Royal Observatory of Belgium

Propagation, in-situ signatures and geoeffectiveness of consecutive solar eruptions simulated in different solar wind conditions

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Numerical code and initial conditions

- MHD code: MPI-AMRVAC (parallelized Adaptive Mesh Refinement Versatile Advection Code)
- 3 grid levels

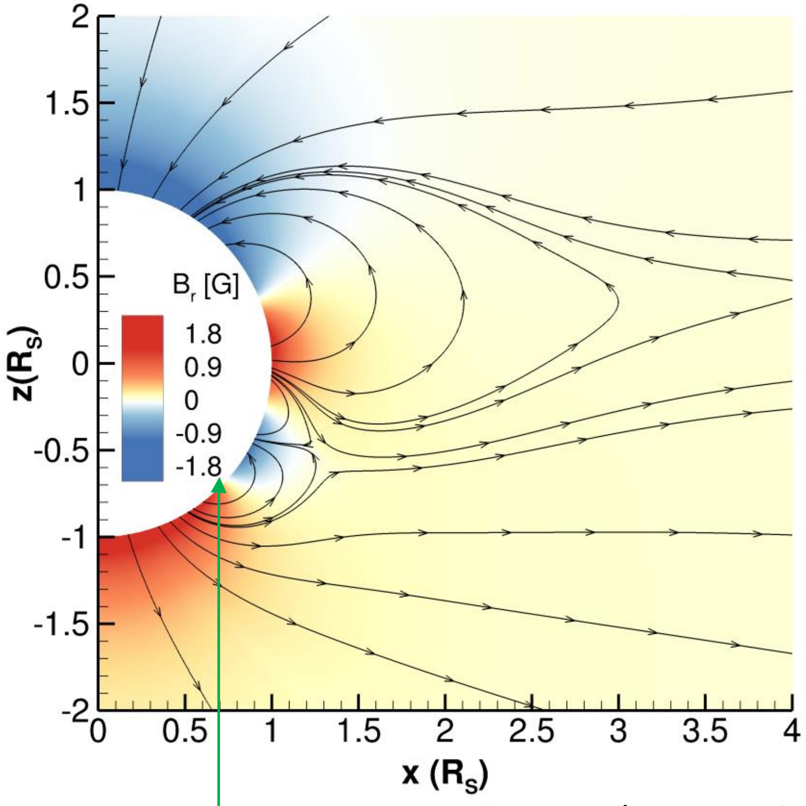
- Domain specs:
  - 2.5D (axisymmetric)
  - spherical
  - non-equidistant (stretched grid)
  - $(r,\theta) \in [1\ R_\odot, 322\ R_\odot] \times [0,\pi]$

- CME triggering:
  - Symmetric shearing motions with respect to the southernmost polarity inversion line

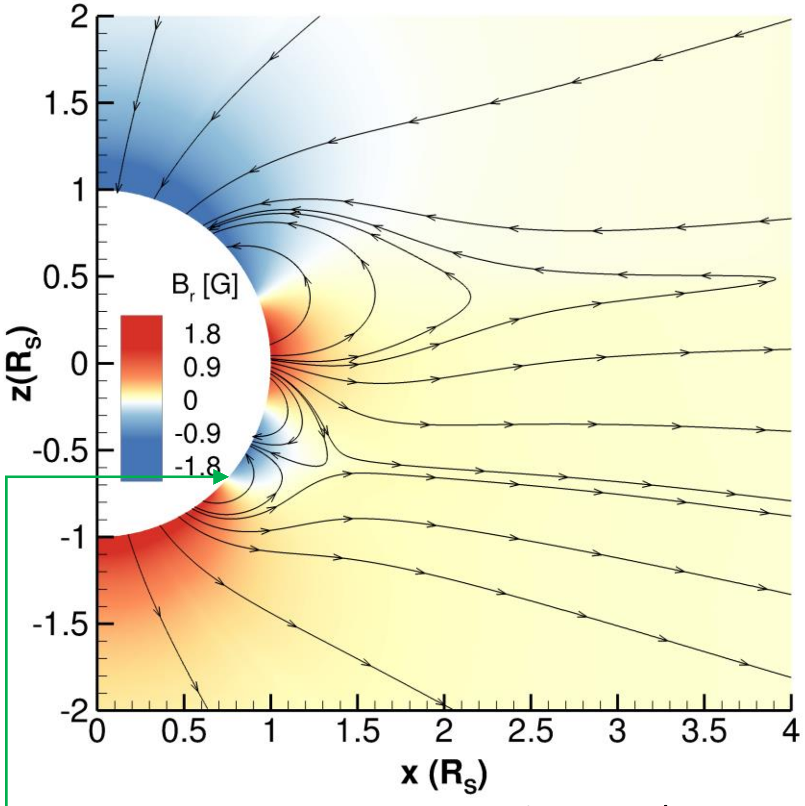
$$v_\phi = v_0(\alpha^2 - \Delta\theta^2)^2 \sin\alpha \sin\frac{\pi(t-t_0)}{\Delta t},$$

