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Progress on Solar Activity (Flares and Coronal Mass Ejections) Prediction in Space Weather Science

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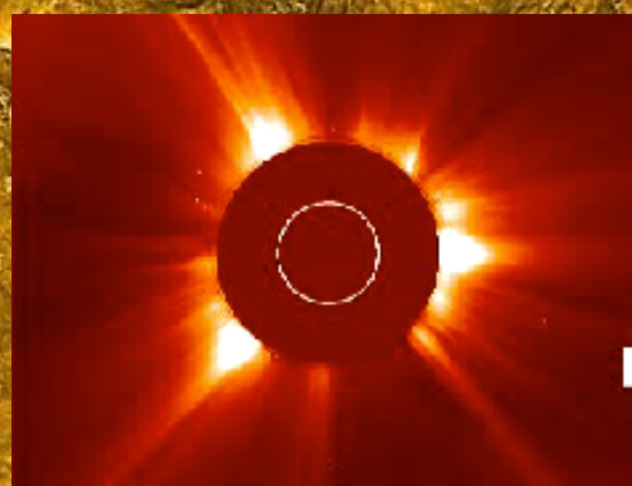

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Prediction

Our prediction capability mainly depends on the quality of observations. It also depends on improved theoretical understandings and the capability of data-driven numerical simulation

Outline

1. The prediction of Time of Arrival (TOA) of CMEs
   - ~days of prediction for geomagnetic storms
   - but not for EM radiation and solar energetic particles

2. Prediction of Solar Flare/CME Onset
   - hours of prediction for EM radiation and solar energetic particles

Predicting TOA of CMEs

If we only had flare observations (prior SOHO):
——>Uncertainty of ~30 hrs

If we only had flare and near-Sun CME observations (with SOHO):
——>Uncertainty of ~15 hrs

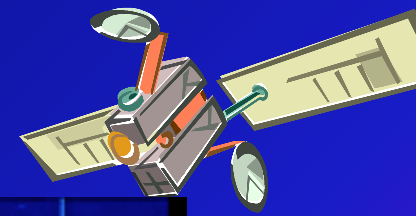
When we have two-point observations (with STEREO:
——>Uncertainty of 2-10 hrs depending on models

