Synthetic Transits of Plasma Sheaths and Shocks: A Pathway to Predict in-situ Arrivals of Shock Waves Associated With Fast Halo CMEs

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What we did

- We developed an **analytical method** to approximate:
  1) **arrival of shocks** associated with halo CMEs, and
  2) **in-situ transit** profiles (synthetic transits) of plasma sheath
- All the method's inputs are initial data from the event, save the quotient between initial densities of CMEs and ambient solar wind.
- This is an experimental tool of SCiESMEX for space weather forecasting.

Why we did it

- Space Weather Service Mexico (SCiESMEX) is a Regional Warning Center of the International Space Environment Service (ISES). SCiESMEX closely works with mexican government agencies, centers and services like Mexican Space Agency (AEM), National Center for Prevention of Disasters (CENAPRED), National Meteorologic Service (SMN), and others.
- We require to provide and share data and services with our partners and costumers. The method that we present in this talk is one of our experimental tools for space weather forecasting.
- We need as many tools as possible to study solar phenomena and for space weather forecasting. The yours are welcome also.
- Analytical tools are: easy to implement, **OPEN & FREE**.

How we did it

Walk through:

- Farris & Russell [1994]. → Present the full -general- polytropic jump conditions for plasmas.
- Canto et.al. [2005] → Work surface (WS) analytical model: interacting parcels of fluid for studying ICME accelerations.
- Corona-Romero & Gonzalez-Esparza [2011] → Compare WS model with hydrodynamic simulations. They develop the “Piston-Shock” model by incorporating the effects of forward shock and find the way to use it to approximate CMEs propagation departing from measured data. Solution of shock shows geometrical issues.
- Corona-Romero & Gonzalez-Esparza [2012] → We address the geometrical issues and now the Piston-Shock model simultaneously approximates CME and shock propagation as well their in-situ arrivals.
- Corona-Romero, et.al. [2013] → Piston-shock model simultaneously approximates arrivals and trajectories of both CMEs and shocks, as well type II radio bursts.
- **Corona-Romero et.al. [in revision] → Piston-shock and polytropic jump conditions to calculate in-situ synthetic transits of shocks and plasma sheaths.**

How we did it

- We use data from coronagraph images (SOHO Catalog) and in-situ registers (OmniWeb Plus). The first as initial conditions of CMEs and the last for boundary conditions of solar wind. We also require the X-ray profile associated to the solar flare (GOES-15).
- We calculate the in-situ arrivals of CMEs and associated shocks (TT and AS) using the model and the commented data as model's inputs.
- We forced the model to match the TT of CMEs by selecting the quotient between initial densities of CMEs and solar wind. **This was our only free paramter.**
- We use the solar wind data and calculated AS of shocks to approximate the synthetic transit of plasma sheath by the polytropic jump conditions.
- The plasma sheath material is enclosed by the shock's front -arrival- and CME's leading edge -arrival-.