$$\alpha = \frac{\pi}{2} - \theta_0 - \theta,$$
$$\theta = colatitude$$
$$\theta_0 = latitude\ of\ the\ PIL$$

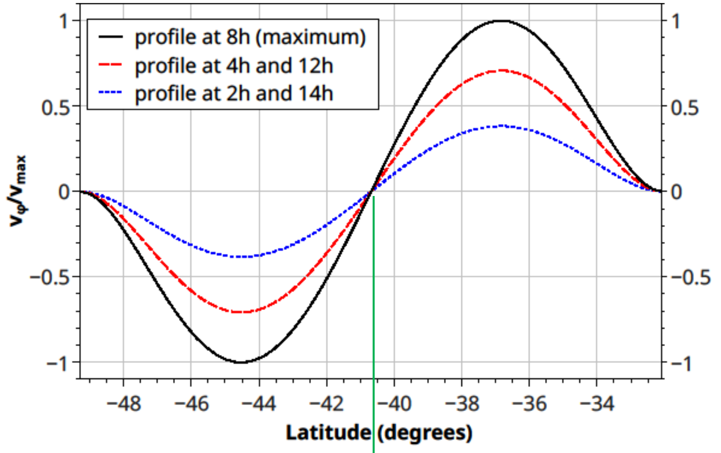
$$\Delta t = 16\text{h};\ t_0 = 0\text{h}$$



Slow wind case (330 km/s at Earth)

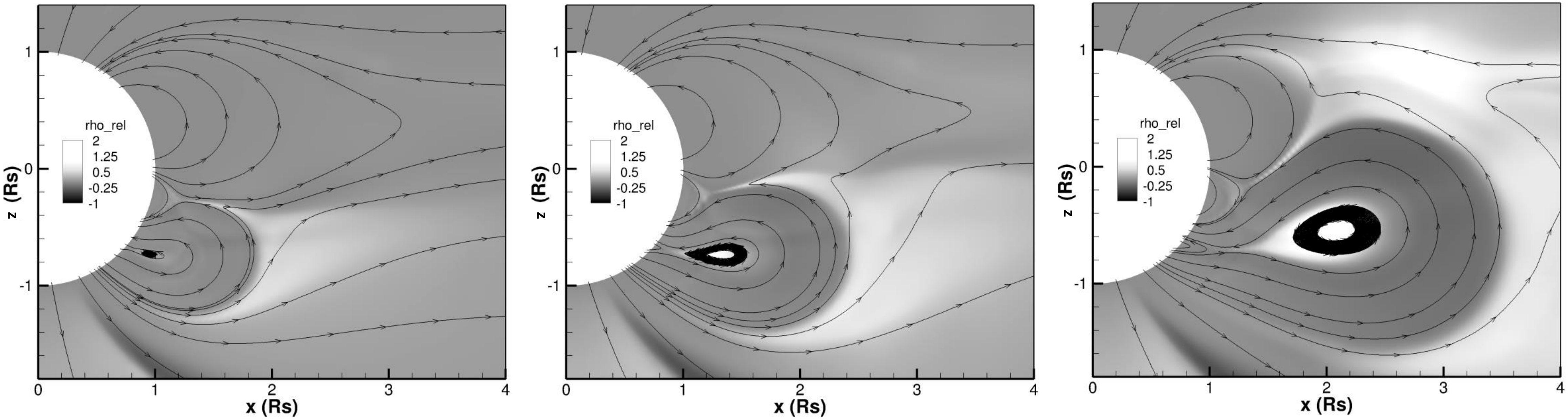


Faster solar wind case (380 km/s at Earth)