The Era of Global Observations

-Magnetic-Flux-Rope-

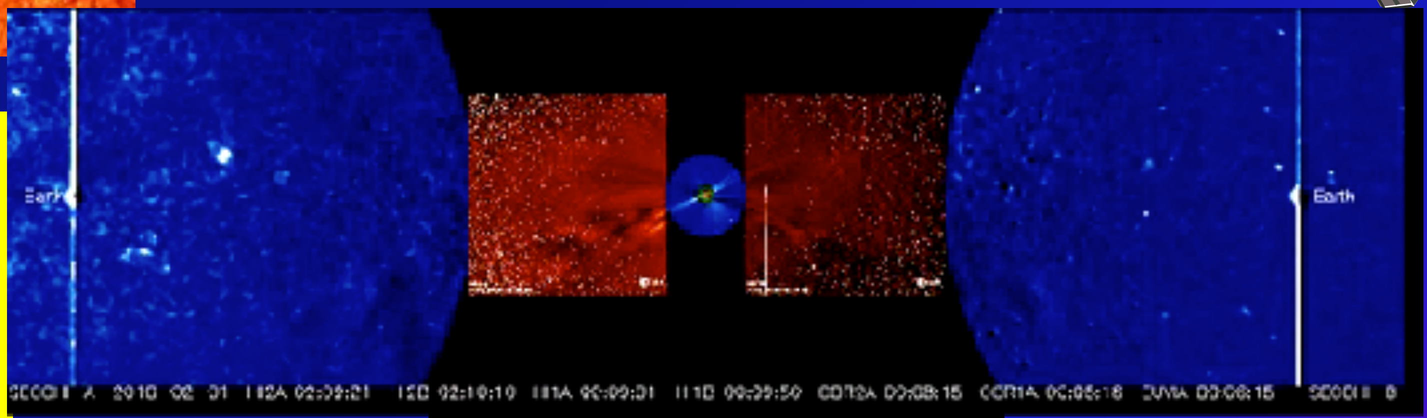
Sun | Interplanetary Space | In-situ

STEREO-A
STEREO-B



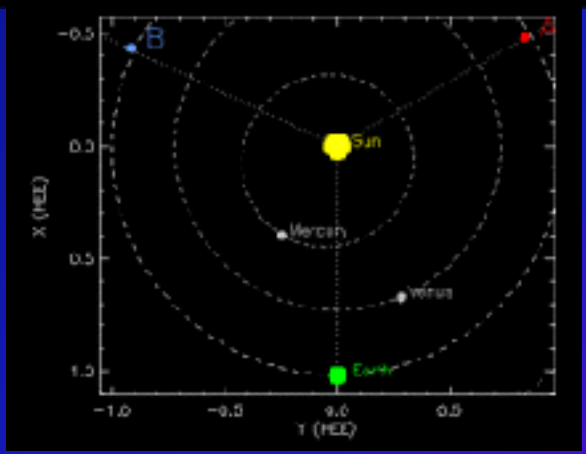
SDO
SOHO

HINODE
IRIS
…



ACE
WIND
DSCOVR

Since 2006



Predictions: the State

- 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 SWPC with ENLIL plus cone model: error 7.5 hr, RMS 8 hr (Millward et al. 2013)
- Prediction using GCS model and a combination of methods: error 8.1 hr, RMS 6.3 hr (Colaninno et al. 2013)
- J-map of HI images, constant speed: error 6.1 hr, rms 5.1 hr (Mostl et al. 2014)

- ESA model using eastward CME: error 7.3 hrs, RMS 3.2 hr (Gopalswamy et al. 2013)

- DBM with CME speed from cone model: error 14.8 hrs, RMS ~14 hr; ENLIL similar errors (Vrsnak et al. 2014)

- Improved DBM model with GCS/spheroid measurement and GCS geometry correction: error 3.5 hrs, RMS 1.5 hrs (Hess & Zhang 2015)

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	< 2 Rs	2 - 20 Rs	20 - > 220 Rs
< 100 km/s	100-3000 km/s	200 - 2500 km/s	300 - 1500 km/s
< 100 m/s^2	100 -10000` m/s^2	-100 - +100 m/s^2	-20 - +20 m/s^2
pre-cursor phase	impulsive-acceleration phase	residual-acceleration phase	drag phase

Phase 4: the drag dominates

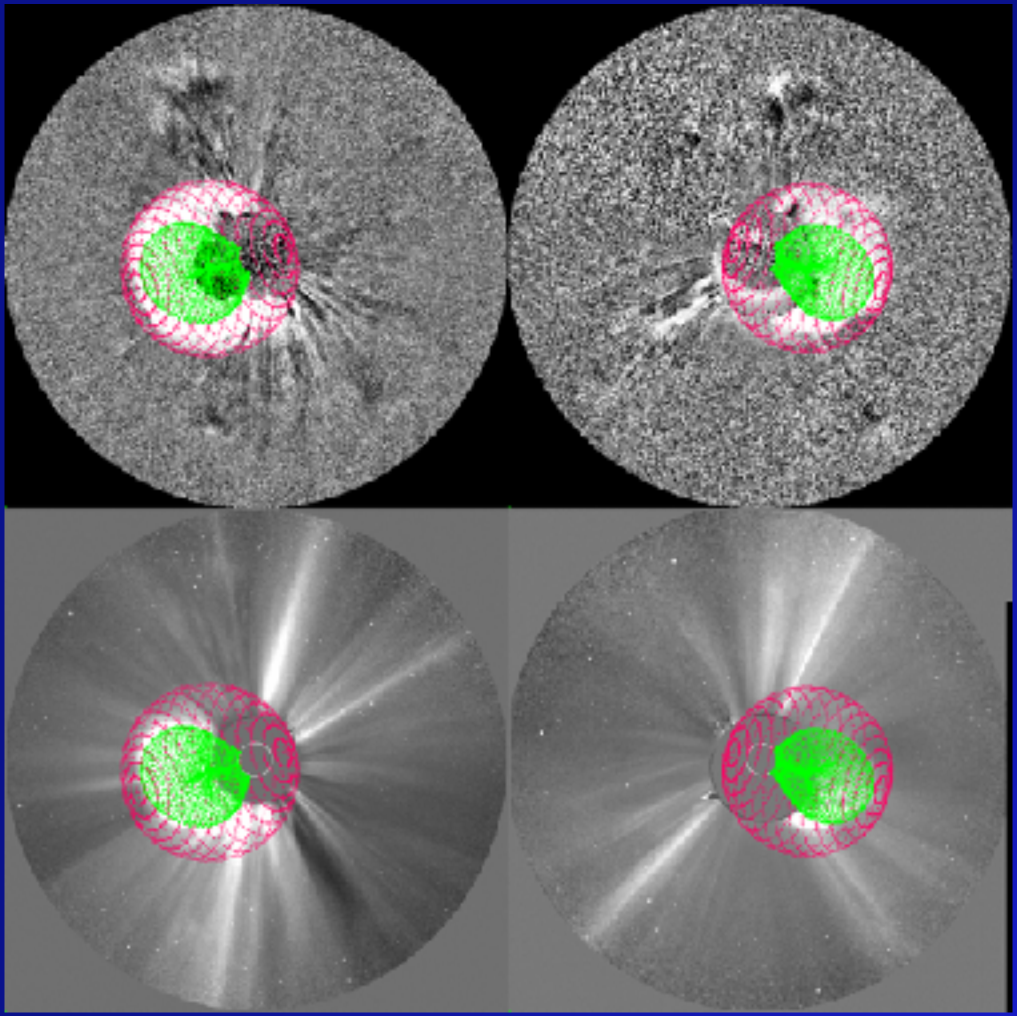
Drag-based model (Vrsnak 2001): velocity changes monotonically and will reach an asymptotic value