Our analysis

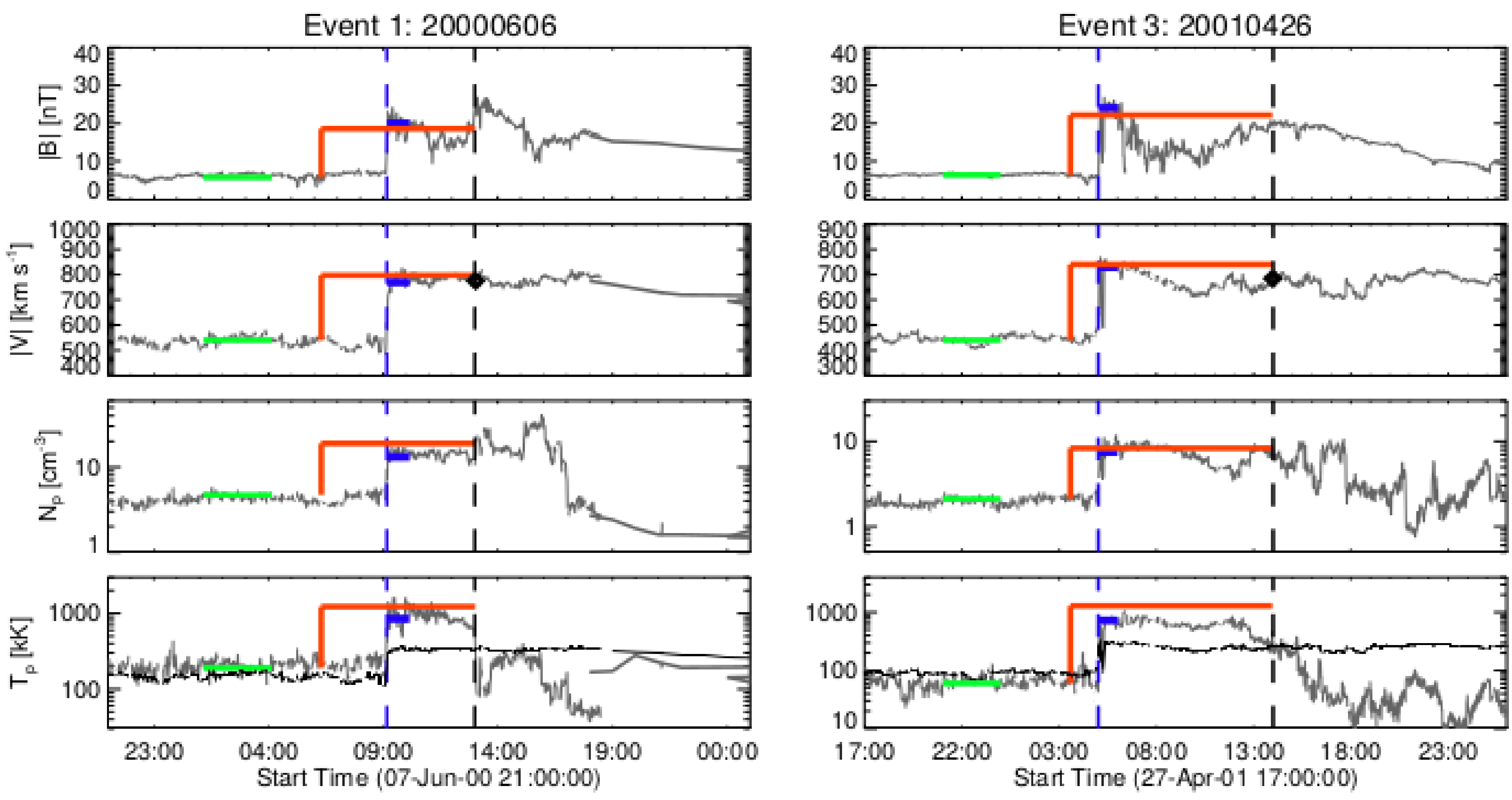
- We analyzed 9 fast (V_{cme0}>800km/s) -Earth directed- not stealth ;) halo-CMEs.

Table 1: Case events. From left to right: event number; CME detection date and hour; CME-solar wind initial density ratio (c); initial position and speed of CME; solar wind bulk speed, density, temperature, and magnetic field magnitude at 1 AU; associated-flare rising time, flare class, flare location and active region, and the angle between the flare location and the Sun-Earth line.