Simulations results

Type of solar wind	Eruption name	Eruption trigger	$\lvert v_\phi \rvert^{max}$ at $t=\Delta t/2$	Blobs occurrence
Slow wind	Single er.	shear	21.9 km/s	Trailing plasma blobs are present
	Er. + stealth	shear + coronal mag. field reconfiguration	37 km/s	
	Double er.	2 FR from shear	37.4 km/s	
Faster wind	Single er.	shear	22.3 km/s	NO trailing plasma blobs
	Stealth speed	2 FR from shear	36.8 km/s	



Simulated relative density ($\rho_{rel} = \frac{\rho-\rho_0}{\rho_0}$) and selected magnetic field lines showing the formation process and equatorial deflection of the first flux rope for all simulations.

Comparison with the observed event on 21-22 Sep 2009

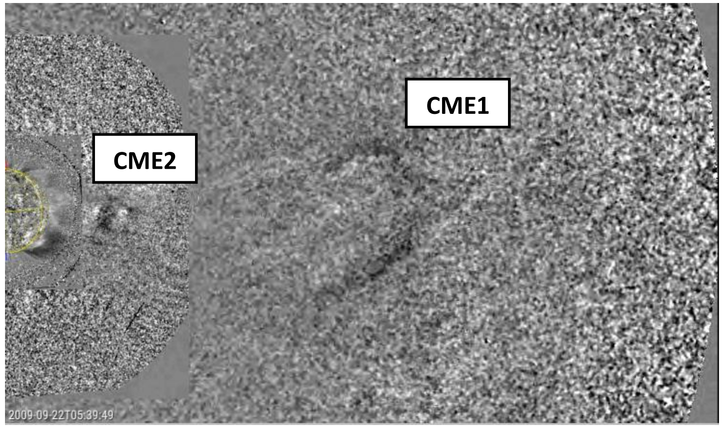
All Δt from 21:00 UT, 21-09-2009

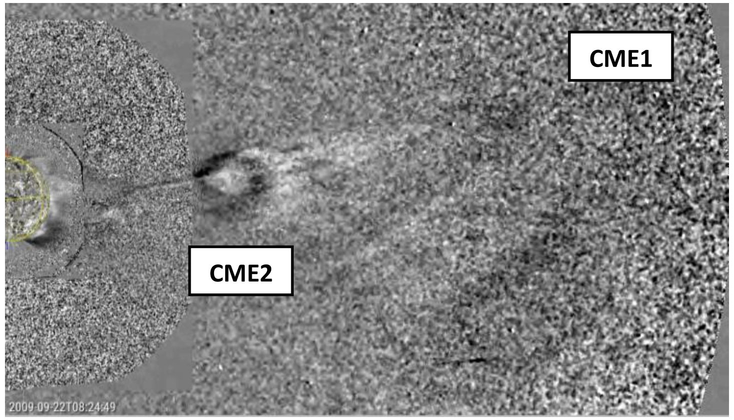
First CME front at 10 Rs

Second CME front at 6 Rs

Event observations taken by STEREO-B

Δt = 08h 39 min

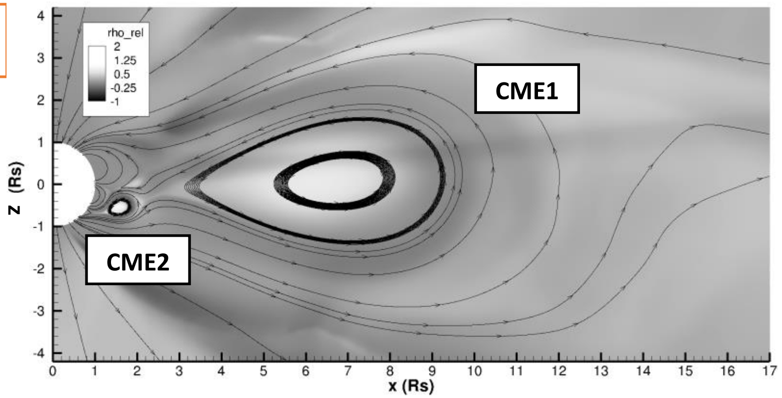


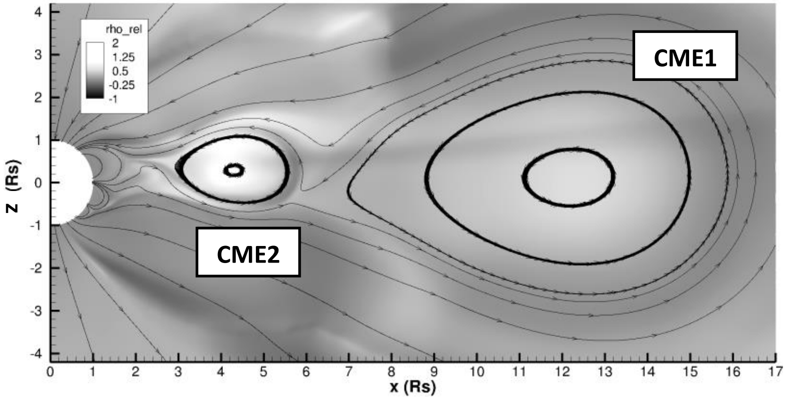


Δt = 11h 24 min

Double eruption

Δt = 08h



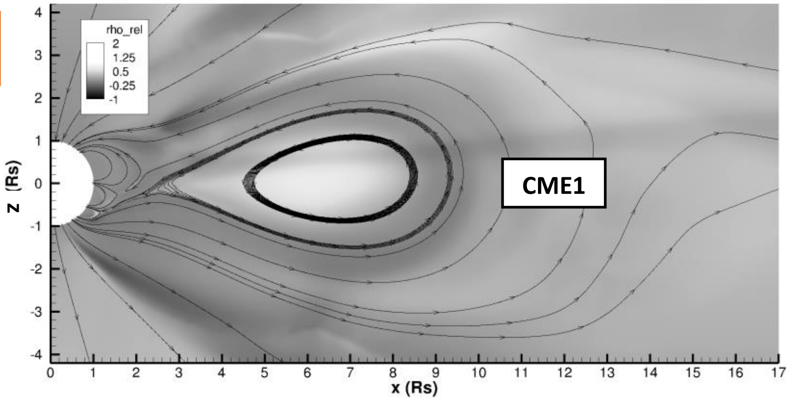


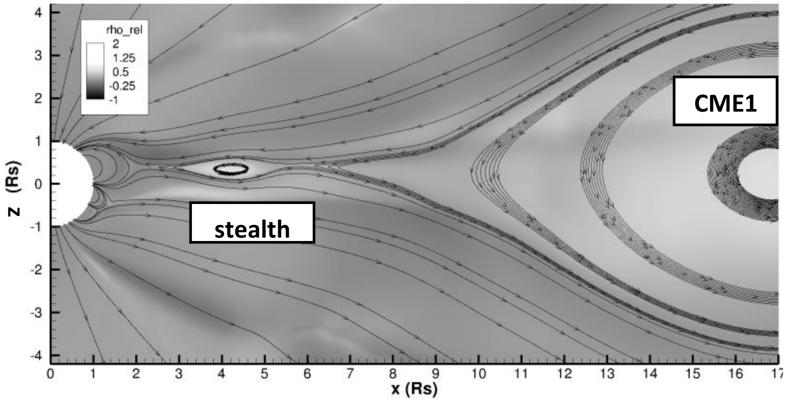
$$\rho_{rel} = \frac{\rho - \rho_0}{\rho_0}$$