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

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

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

3D Measurement



Propagation Direction

Lat: S10º
Lon: W01º

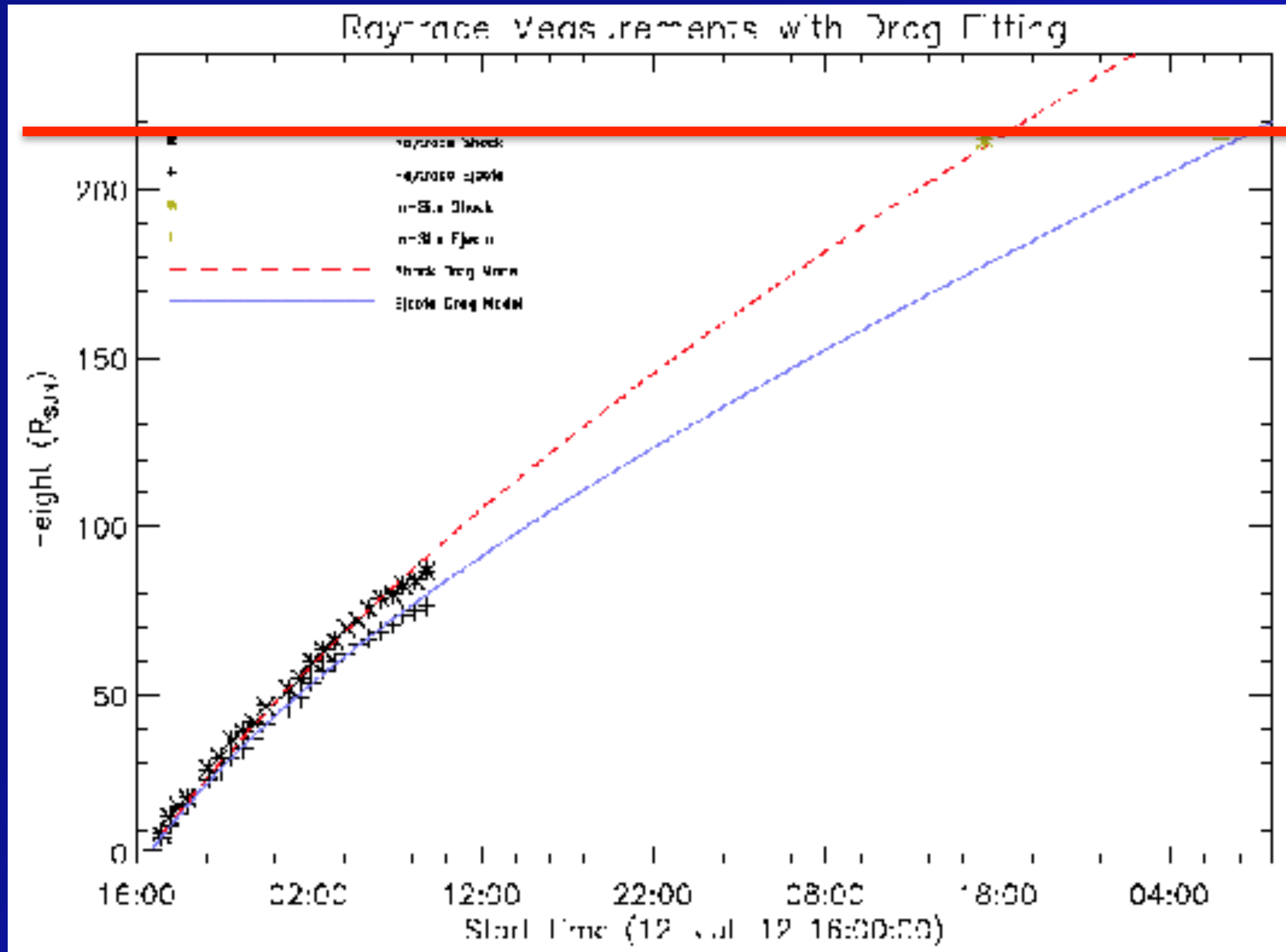
(Hess & Zhang 2014)

