Cho	KASI (South Korea)
Peter Gallagher	Trinity College Dublin (Ireland)
Manolis K. Georgoulis	Academy of Athens (Greece)
Nat Gopalswamy (co-leader)	NASA (USA)
Alejandro Lara	National Autonomous University (Mexico)
Noe Lugaz,	University of New Hampshire (USA)
Alexis Rouillard	CNRS/IRAP (France)
Nandita Srivastava	Physical Research Lab (India)
Manuela Temmer (co-leader)	University of Graz (Austria)
Yuri Yermolaev	Space Research Institute (Russia)
Yu-Ming Wang	Univ. of Science and Technology (China)
David Webb	Boston College (USA)
Bojan Vrsnak	Hvar Observatory (Croatia)
Jie Zhang (co-leader)	George Mason University (USA)

Working Groups



VarSITI

ISEST

Jie Zhang

WG1:
Data

Bojan Vrsnak

WG2:
Theory

Fang Shen

WG3:
Simulation

David Webb

WG4:
Campaign
Events

Spiros
Patsourakos

WG5:
Bs
Challenge

Olga Malandraki

WG6:
SEP

Manuela Temmer

WG7:
MiniMax
Campaign
(year-long)

ISEST - 2013
June 17-20, 2013, Hvar, Croatia

Bojan Vrsnak

ISEST - 2015
Oct. 26-30, Mexico City, Mexico


Alejandro Lara

ISEST 2017
Sep. 18 - 22, Jeju, South Korea

Kyungsuk Cho

ISEST Mini-Workshops

June 12, 2015
Hefei, China

August 18, 2016
Beijing, China

ISEST Online Portal

ISEST Portal (Wiki based):

- Data repository from observations and analysis
- Discussions and comments
- User registration

http://solar.gmu.edu/heliophysics/

Acknowledge: Phil Hess

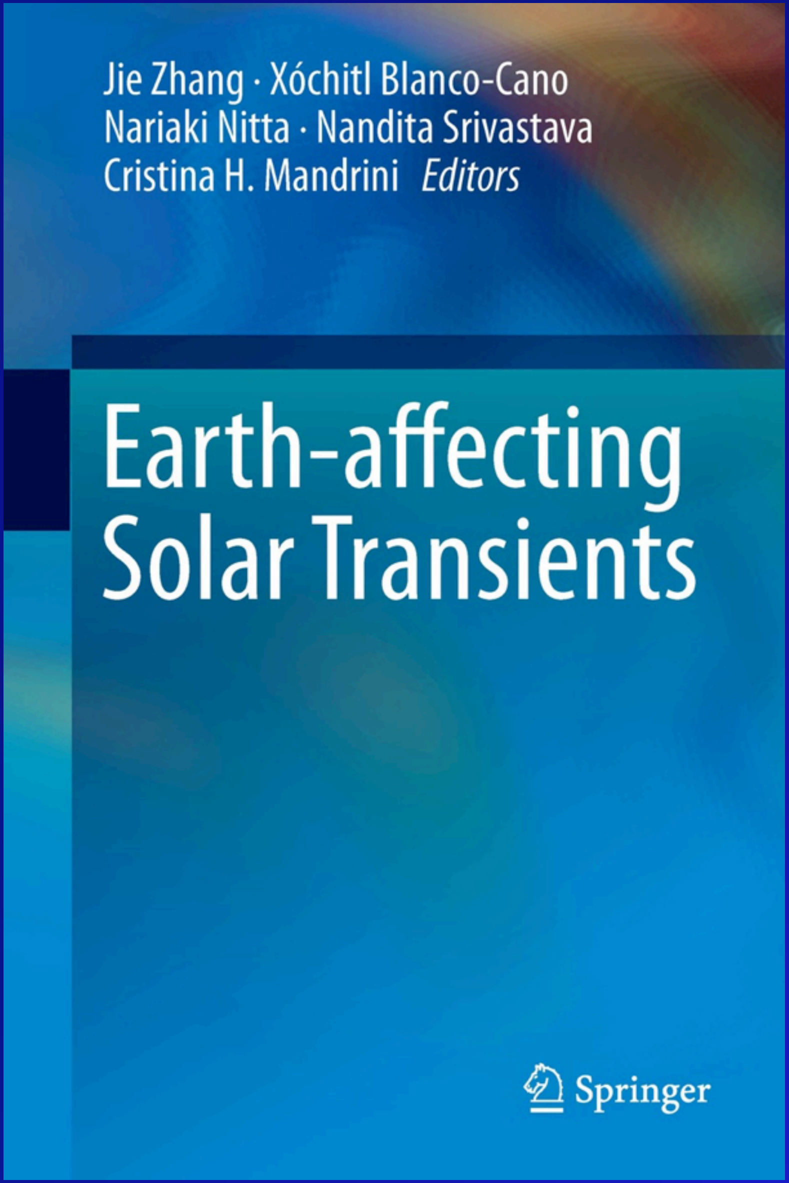
MiniMax24 Portal

Daily updates of any relevant solar events

(https://igam02ws.uni-graz.at/mediawiki/)

Acknowledge: Manuela Temmer and the team

Publication



Jie Zhang · Xóchitl Blanco-Cano
Nariaki Nitta · Nandita Srivastava
Cristina H. Mandrini *Editors*

Earth-affecting
Solar Transients

Springer

ISEST Topical Issue in Solar Physics

- 44 papers submitted
- 10 rejected by reviewers or editors
- 34 papers accepted for publication

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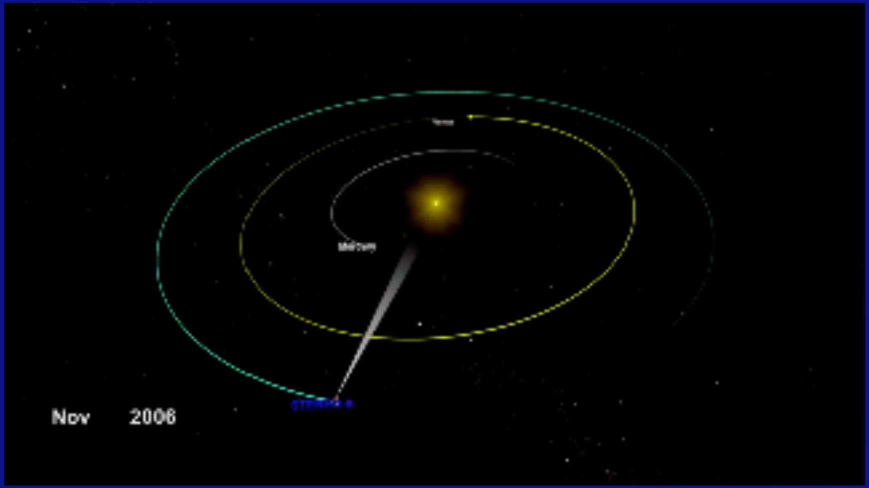
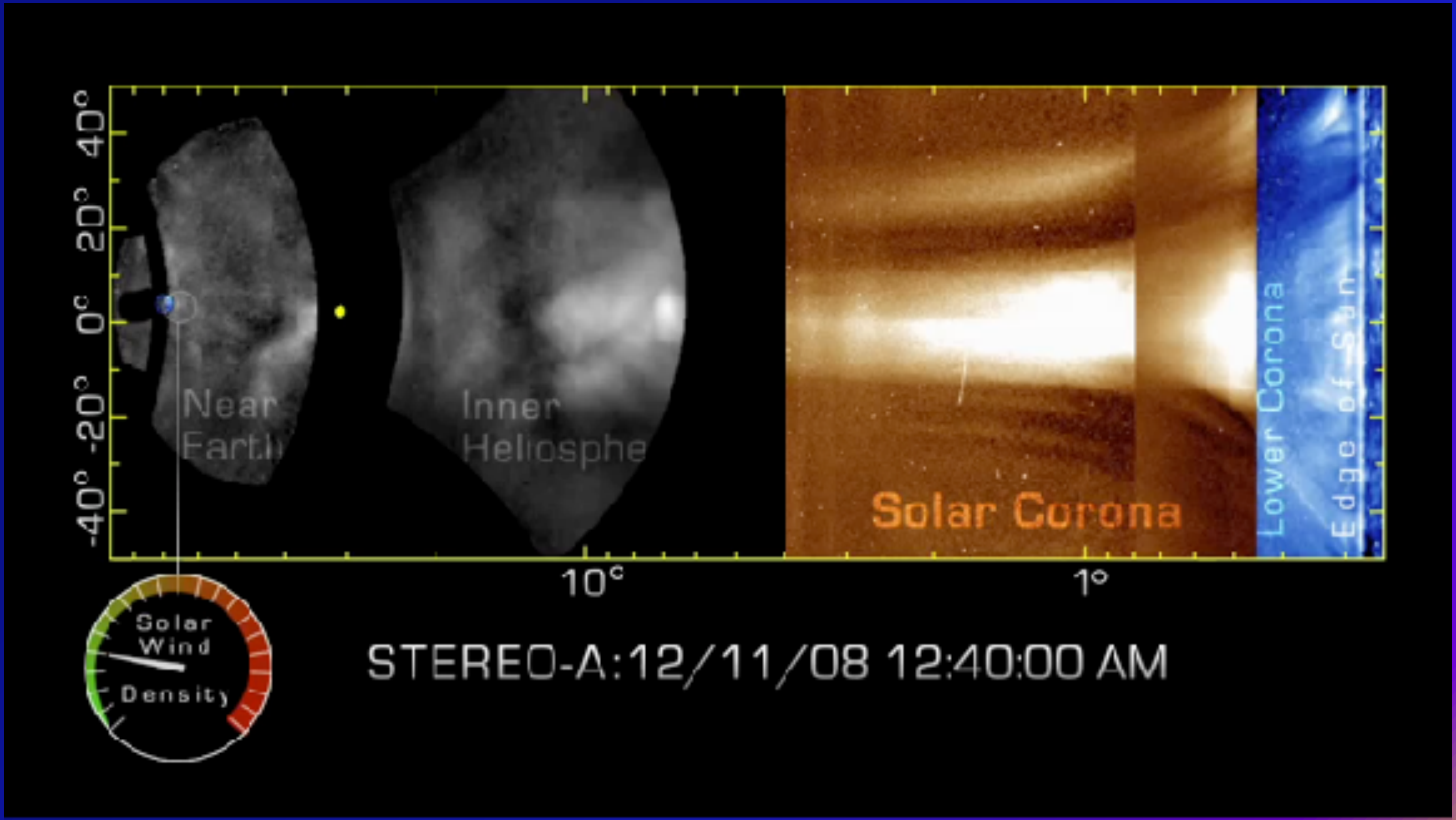