Δt = 12h 20 min

Er. + stealth

Δt = 08h

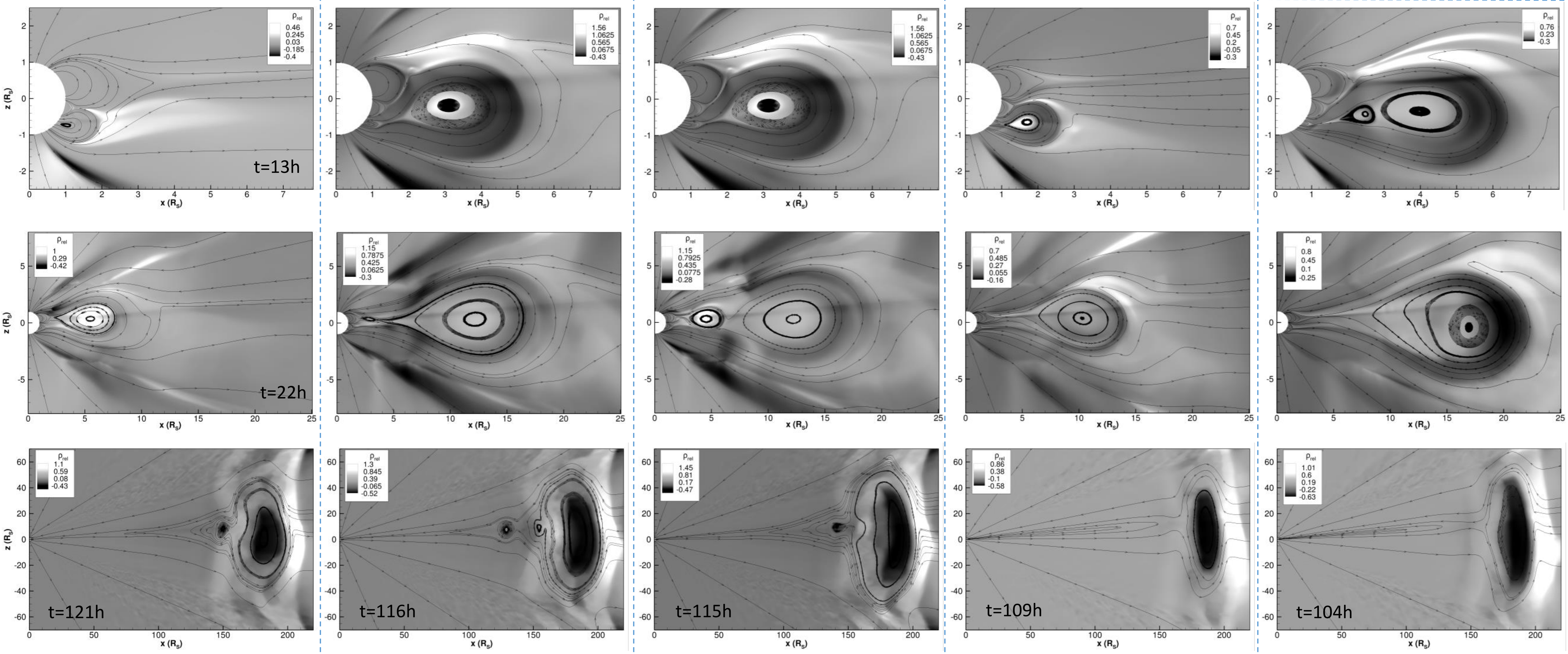




Δt = 15h 20 min

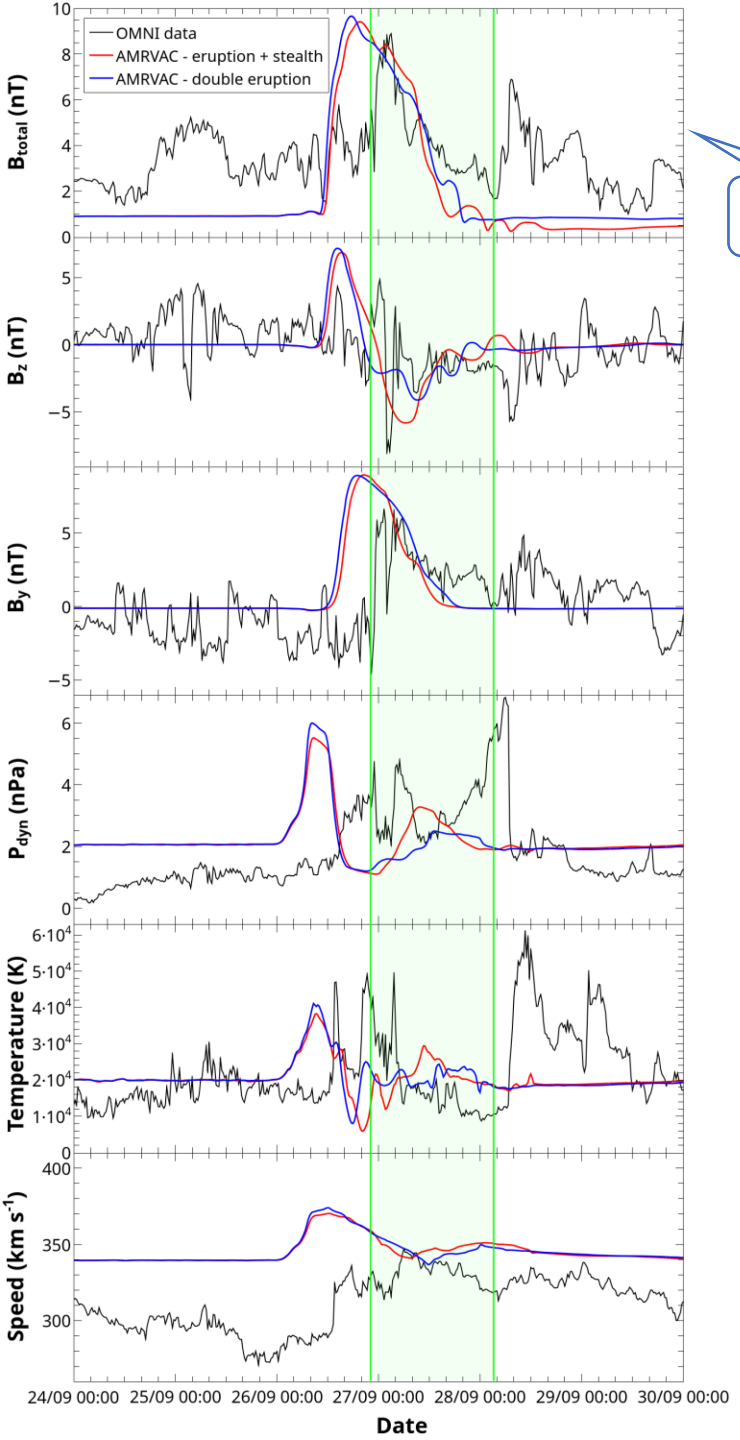
Propagation of simulated eruptions to 1AU

Slow wind - single er. | Slow wind - er. + stealth | Slow wind - double er. | Faster wind - single er. | Faster wind - stealth speed