•Shock Front: spherical/spheroid model
•Ejecta Front: GCS model

True Height-Time: Shock and Ejecta

Event 2012/07/12

Distance



Time

- Drag model: shock front (not an optimal one) (Hess & Zhang 2014)
- Drag model: ejecta front

Events of Study

Table 1
A Summary of the Observed Characteristics for the Seven CMEs in Our Study

First Measurement[a]	SH Arrival[b]	EJ Arrival[b]	Direction[c]	Width[c]	κ^c	V_0^d	V_{sw}^e	R_0^f	R_f^f
04/03/2010 10:24	04/05 08:00	04/05 11:30	E06S26	25.0	.379	854.7	512.4	5.5	62.8
05/24/2010 14:54	05/28 02:00	05/28 07:00	E28N03	22.6	.468	605.7	362.3	4.6	45.0
09/14/2011 00:24	09/17 02:00	09/17 19:00	W20S16	24.0	.489	519.5	396.9	5.3	28.1
07/12/2012 16:54	07/14 17:00	07/15 07:15	W00S09	25.4	.370	1492.0	353.7	4.3	76.6
09/28/2012 00:24	09/30 23:00	10/01 06:00	E28N17	33.3	.327	1230.5	310.4	6.3	74.1
10/27/2012 17:24	10/31 15:00	11/01 00:00	E12N12	31.9	.407	400.1	289.8	6.2	49.0
03/15/2013 07:24	03/17 15:30	03/18 00:00	W24S07	27.1	.389	1220.2	429.3	7.4	37.0

We use (1) seven best observed events, (2) with best measurement, and (3) considering a variety of corrections, for the prediction of TOA
(Hess & Zhang 2015)

Results

Table 2
The Predictions for Each Front in Time, Velocity, and Density as Derived from the Model, Compared to In Situ Observations from ACE