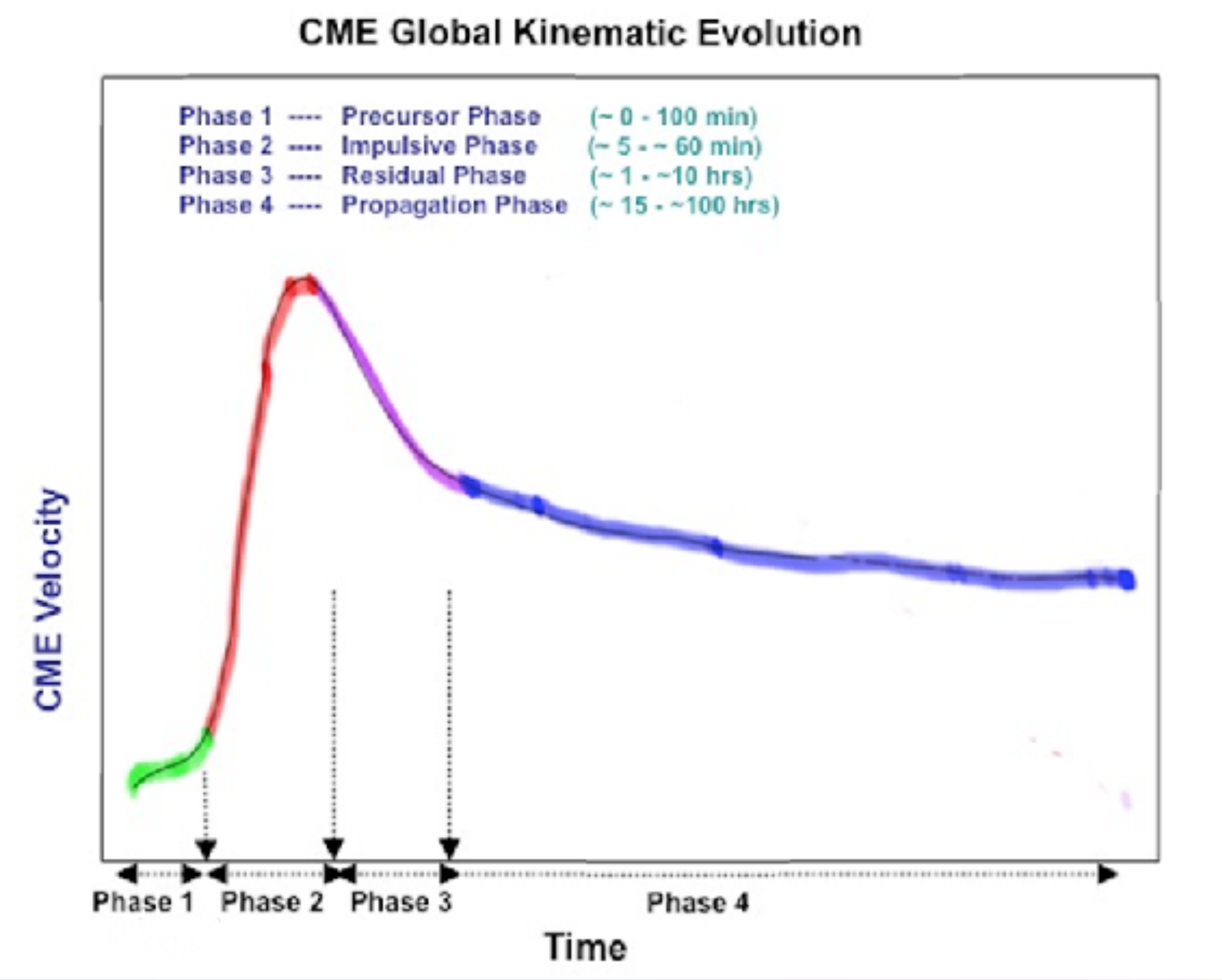
(Credit: NASA)

Sun-Earth connection has never been so clear! Thanks to STEREO!

(Credit: NASA and Deforest)



CME Global Kinematic Evolution



Global Kinematic Evolution:
A four-phase scenario

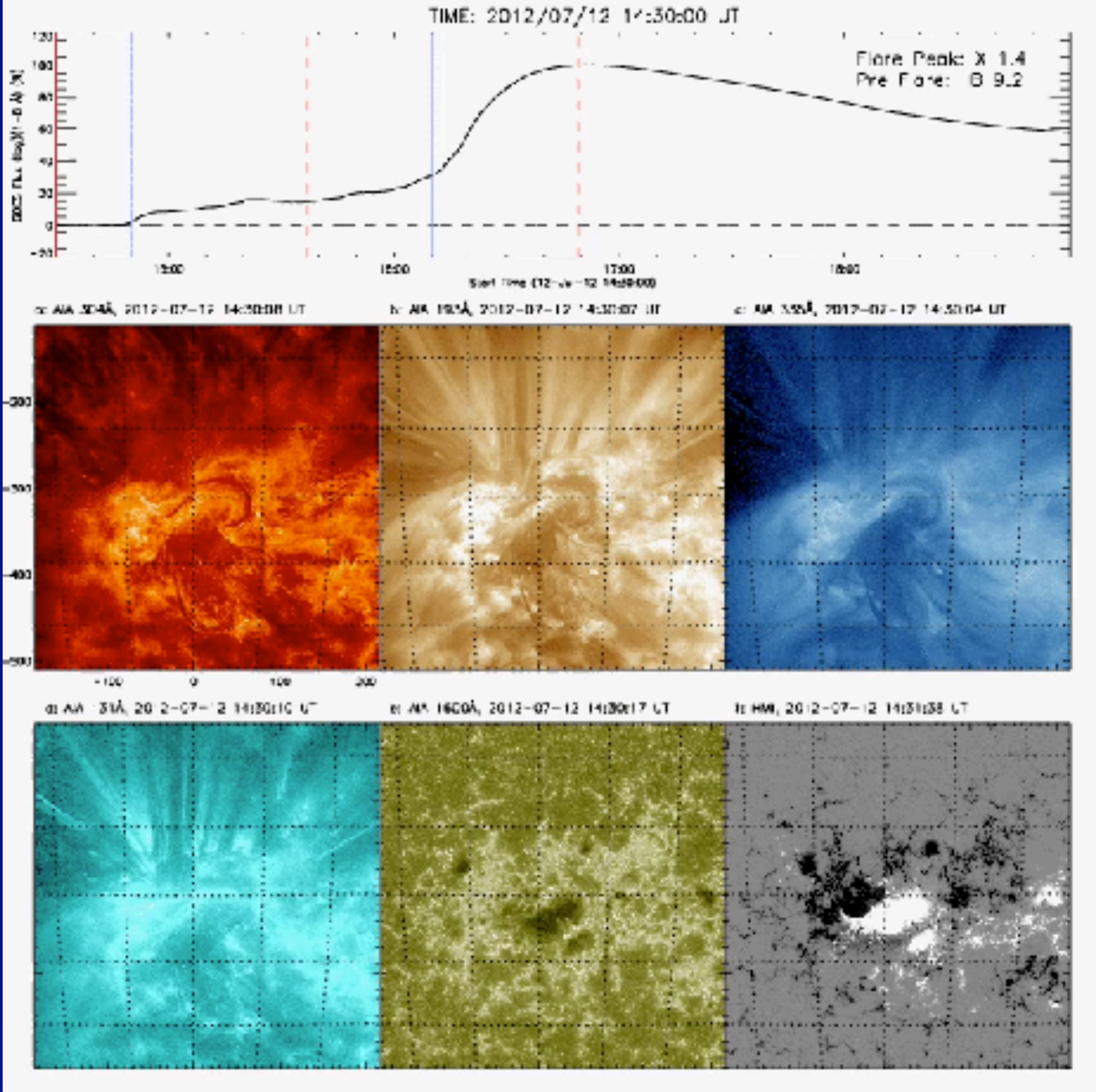
Phase 1	Phase 2	Phase 3	Phase 4
near surface	inner corona	outer corona	Interplanetary space
< 0.2 Rs	< ~ 3 Rs	< ~20 Rs	> 215 Rs
< ~100 km/s	~ 0- ~3000 km/s	< ~ 2500 km/s	~ 300 - ~1000 km/s
< 50 m/s^2	100 -10000 m/s^2	-150 - +150 m/s^2	~ - 20 - +10 m/s^2
pre-cursor phase	impulsive phase	residual phase	Propagation phase

Sun-to-Earth Event: An Example

2012 July 12 - 14 STE event (Dudik et al. 2014; Cheng et al. 2014; Moestl et al. 2014; Hess & Zhang 2014; Shen et al. 2014; Hu et al. 2016)

•07:12 14:50 UT: Onset of Precursor Phase	- 1 hr 20 min
•07/12 16:10 UT: Onset of Impulsive Phase	0 hr 0 min
•07/12 16:49 UT: Flare peak (X1.4, S17W08, AR11520)	0 hr 39 min
•07/12 16:48 UT: CME first appearing in C2	0 hr 38 min
•07/12 18:54 UT: CME at 20 Rs	2 hr 44 min
•07/13 00:49 UT: CME at 50 Rs	8 hr 38 min
•07/13 06:49 UT: CME at 80 Rs	15 hr
•07/14 17:00 UT: Shock arrival at 1 AU	49 hr
•07/15 06:00 UT: Magnetic Cloud arrival at 1 AU	62 hr
•07/15 19:00 UT: Peak time of Dst (-127 nT)	75 hr
•07/17 14:00 UT: Magnetic Cloud end at 1 AU	118 hr