Event		CME[a]			SW[b]				Flare[c]		
#	Date-hour[a] [UT]	c	r_{cme0} $[R_\odot]$	v_{cme0} $[km\ s^{-1}]$	$^\ddagger v_{sw1}$ $[km\ s^{-1}]$	n_{sw1} $[cm^{-3}]$	T_{sw1} $[kK]$	B_{sw1} $[nT]$	$^d\Delta t_f$ $[h]$	Class/Location/AR	$\alpha_\oplus$ $[^\circ]$
1	20000606-15:54	14.20	3.98	1119	540	4.7	190	5.7	0.42	M7.1/N21E10/09026	23.2
2	20000714-10:54	8.55	5.21	1674	700	3.5	120	9.0	0.38	X5.7/N22W07/09077	23.0
3	20010426-12:30	3.80	4.83	1006	440	2.1	60	6.3	1.50	C6.8/N20W05/09433	20.6
4	20011104-16:35	8.22	4.41	1810	415	15.0	30	17.0	0.33	X1.0/N06W18/09684	18.9
5	20011122-23:30	6.05	4.77	1437	450	4.2	160	7.0	0.79	X1.0/S15W34/09704	36.8
6	20031028-11:30	15.60	5.84	2459	650	1.7	500	10.0	0.24	X17.0/S16E08/10486	17.8
7	20050513-17:12	8.95	4.60	1689	410	3.5	100	5.0	0.45	M8.0/N12E05/10759	13.0
8	20061213-02:54	1.76	5.31	1774	560	1.3	155	4.0	0.42	X3.4/S06W23/10930	23.7
9	20120712-16:48	10.10	2.85	885	320	4.5	50	4.5	0.80	X1.4/S15W01/11520	15.0

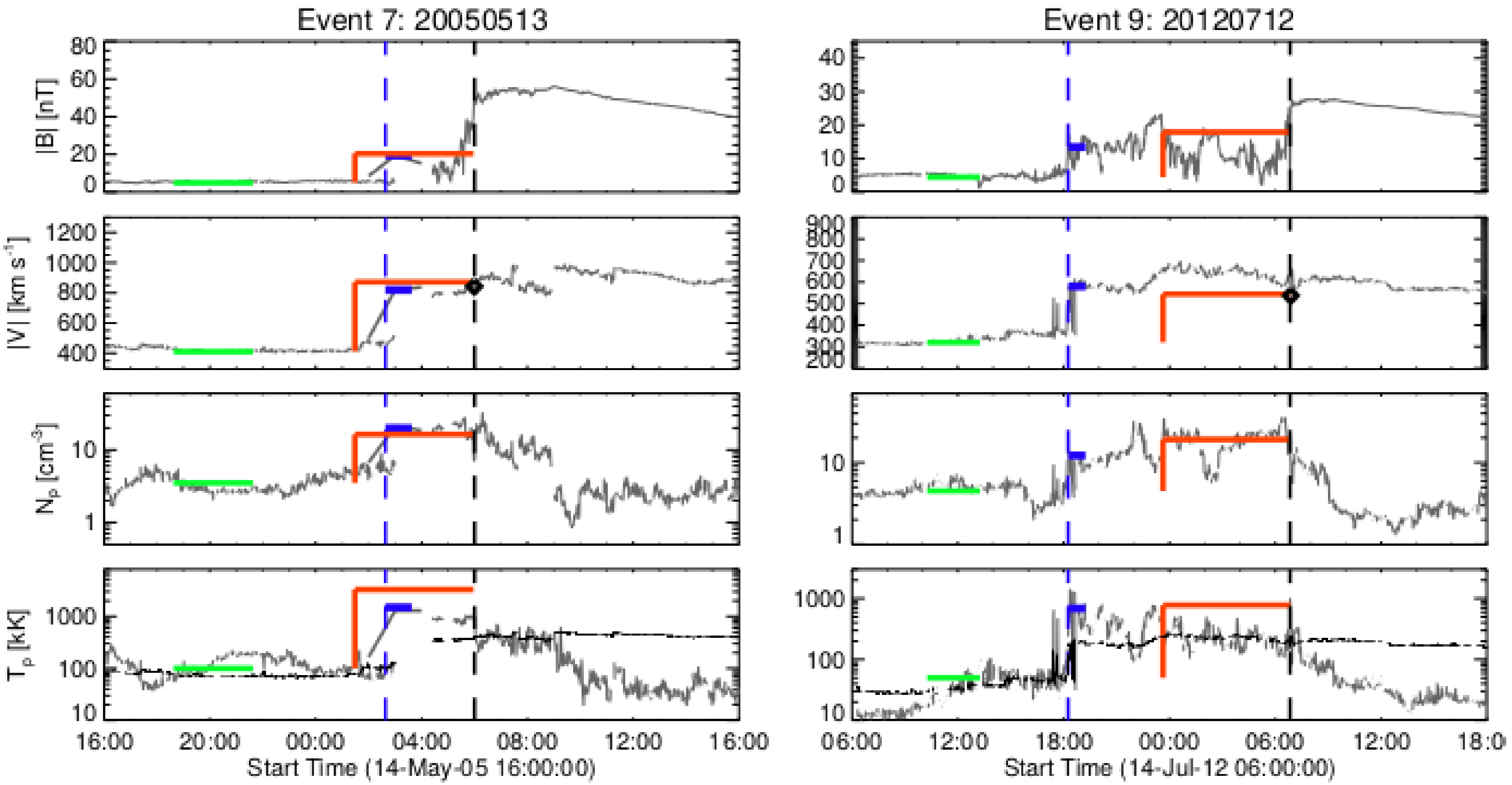
[a] LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/halo/halo.html).
[b] Detected *in-situ* (http://omniweb.gsfc.nasa.gov/).
[c] From NOAA catalog (http://www.solarmonitor.org/).
[d] GOES registers (http://www.swpc.noaa.gov/Data/goes.html).