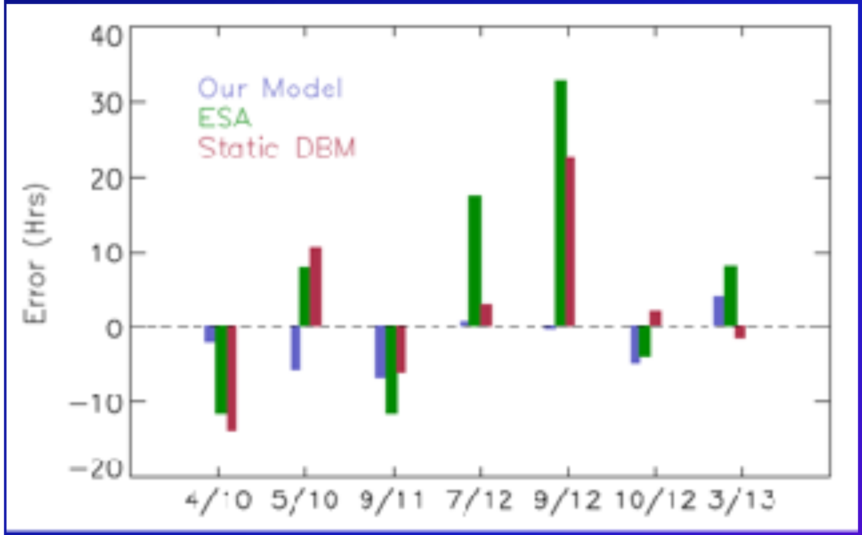
ICME Date[a]	ΔT_{SF}[b]	ΔT_{EJ}[b]	ΔV_{SF}[c]	ΔV_{EJ}[c]	$\rho_{ratio}(R(0))$[d]	$\rho_{ratio}(L1)$[d]	$\rho_{ratio}(ACE)$[e]
04/05/2010	1.89	0.38	23.3	26.4	32.17	0.91	0.41
05/24/2010	5.69	2.52	96.3	38.1	6.70	0.15	1.21
09/14/2011	6.68	4.39	15.8	13.0	3.24	0.09	0.71
07/12/2012	0.84	1.51	24.8	22.4	18.61	0.41	0.61
09/28/2012	0.34	0.9	61.6	45.6	10.31	0.31	0.97
10/27/2012	4.99	0.28	24.5	19.0	14.78	0.47	0.67
03/15/2013	3.91	0.26	22.9	7.2	5.98	0.21	0.38
Average	3.47	1.46	38.5	24.5	13.11	0.36	0.80
rms	1.58	0.76	17.9	12.9	...	...	...

- Ejecta: error 1.46 hrs, rms 0.76 hrs
- Shock Front: error 3.47 hrs, rms 1.58 hrs
- Drag coefficient is chosen as Cd = 1.35 for all events
- density ratio varies from 3 to 33

A “Fair” Comparison

Table 3
A Comparison of the Error in Hours between Our Method and the ESA and DBM Models for Each Event

ICME Date	Constrained Drag Model	ESA	Static DBM
04/05/2010	−1.89	−11.6	−14.0
05/24/2010	−5.69	7.91	10.6
09/14/2011	−6.68	−11.5	−6.00
07/12/2012	0.84	17.4	2.88
09/28/2012	−0.34	32.9	22.5
10/27/2012	−4.99	−3.70	2.11
03/15/2013	3.91	8.00	−1.45
Average	3.47	13.27	8.5
rms	1.58	6.04	4.20



TOA error
(Hess & Zhang 2015)

- **In blue: our improved DBM model (Hess & Zhang 2015)**
- **In green: Empirical Shock Arrival model (ESA) (Gopalswamy et al. 2013)**
- **In red: Static Drag-based Model (DMB) (Vrsnak et al. 2014)**

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

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

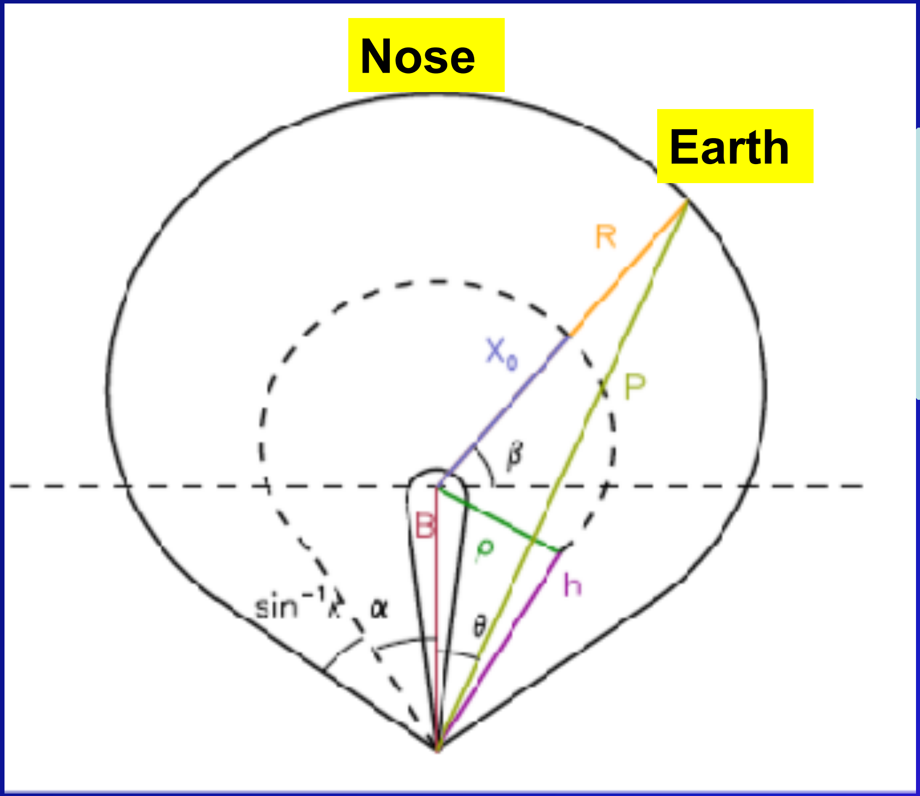
$$\gamma = \frac{C_d A \rho_{sw}}{M + M_v} = \frac{C_d}{r(\frac{\rho}{\rho_{sw}} + \frac{1}{2})}$$