Phase 1: Precursor Phase



2012/07/12
Event
GOES X-ray

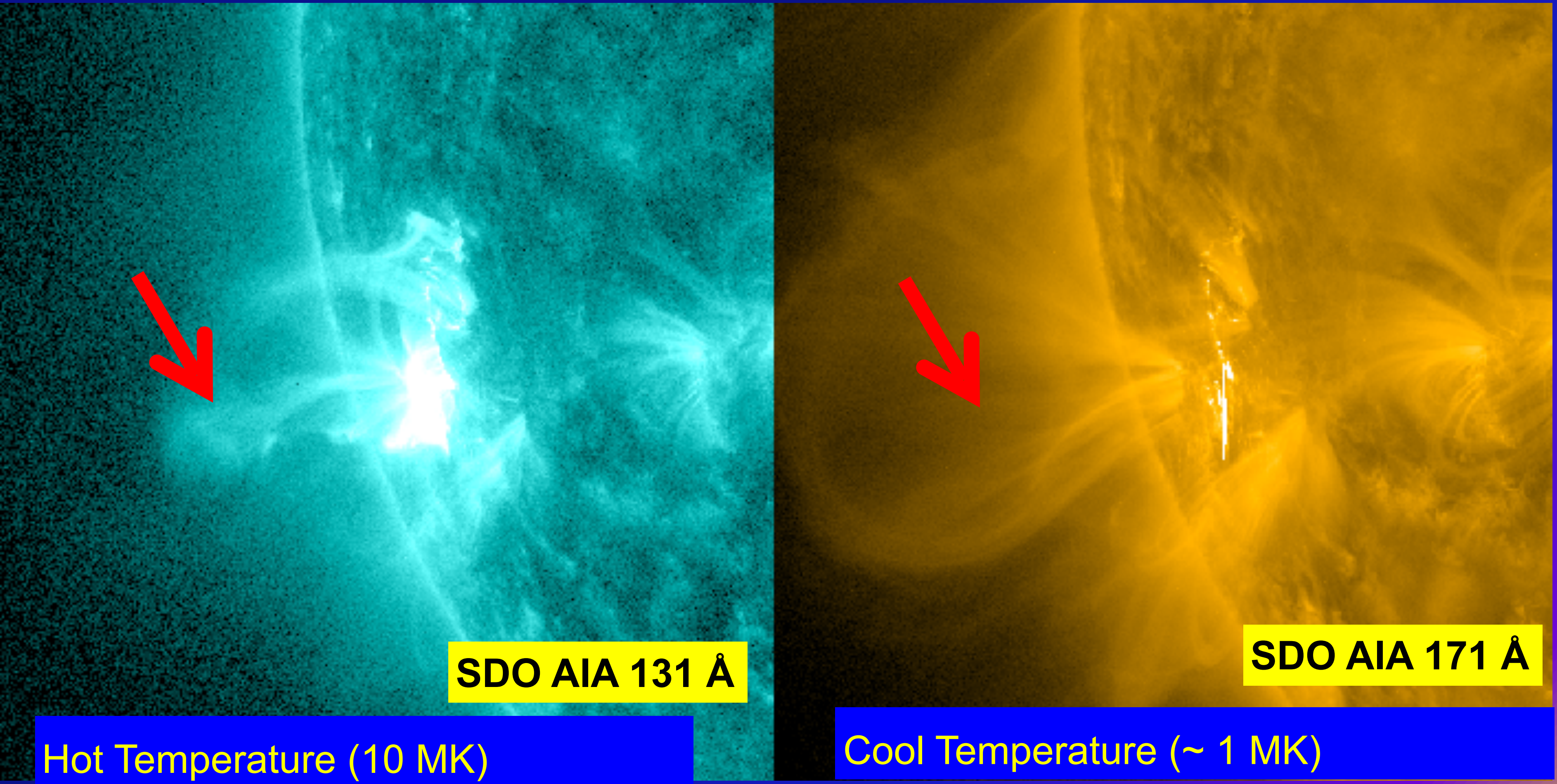
SDO AIA
Coronal Image

Transition
Region Image

SDO/HMI
Magnetogram

Morphology in Precursor Phase

EUV hot channel: the signature of magnetic flux rope

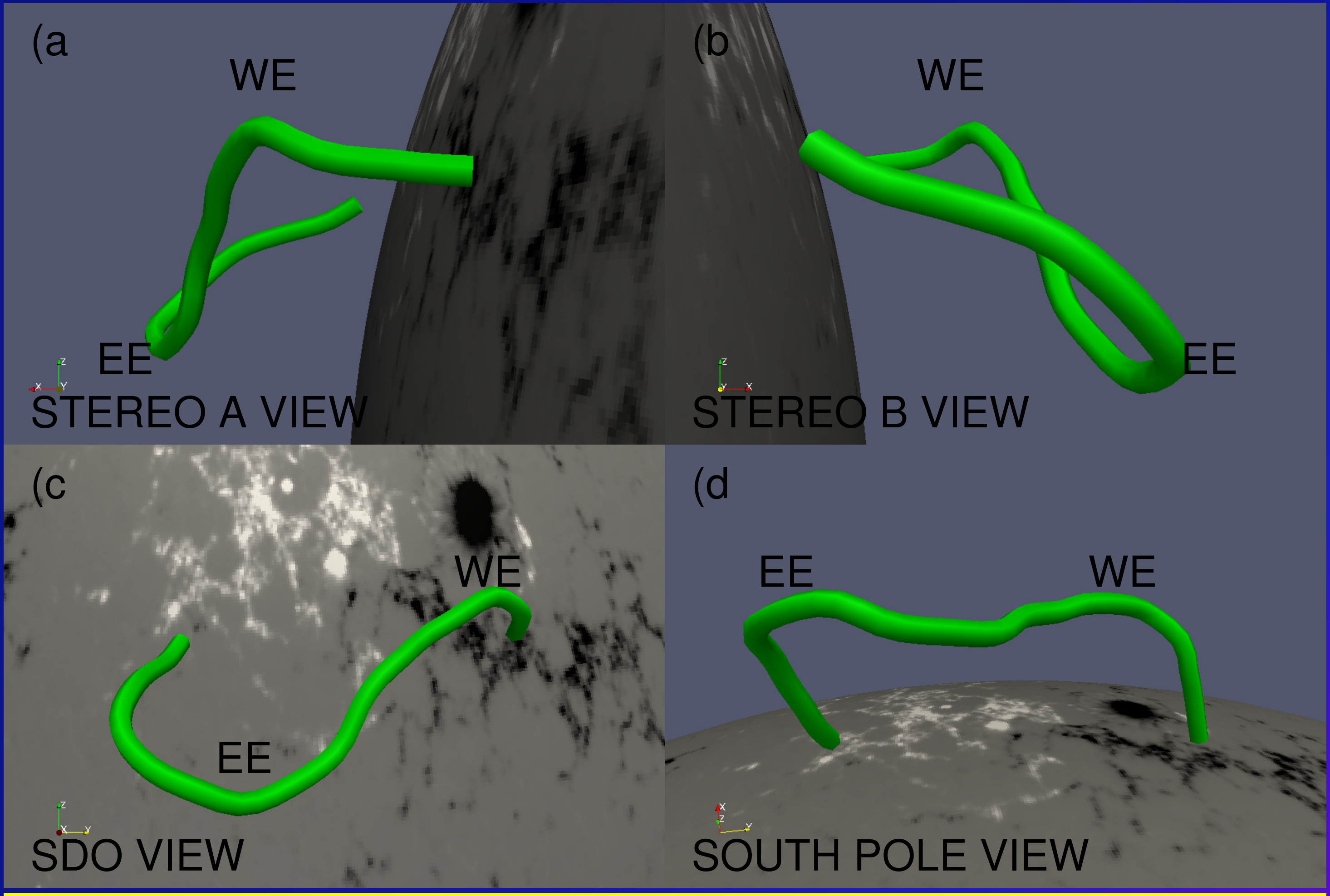


Hot Temperature (10 MK)

Cool Temperature (~ 1 MK)

(Zhang, Cheng & Ding, Nature Communications, 2012)
Also see (Cheng et al., ApJ Lett., 2011)

Pre-eruption Morphology



The sigmoid in 2-D is of an M-shape in 3-D

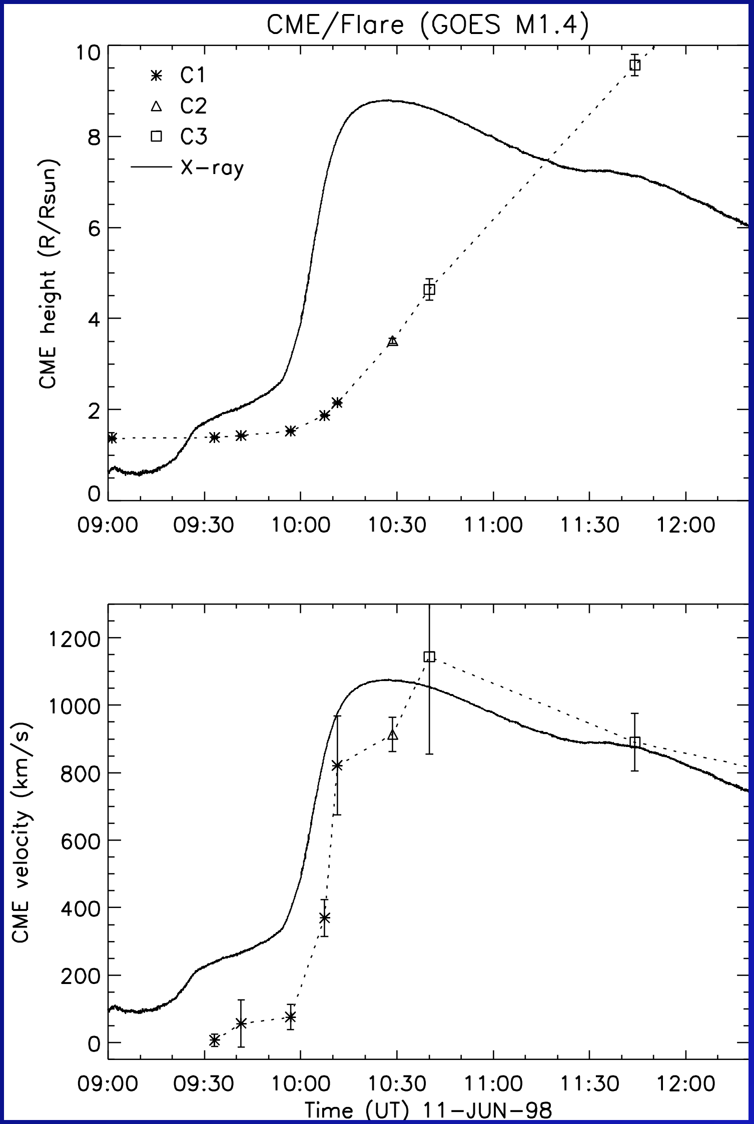
(Zhou et al. 2016)