Our results



Event 1: 20000606
Event 3: 20010426
|B| [nT]
|V| [km s^-1]
N_p [cm^-3]
T_p [kK]
23:00 04:00 09:00 14:00 19:00 00:00
Start Time (07-Jun-00 21:00:00)
17:00 22:00 03:00 08:00 13:00 18:00 23:00
Start Time (27-Apr-01 17:00:00)

Our results



Event 7: 20050513
Event 9: 20120712
|B| [nT]
|V| [km s⁻¹]
N_p [cm⁻³]
T_p [kK]
Start Time (14-May-05 16:00:00)
Start Time (14-Jul-12 06:00:00)

Our results

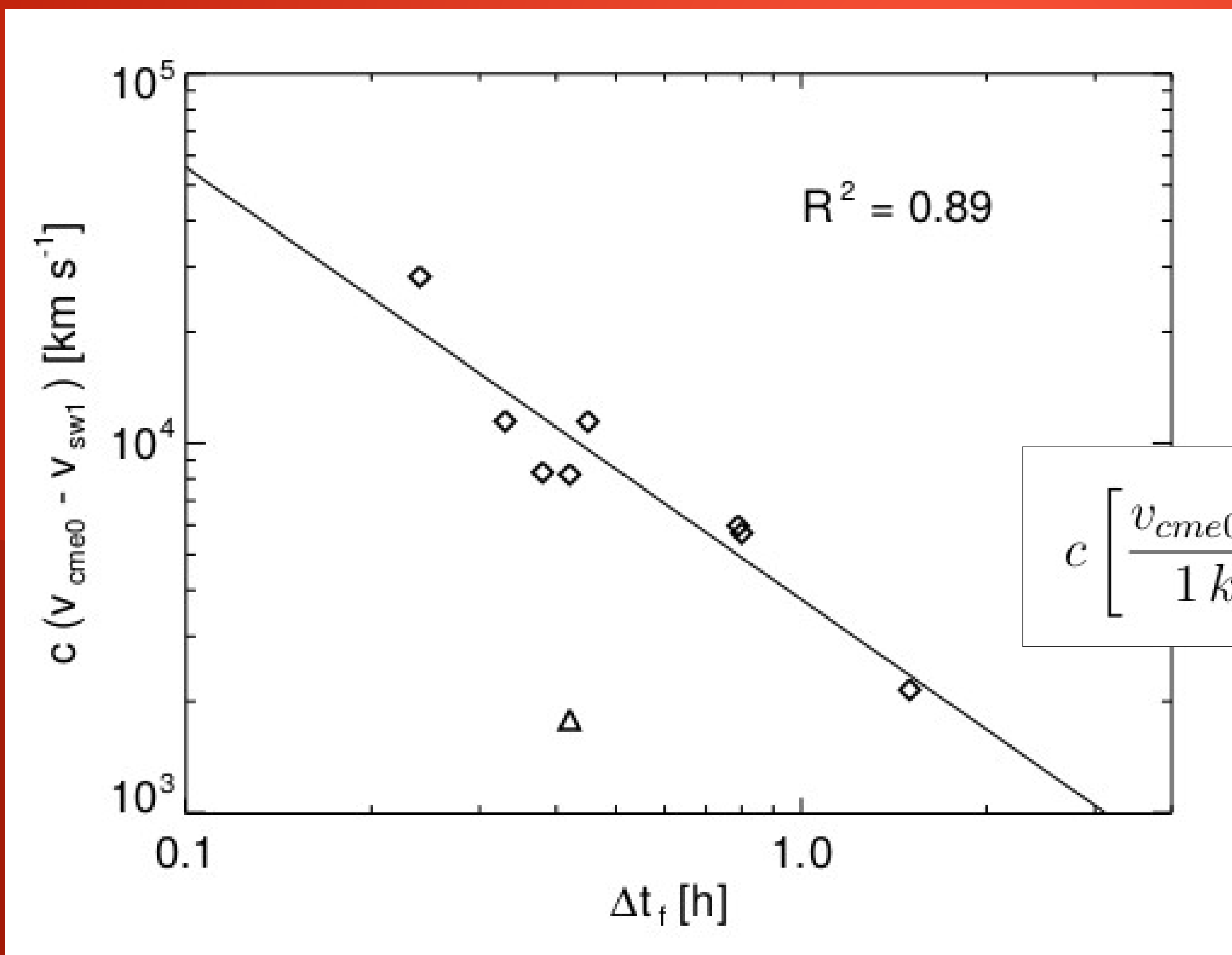
Table 2: Comparison between our results and data. From left to right: event number; arrival speed and transit time of shocks; ICME arrival speed; plasma sheath values of magnetic field intensity, speed, density and temperature of protons; and DST-index minimum associated with the event's transit.