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

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

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



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

Predict Flare/CME Onset

(Barnes, Leka et al. 2016, and references therein)
"For M-class flares and above, the set of methods tends towards a weakly positive skill score, with no participating method proving substantially better than climatological forecasts."

Table 4. Performance on All Data with Reference Forecast

Parameter/ Method	Statistical Method	C1.0+, 24 hr ApSS	C1.0+, 24 hr BSS	M1.0+, 12 hr ApSS	M1.0+, 12 hr BSS	M5.0+, 12 hr ApSS	M5.0+, 12 hr BSS
B_{eff}	Bayesian	0.12	0.06	0.00	0.03	0.00	0.02
ASAP	Machine	0.25	0.30	0.01	-0.01	0.00	-0.84
BBSO	Machine	0.08	0.10	0.03	0.06	0.00	-0.01
WL_{SG2}	Curve fitting	N/A	N/A	0.04	0.06	0.00	0.02
NWRA MAG 2-VAR	NPDA	0.24	0.32	0.04	0.13	0.00	0.06
$\log(\mathcal{R})$	NPDA	0.17	0.22	0.01	0.10	0.02	0.04
GCD	NPDA	0.02	0.07	0.00	0.03	0.00	0.02
NWRA MCT 2-VAR	NPDA	0.23	0.28	0.05	0.14	0.00	0.06
SMART2	CCNN	0.24	-0.12	0.01	-4.31	0.00	-11.2
Event Statistics, 10 prior	Bayesian	0.13	0.04	0.01	0.10	0.01	0.00
McIntosh	Poisson	0.15	0.07	0.00	-0.06	N/A	N/A

So, the State-of-the-Art:

- The prediction of CME Time of Arrival at the Earth has improved significantly in the last decade, thanks to STEREO observations, development in theory and numerical simulation

- The prediction of geomagnetic storm intensity of arrival CMEs remains to be poor and challenging.

- The prediction of CME/flare onset remains to be none or very poor

How to improve?

- Multiple observations from space to achieve the global 3D measurement, i.e, L3, L5 missions
- Direct measurement of magnetic field in the corona, in additional to photospheric and chromospheric measurements

- Improve theory-based empirical modeling
- Integrate Sun-to-Earth numerical simulation with improved ambient solar wind modeling
- Data assimilation approach, integrating theory, observation, and simulation in real time

The End

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: Pre-flare brightening	- 0 hr 47 min
•07/12 15:37 UT: Flare onset	0 hr
•07/12 16:49 UT: Flare peak (X1.4, S17W08, AR11520)	1 hr 12 min
•07/12 16:48 UT: CME first appearing in C2	1 hr 11 min
•07/12 18:54 UT: CME at 20 Rs	3 hr 17 min
•07/13 00:49 UT: CME at 50 Rs	9 hr 12 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

Predict Intensity of Geomagnetic Storms?

The status is very poor, It is challenging!