Phase 1: Precursor Phase

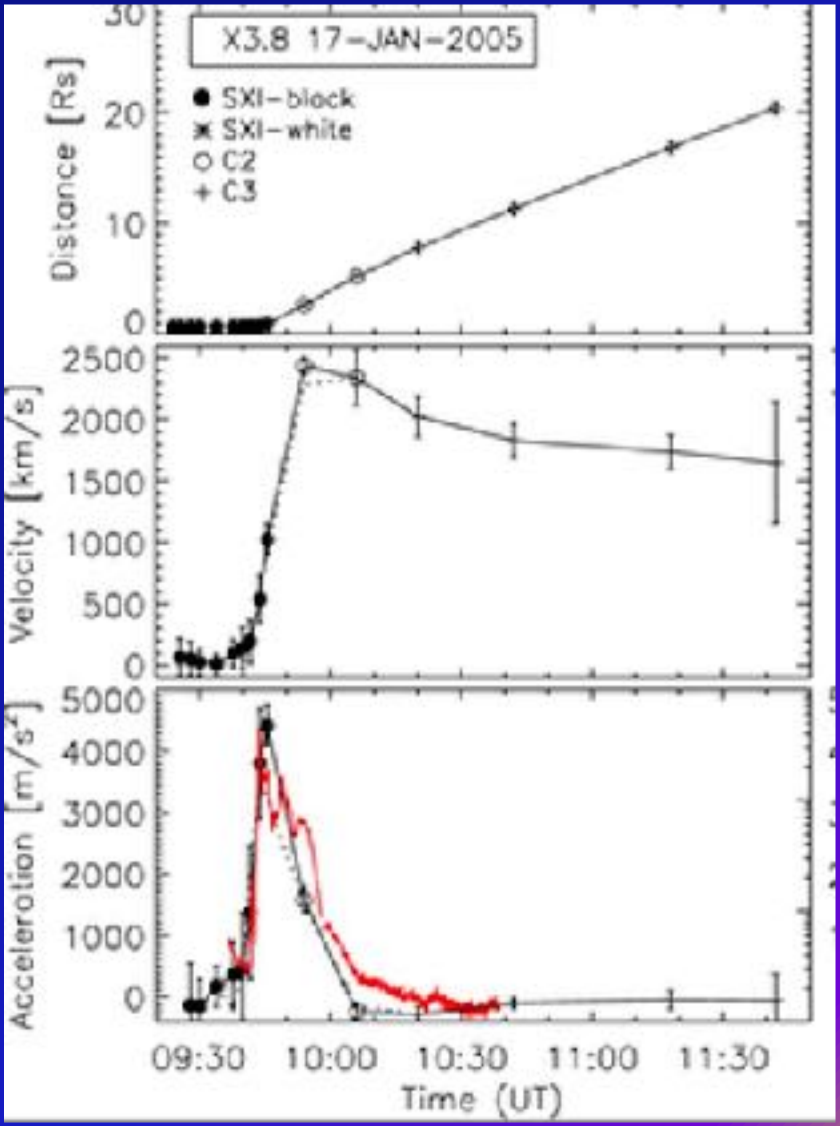
- Slow rise motion of the erupting structure (Zhang et al. 2001; Sterling & Moore 2005)
- Weak electromagnetic emission: X-ray, EUV
- Weak pre-flare activity (Chifor et al. 2007)
- Appearance of hot channels in EUV (Zhang et al. 2012; Cheng et al. 2013)
- A magnetic flux rope has formed prior to the precursor phase

The precursor phase is least understood

Phase 2: Impulsive Phase



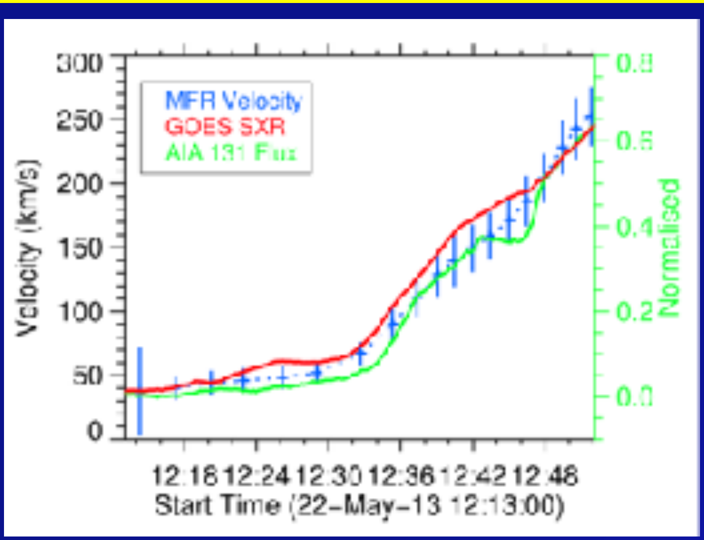
(Zhang et al. 2001)

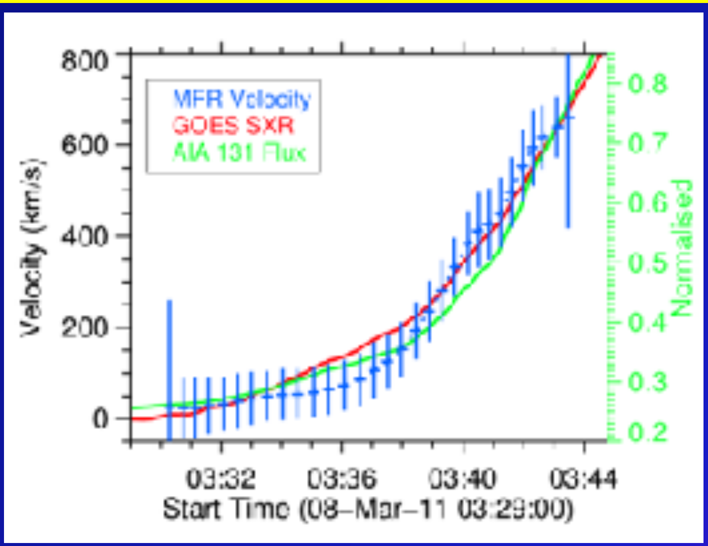


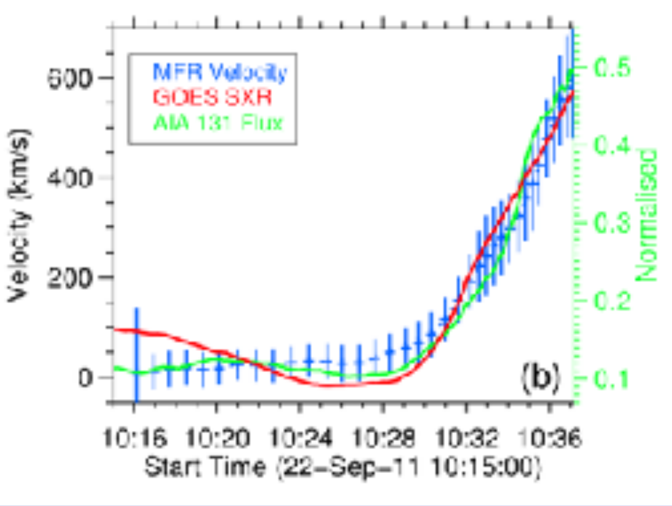
(Temmer et al. 2008)

Phase 2: Impulsive Phase

Nearly synchronized temporal relation between eruption (CME) and EM emission (flare)







(Cheng et al. In preparation)

$$V(t) = V_0 + at + be^{t/\tau}$$

Phase 2: Impulsive Phase

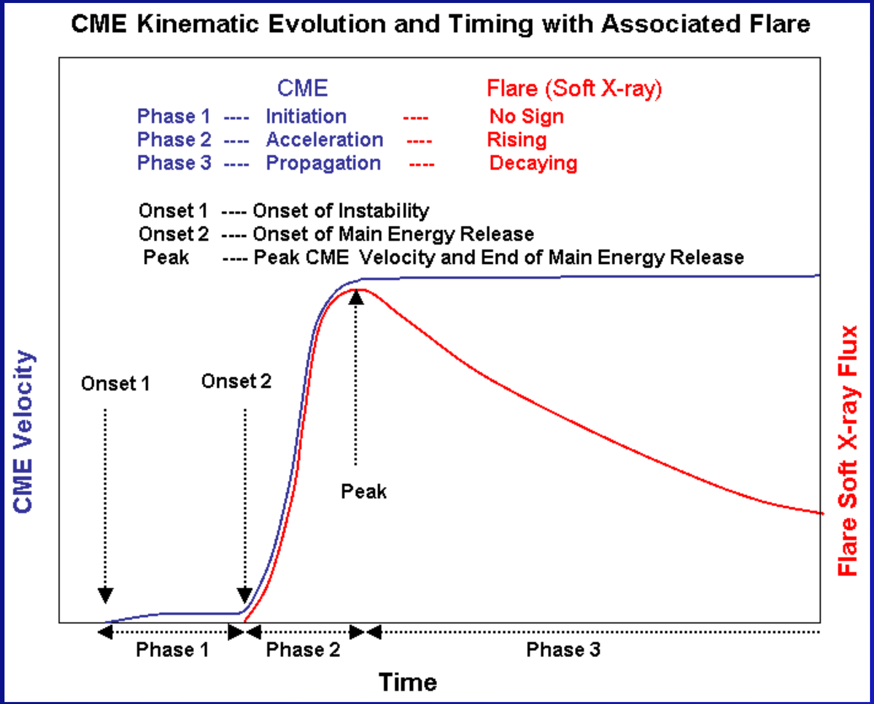
This is it! The main phase of energy release

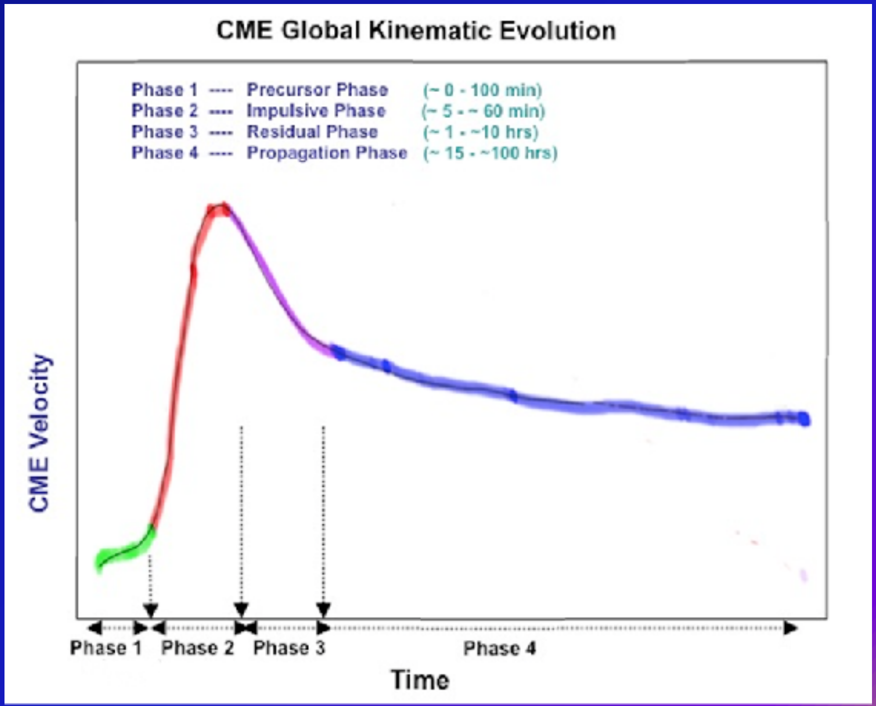
- Fast and impulsive acceleration (up to 10 km/s^2)
- Flare hard X-ray emission
- Flare EM enhancement in all wavelength
- Flare footpoint ribbon separation
- Coronal dimming
- Coronal waves

- Nearly synchronous evolution of CMEs and flares
- A hybrid process of involving both ideal MHD instability (Torus Instability, Kliem & Torok 2006) and non-ideal MHD process (Magnetic Reconnection, CSHKP and many variants)
- Also a mutual feeding process between Torus Instability and Magnetic Reconnection

Phase 3: Residual Phase

- Add the “residual phase” into the original three phase scenario in the setting of global evolution
- It is a transition phase in which Lorentz force and drag force both are important