	Calculations / In-situ Measurements[a]							
	Shock and ICME			Plasma Sheath				DST[f]
Event	v_{sh1} $[km\ s^{-1}]$	TT_{sh} $[h]$	v_{cme1} $[km\ s^{-1}]$	$\|B\|$ $[nT]$	$\|V\|$ $[km\ s^{-1}]$	N_p $[cm^{-3}]$	T_p $[kK]$	[nT]
1	883/871	38.4/41.3	776/770	18.6/20.0	798/770	18.9/13.1	1223/850	-90
2	1308/1120	24.8/27.1	1053/1000	29.4/26.0	1175/950	15.9/18.5	3444/1400	-301
3	840/812	39.1/40.5	685/730	22.2/24.0	741/730	8.3/7.5	1286/730	-47
4	1034/[b]1256	30.5/33.4	798/[b]1060	67.9/60.0	898/[c]	67.9/60.0	3377/[c]	-292
5	983/1008	33.5/30.5	835/720	26.6/40.0	863/920	18.6/23.0	2700/2000	-221
6	1596/[d]2162	19.7/18.7	1373/1600	33.0/28.0	1384/[e]1600	7.5/[c]	8477/[e]10000	-353
7	996/942	32.3/33.4	842/950	20.5/19.5	871/820	16.4/20.0	3288/1500	-247
8	1103/1005	29.3/35.3	785/900	14.2/12.0	983/890	5.9/5.9	2830/900	-162
9	613/688	54.8/49.5	538/620	17.9/13.5	544/580	19.1/12.2	778/690	-127
Diff.[g] [%]	10.5	8.2	11.6	16.5	10.7	23.2	82.8	

[a] Detected *in-situ* (`http://omniweb.gsfc.nasa.gov/`).
[b] Transit speed, due to data gap ($v_{sh1/cme1} = (1AU - r_{cme0})/TT_{sh/cme}$).
[c] No available due to data gap.
[d] Calculated through velocity coplanarity, velocity magnitude only.
[e] Values reported by Skoug et al. (2004).
[f] Kyoto Dst index service (`http://wdc.kugi.kyoto-u.ac.jp/dstdir/`).
[g] Average absolute difference between results and data.