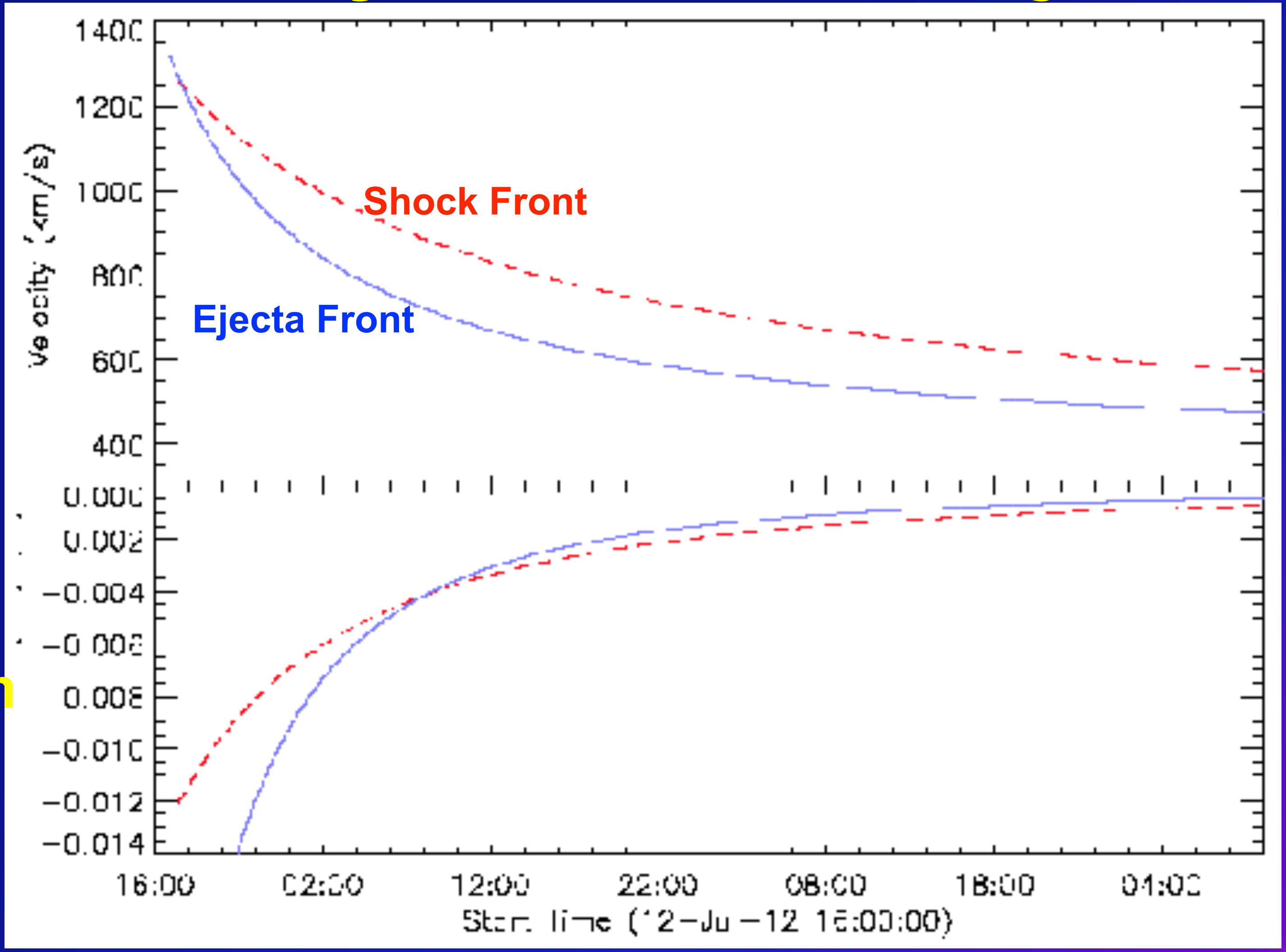
- **can not predict Bz**
- **No direct observation of coronal magnetic field**
- CME deflection near the Sun
- CME deflection in the interplanetary space
- CME interaction with CIR
- CME interaction with CME
- “stealth” CMEs, silent CMEs
- Problem ICMEs

True Velocity: Shock and Ejecta

Event 2012/07/12

Velocity

Acceleration



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