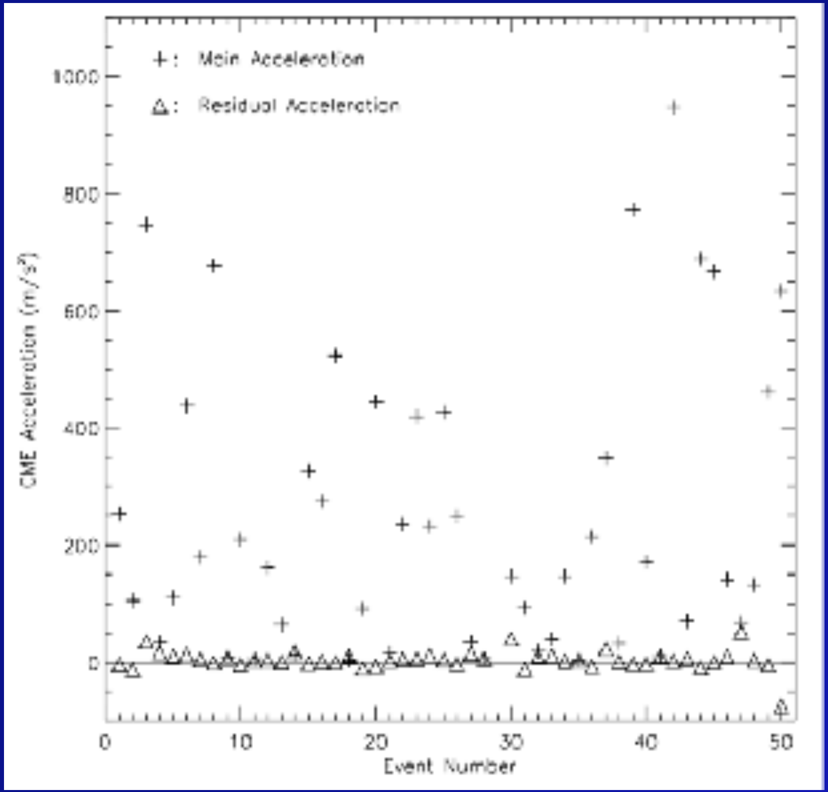
(Zhang & Dere 2006)
Based on SOHO

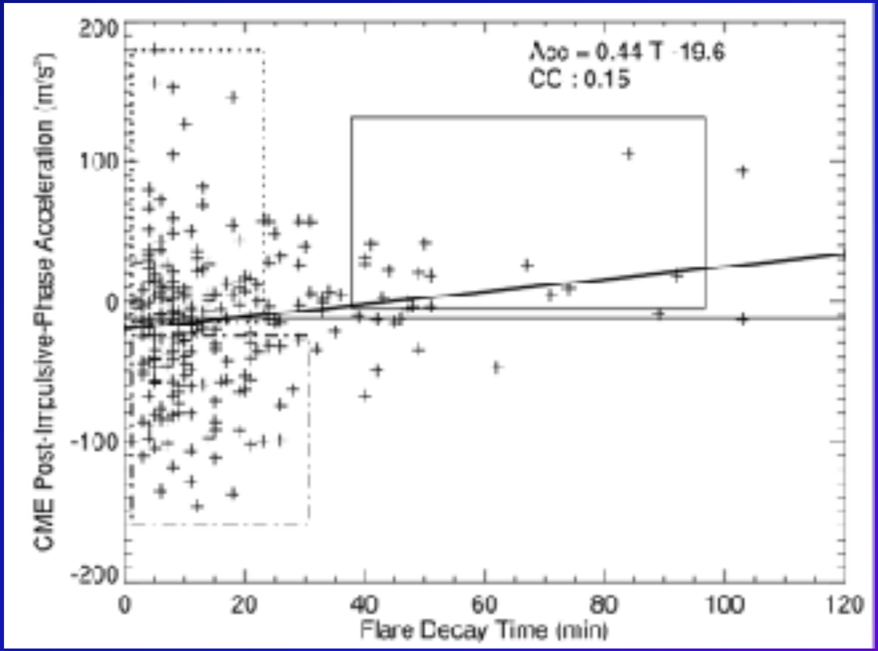
Based on STEREO

Phase 3: Residual Phase

- "Residual Acceleration" is originally proposed in Chen & Krall (2003). It differs from the main acceleration in their model, in which Lorentz self-force has decreased and the drag force of solar wind starts to dominate
- Zhang et al (2006) made a statistical study of main and residual acceleration
- It is also named as "post-impulsive-phase acceleration" in Cheng et al. (2010).
- It is in time associated with the decay phase of long duration flares.

Phase 3: Residual Phase





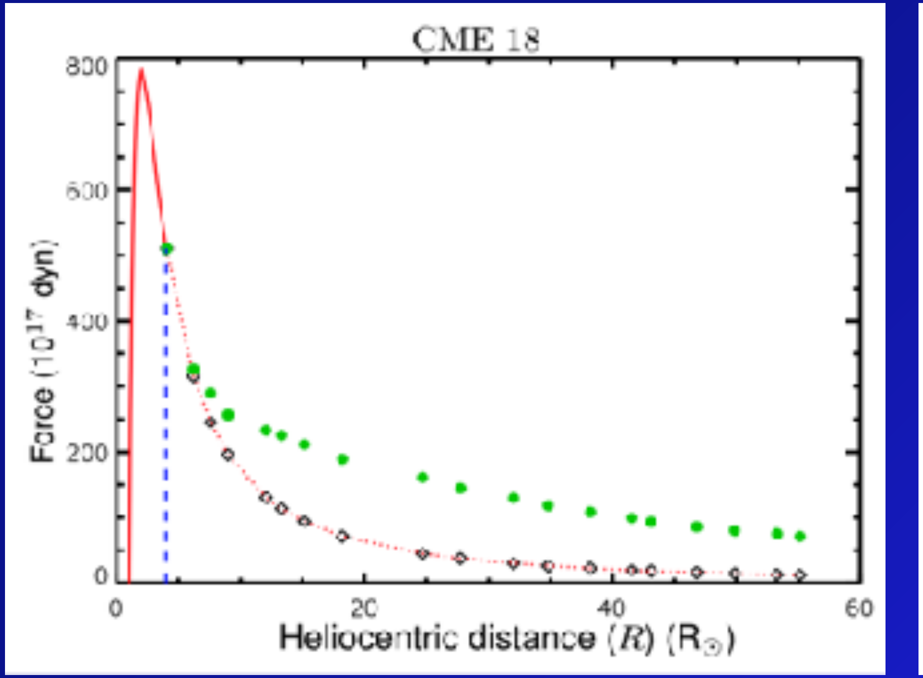
Main acceleration versus residual acceleration (Zhang & Dere 2006)

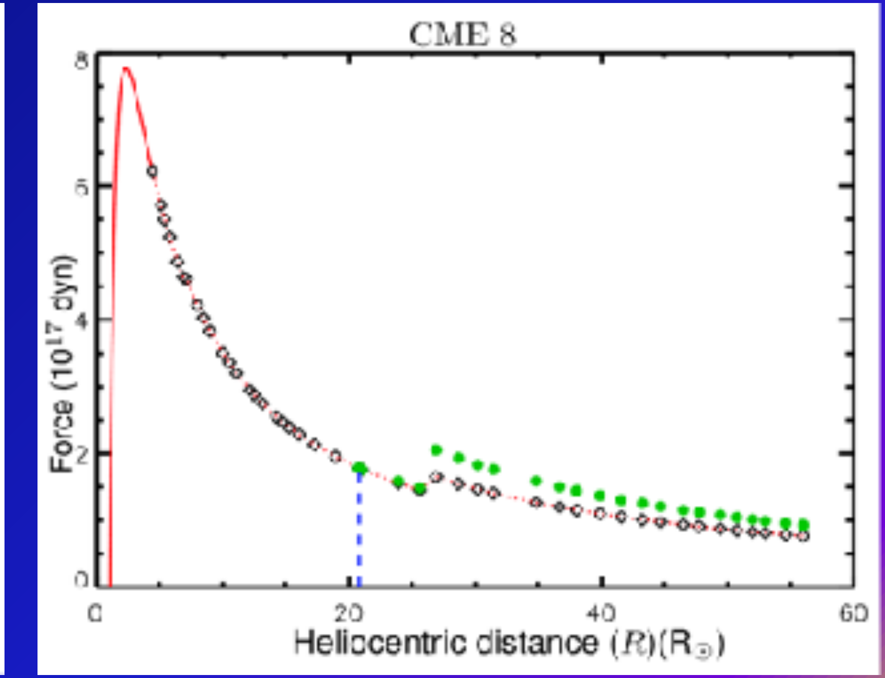
Residual acceleration (Cheng et a. 2010)

Phase 3: Residual Phase

Drag force dominates early (at ~ 4 Rs)
Event: 2011/10/22

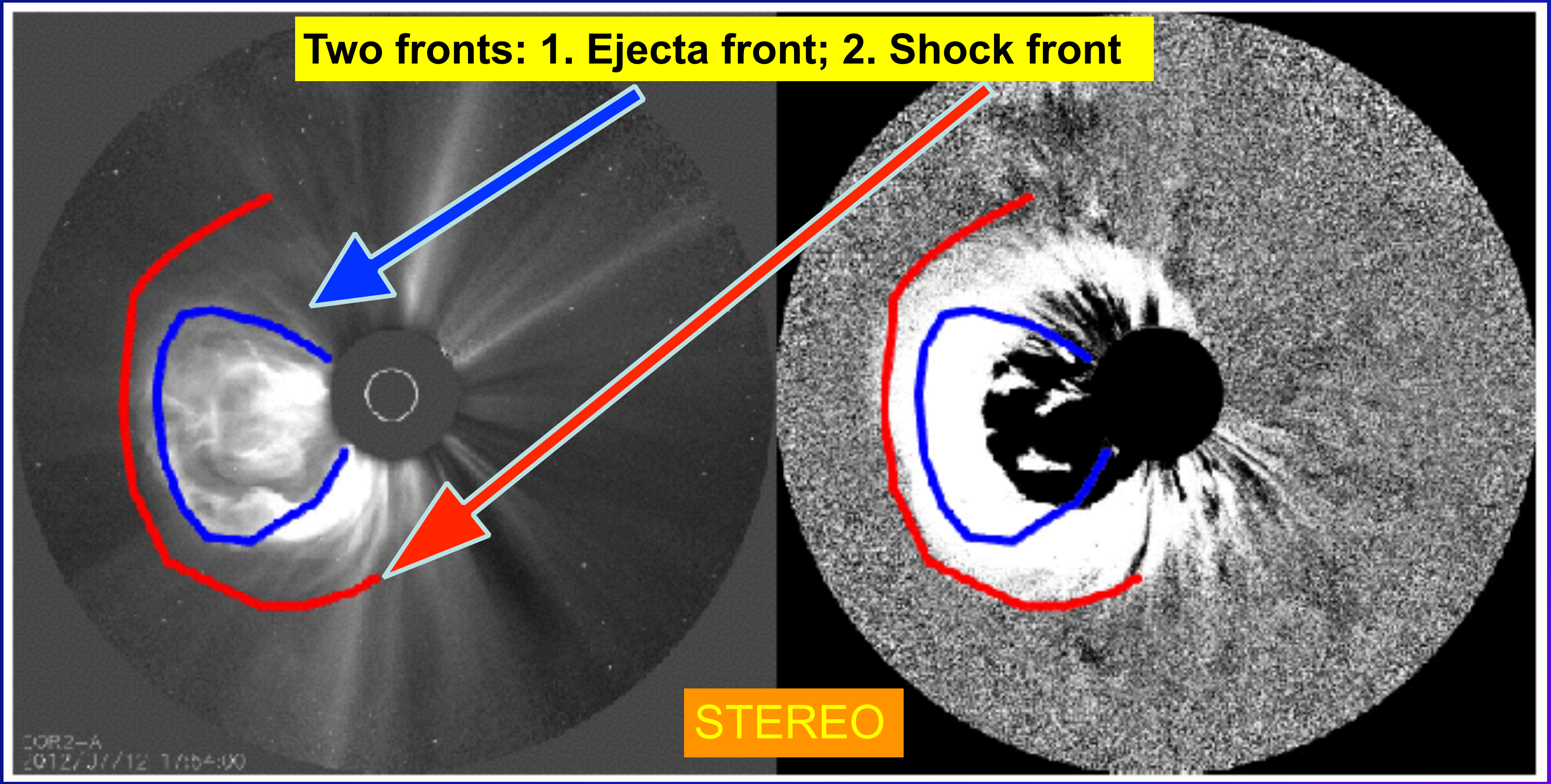
Drag force dominates later (at ~ 20 Rs)
Event: 2011/01/24