Pathway for prediction?

- Piston-Shock model has one free parameter related with initial density of CMEs. This parameter might guard a relation with input data. If this probe to be true, we could estimate the free parameter from the very beginning of the event. This would lead to a forecasting process.



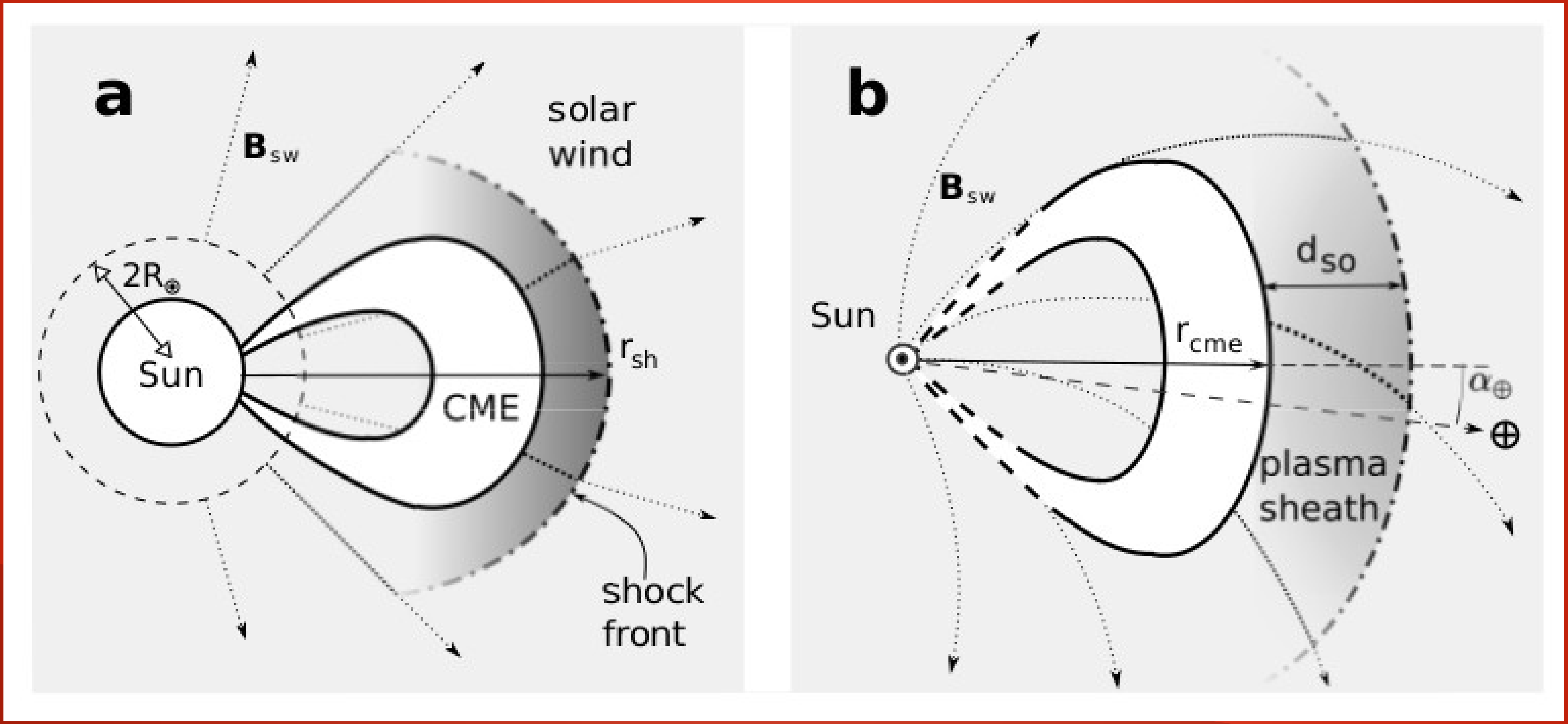
$$c\left[\frac{v_{cme0}-v_{sw1}}{1\,kms^{-1}}\right] = 3776.04\left[\frac{\Delta t_f}{1\,h}\right]^{-1.17}$$