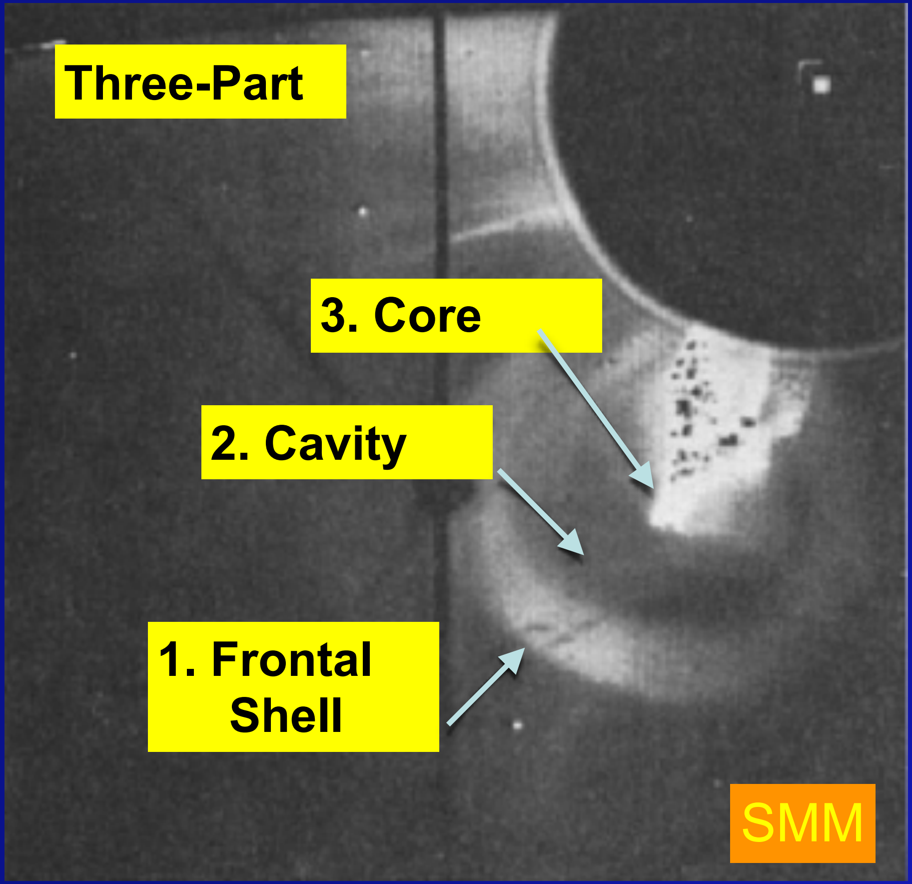
(Sachdeva et al. 2017)

Separation of Shock and Ejecta

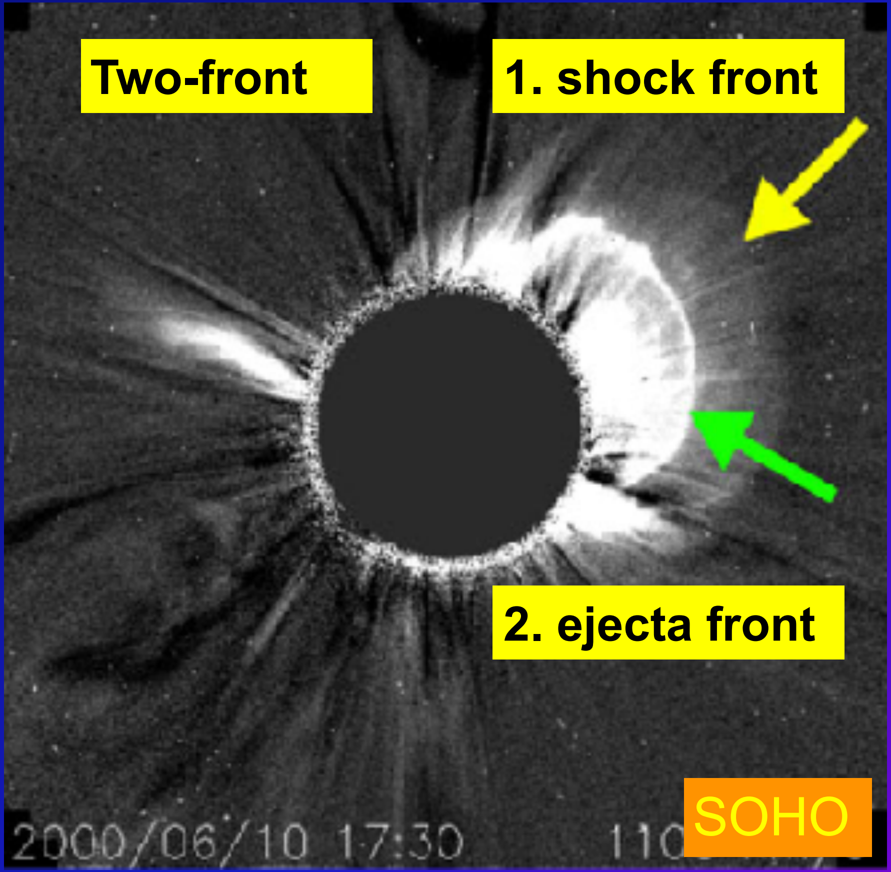


(Hess & Zhang 2014)

CME Morphology



(Illing & Hundhausen 1986)

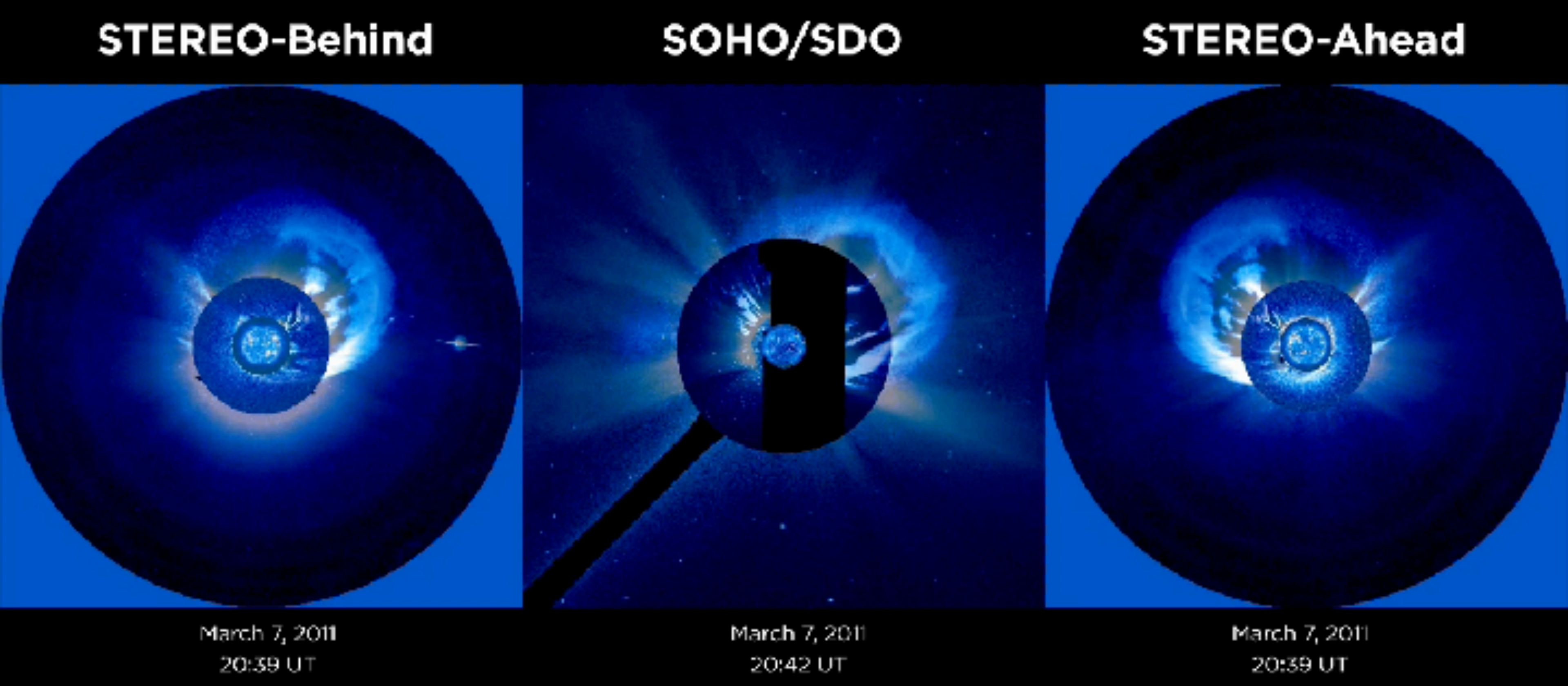


(adapted from Vourlidas et al. 2013)

Three-part structure

Two-front Three-part structure

Separation of Shock and Ejecta



(Credit: Kwong)

Phase 4: Propagation Phase

- This is the "drag phase", i.e., solar wind aerodynamic drag force dominates.
- The acceleration profile is monotonic.
- The acceleration magnitude is small (< 20 m/s²)
- The velocity is asymptotically approaching solar wind speed

(Vrsnak 2013)

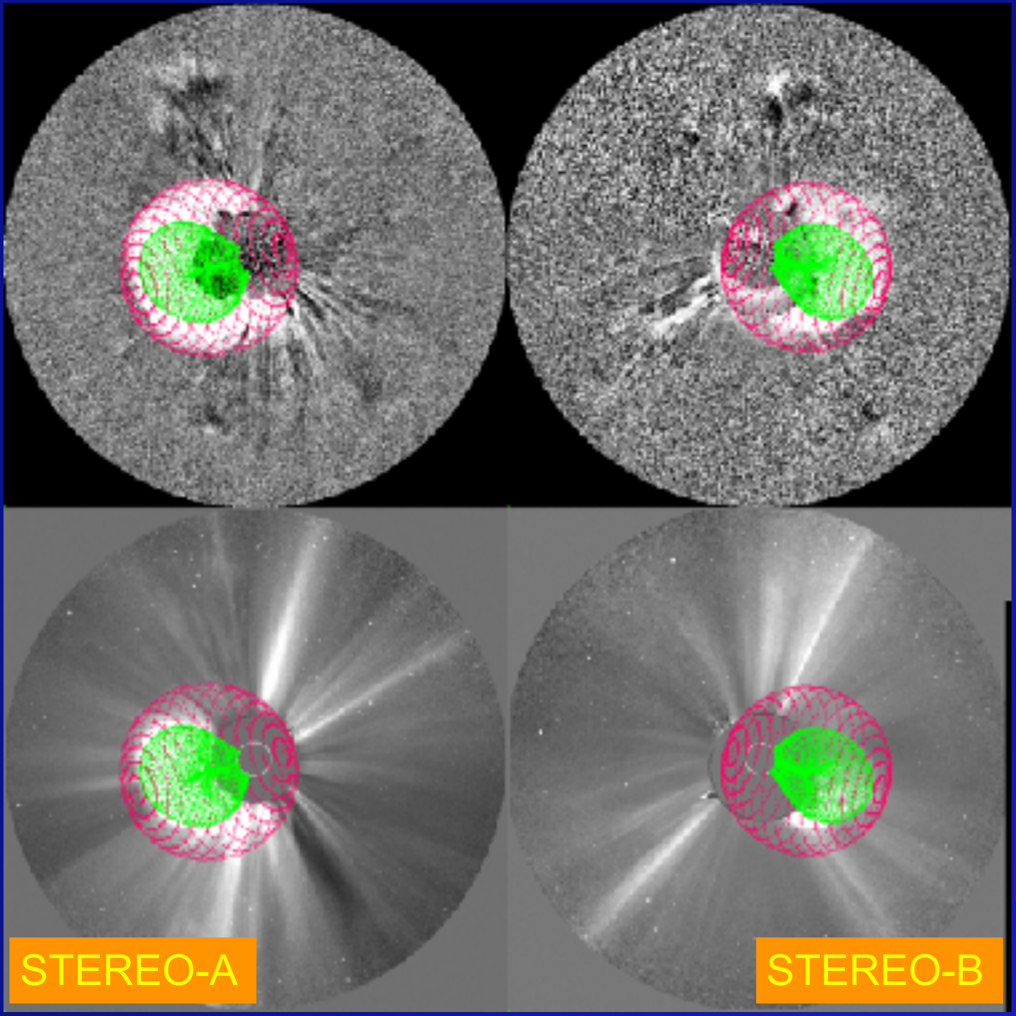
$$a(t) = -\gamma\,(V(t) - V_{sw})\left|V(t) - V_{sw}\right|$$

$$V(t) = \frac{V_0 - V_{sw}}{1 + \gamma\,(V_0 - V_{sw})t} + V_{sw}$$

$$r(t) = \frac{1}{\gamma}\ln[1 + \gamma\,(V_0 - V_{sw})t] + V_{sw}t + r_0$$

Evolution can be largely modeled by the DBM model (e.g., Vrsnak et al. 2014; Hess & Zhang 2015; Zic et al. 2015)

Phase 4: Propagation Phase



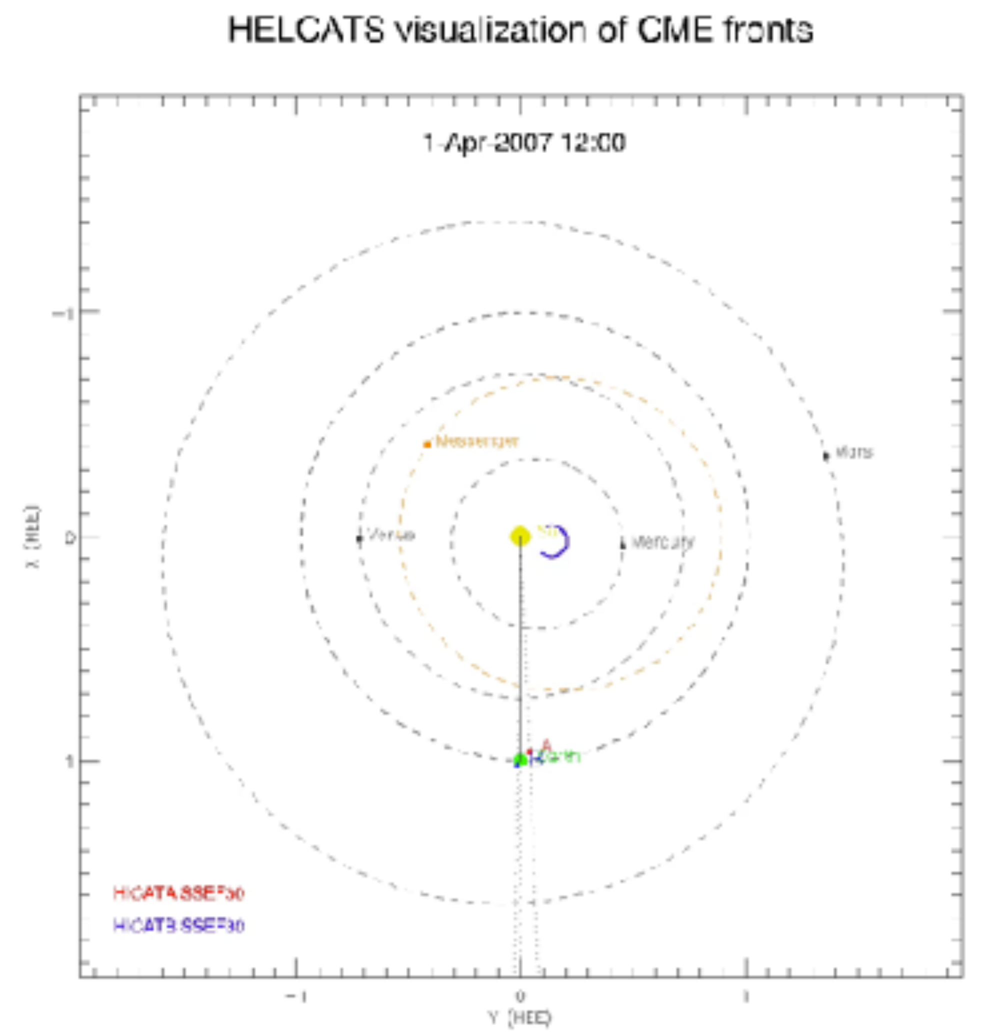
Propagation Direction

Lat: S10º
Lon: W01º

(Hess & Zhang 2014)

1. Ejecta Front: GCS model
2. Shock Front: spherical model

Phase 4: Propagation Phase


HELCATS visualization of CME fronts

Plotted CMEs extend over PAs 90/270 and SSEF was successfull. C. Moestl & P. Boakes (Graz) and Jackie Davies (RAL)

Self-similar expansion

(Credit: Mostl)

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4. Conclusions and Discussion

Predict TOA (Time of Arrival)

- Real time prediction based on beacon data: -12 hr to +12 hr for 11 April 2010 event (Davis et al. 2011)
- Real time prediction by NOAA SWPC with ENLIL+Cone model: MAE (mean absolute error) of 7.5 hr, RMS 8 hr (Millward et al. 2013)
- Prediction using GCS model and a combination of methods: MAE 8.1 hr, RMS 6.3 hr (Colaninno et al. 2013)
- J-map of HI images, constant speed: MAE 6.1 hr, RMS 5.1 hr (Mostl et al. 2014)
- ESA model using eastward CME: MAE 7.3 hrs, RMS 3.2 hr (Gopalswamy et al. 2013)
- DBM with CME speed from cone model: MAE 14.8 hrs, RMS ~14 hr; ENLIL similar errors (Vrsnak et al. 2014)

Predict TOA (Time of Arrival)

- Improved DBM model with GCS/spheroid measurement and geometry correction: MAE 1.5 hrs, RMS 0.8 hrs (Hess & Zhang 2015)
- NASA CCMC CME scoreboard of real time prediction (including 32 models): MAE10 hrs, RMS 20 hrs (Riley et al. 2018, in press)
- CCMC WAS-ENLIL+Cone model: MAE 10.4 hrs (Wold et al. 2018)

Predict TOA (Time of Arrival)

How can we achieve the mean absolute error (MAE) of only 1.5 hours? (Hess & Zhang 2015)

$$\Gamma = \frac{c_d}{\dfrac{\rho_0 \kappa R_0}{\rho_{\mathrm{sw}0}} + \dfrac{\kappa R}{2}}.$$