Our conclusions

- We present a **method to estimate in-situ synthetic transits** of shocks/plasma sheaths.
- The method is **a collage of works** already present in literature (polytropic jump conditions for plasmas and Piston-Shock model).
- The method **requires a number of inputs related with initial conditions** of CMEs, solar wind and associated solar flare.
- The results are **highly sensitive to inputs**. Thus it is more suitable for quiet periods of solar activity.
- Calculated synthetic profiles of magnetic fields and speeds of plasma sheaths showed, in average, consistencies of about 83% and 89%, respectively. Those variables are of main interest for space weather purposes.
- We found **a possible way to use the method for forecasting** applications.
- We require **further estudies to confirm/reject the relation** between our free parameter and initial inputs.

Thank you!!!

Sketch of the system



Our Equations - CME

$$TT_{cme} = a^2 c \Delta t_f + \frac{1\mathrm{AU} - r_{cme0}}{v_{sw1}} - \sqrt{2ac\Delta t_f (a-1)\left[\frac{1\mathrm{AU} - r_{cme0}}{v_{sw1}}\right] + a^2 c (a^2 c - 1) \Delta {t_f}^2}$$

$$a = \frac{v_{cme0}}{v_{sw1}} + \frac{1}{\sqrt{c}}\left(\frac{v_{cme0}}{v_{sw1}} - 1\right), \quad \tau_{c1} = \frac{a\,(1+\sqrt{c})}{a-1}\,\Delta t_f \,.$$

$$v_{cme1} = v_{sw1}\left(1 + (a-1)\sqrt{ac}\,\Delta t_f \times \left[2(a-1)\,\Delta t_f\, TT_{cme} - a(1-c)\Delta t_f^2\right]^{-1/2}\right),$$

Our Equations - Shock

$$TT_{sh}^3 + (3B + A^3)TT_{sh}^2 + 3B^2TT_{sh} + B^3 = 0 \ ,$$

$$A = \frac{3(v_{cme0} - v_{sw1})}{2v_{sw1}}\tau^{1/3}$$

$$B = \frac{2r_{cme0} + 2d_{so} - 2\text{AU} - (v_{cme0} - v_{sw1})\tau_{c2}}{2v_{sw1}} \ .$$

$$v_{sh1} = (v_{cme0} - v_{sw1})\left(\frac{TT_{sh}}{\tau_{c2}}\right)^{-1/3} + v_{sw1} \ . \qquad \tau_{c2} = \frac{d_{so}}{\sqrt{c_A^2\left(\frac{B_*^2}{n_*}\right) + c_S^2\left(\frac{p_*}{n_*}\right)}} + \tau_{c1}$$

$$\frac{d_{so}}{1\ \text{AU}} = 0.264\left[\frac{(\gamma_{sw} - 1)\,M_1^2 + 2}{(\gamma_{sw} + 1)\,(M_1^2 - 1)}\right] \times \left(\frac{\tau_{c1}v_{cme0} + r_{cme0}}{1\ \text{AU}}\right)^{0.78} \ .$$

Our Equations – Plasma Sheath

$$
\begin{aligned}
N_p &= n_{sw1} n_* \,, \\
T_p &= T_{sw1} \frac{p_*}{n_*} \,, \\
V^r &= v_{sh1} \left(1 - \frac{1}{n_*} \right) + \frac{1}{n_*} v_{sw1} \,, \\
B^r &= B_{sw1} \cos(\theta_{Bv}) \,, \\
B^t &= B_{sw1} \sin(\theta_{Bv}) B_* \,, \\
V^t &= B^r \left[\frac{(B_* - 1) B_{sw1} \sin(\theta_{Bv})}{\mu_0 m_p n_{sw1} \left(v_{sh1} - v_{sw1} \right)} \right] \\
|V| &= \sqrt{(V^r)^2 + (V^t)^2} \,, \\
|B| &= \sqrt{(B^r)^2 + (B^t)^2} \,.
\end{aligned}
$$

More results