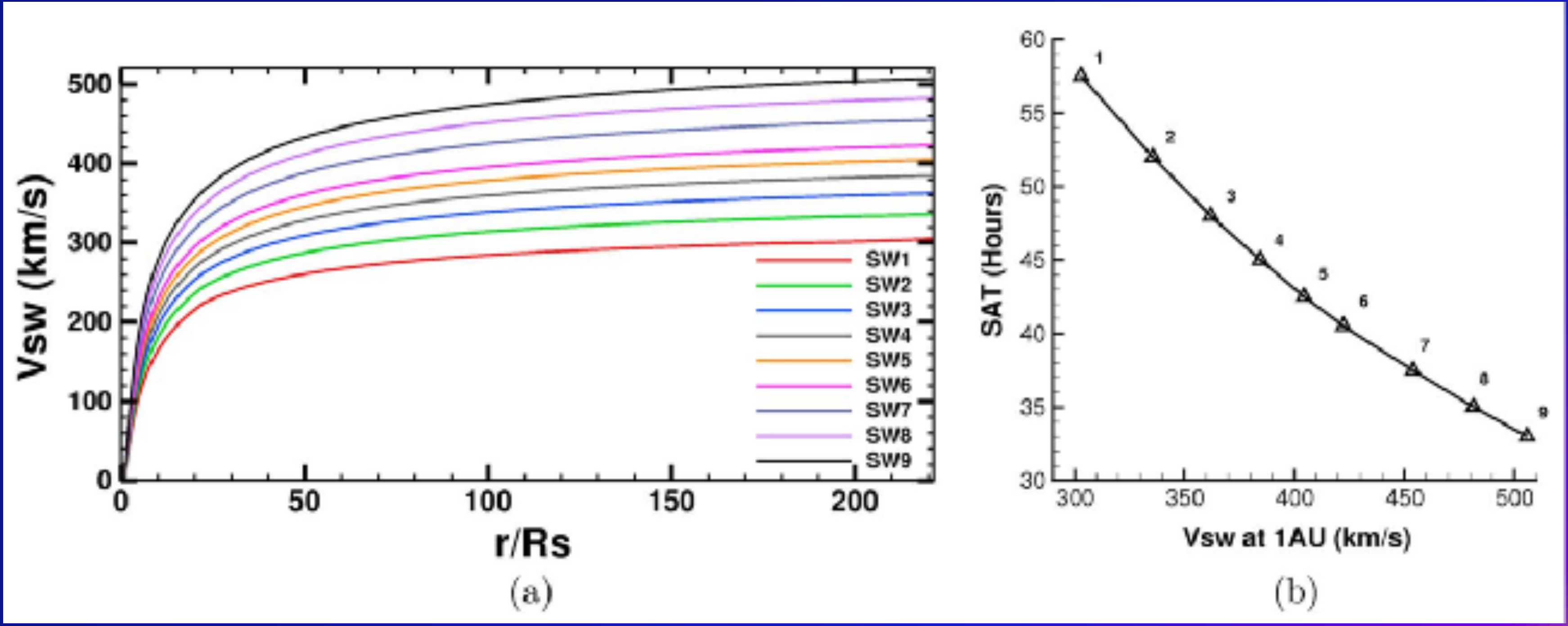
1. Separate the ejecta from the shock
2. We use an improved theory: the distance-dependent drag number in the drag-based model
3. We consider the geometric correction: the off-Sun-Earth-line angle of CME nose

Accurate prediction is possible, but need much improved stereoscopic measurement

What affects TOA prediction?

- In DBM models:
  1. Improved treatment of drag number
  2. Use true ambient solar wind speed

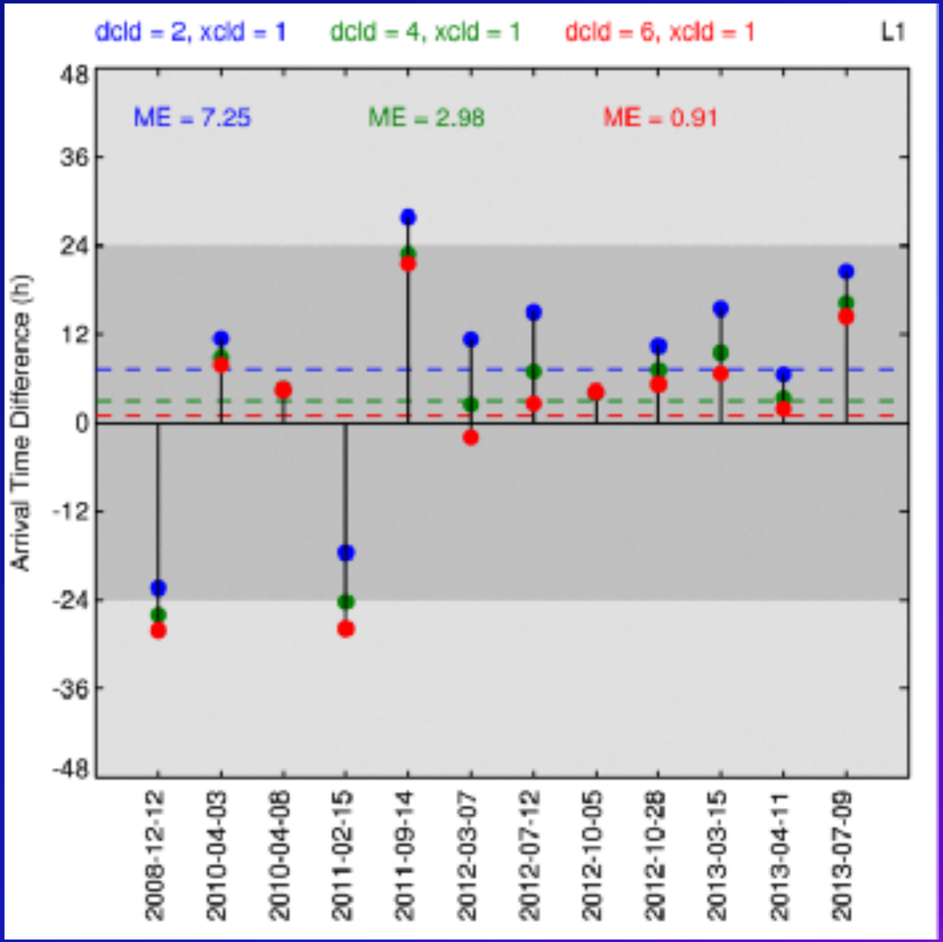
(Shen et al .2014)



Arrive time changes ~1 hr, when SW speed changes ~10 km/s,
~5 hrs, 50 km/s

What affects TOA prediction?

- In MHD models:
  1. Initial CME density, which is event dependent (may vary from 1 to 8), but not the nominal value of 4 as in current operational model
     - denser, arrive earlier
  2. Initial CME size: larger the CME angular width, the earlier the arrival time



(Credit: Odstrcil)

See poster by Odstrcil et al

Predict Hit/Miss

This is currently problematic!

- NASA CCMC WAS-ENLIL+Cone model for the period March 2010 - December 2016 (Wold et al. 2018)

Hits: 121; False Alarms: 180; Misses: 106

- Do not mix the ejecta and the shock sheath. This is important for obtaining correct propagation direction and size of the CME ejecta

Predict Geo-effectiveness

It is currently challenging, the so-called “Bz” issue

- The prediction might be possible, given that the whole Sun-Earth connection is controlled by a single magnetic flux rope
- The magnetic flux rope largely undergoes a self-similar expansion
- However, a magnetic flux rope may deflect from its original radial direction
- The axis of an erupting magnetic flux rope may rotate as it rises .
- Do not know how much magnetic flux is contained in an erupting magnetic flux rope

Refer to Group 6.

Conclusions (1)

- The global Sun-to-Earth (planets) evolution of CMEs can be divided into four phases: (1) precursor phase, (2) impulsive phase, (3) residual phase, and (4) propagation phase.

- Each phase has its unique acceleration profile, controlled by different dominant forces acting on the erupting structure.

- The global evolution is organized by a single magnetic flux rope.
-

Conclusions (2)

- Predicting TOA of CMEs has improved significantly in the last decade (MAE = 10 hrs)
- Predicting HIT/MISS of CMEs is still problematic (~ 1 out 3).
- Predicting geo-effectiveness of CMEs remains challenging (the Bz issue)

The End

Backup

“my wish list”

- Multiple-point observations from space to achieve the global 3D measurement, i.e, L1+ L4+L5 missions, or a series of missions around the eclipse
- Direct measurement of magnetic field in the corona, in addition to photospheric and chromospheric measurements

- Develop Sun-to-Earth numerical simulation with improved ambient solar wind model
- Data assimilation approach, integrating observation and simulation in real time
- Improve theoretical understanding

Correction to the drag model

- The drag number ϒ is not constant
- The drag coefficient Cd is a constant (=1.35)
- One un-constrained free parameter: initial density ratio

$$a(t) = -\gamma (V(t) - V_{sw}) \left| V(t) - V_{sw} \right|$$

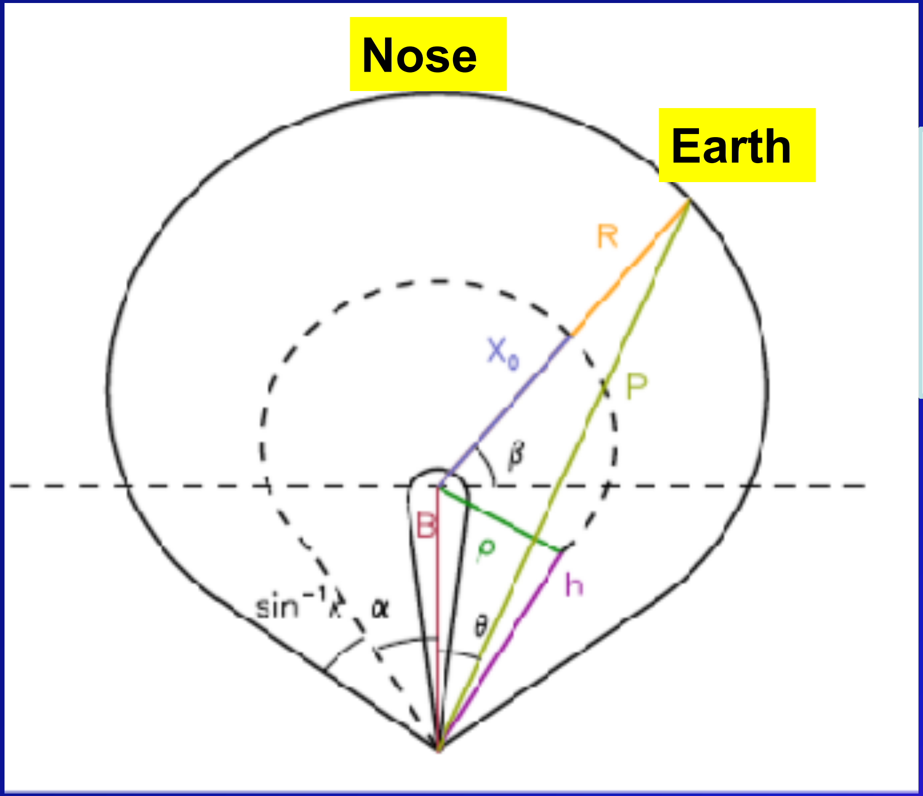
$$\gamma = \frac{C_d A \rho_{sw}}{M + M_v} = \frac{C_d}{r\left(\frac{\rho}{\rho_{sw}} + \frac{1}{2}\right)}$$

$$\text{Assuming: } \rho = \rho_0 \frac{r_0{}^3}{r^3} \; ; \rho_{sw} = \rho_{sw0} \frac{R_0{}^3}{R^3}$$

$$\gamma = \frac{C_d}{\frac{\rho_0}{\rho_{sw0}} \kappa R_0 + \frac{\kappa R}{2}}$$

Correction to the geometry

- The distances to the Sun of the nose is different from that of the interception point
- The shape of CME ejecta and shock is not exactly a GCS



$$h_{final} = 0.65 h_{nose} + 0.35 h_{Earth}$$