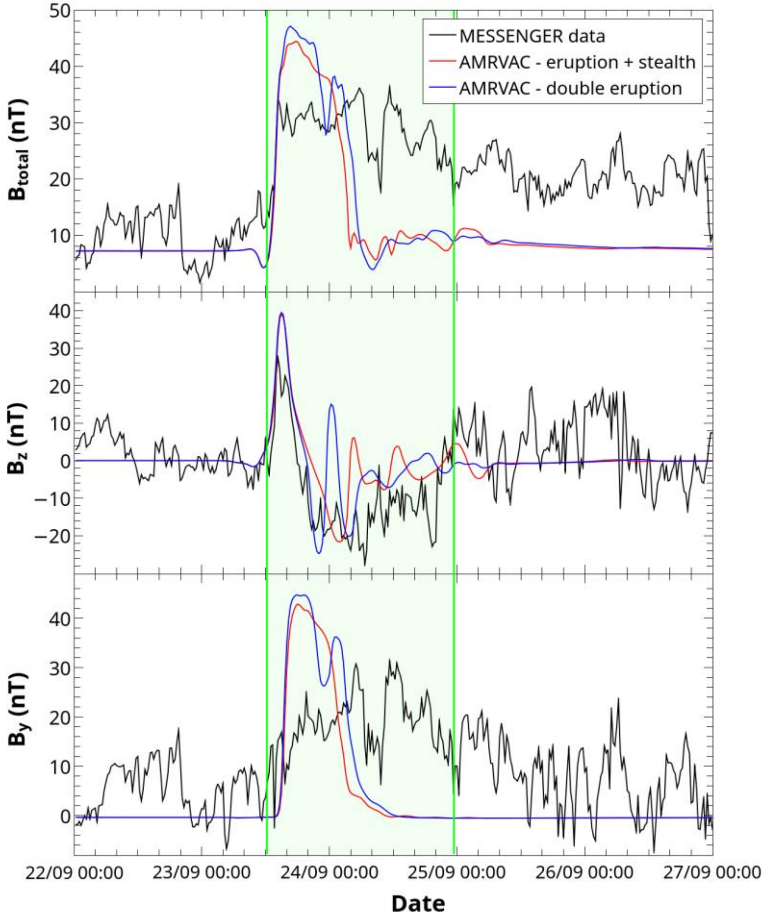


In-situ signatures

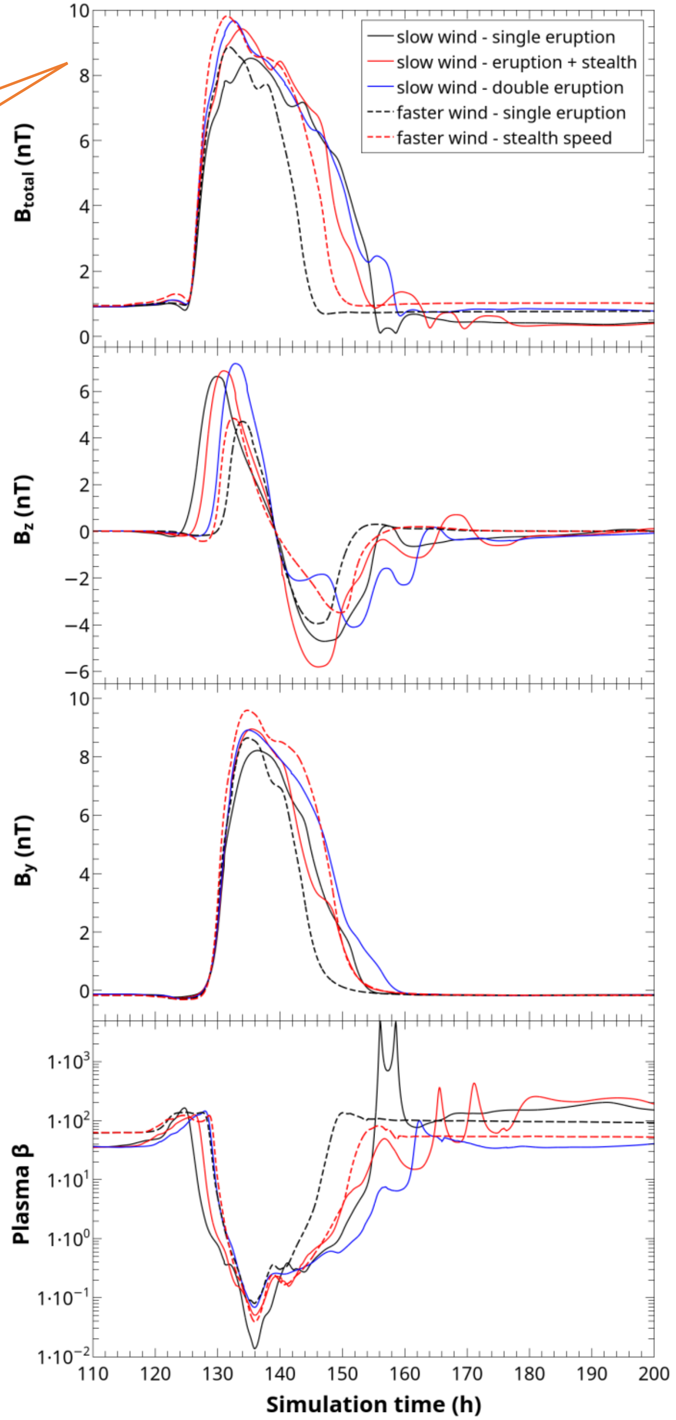
at Earth



at MESSENGER



all simulations, at 1AU



- Work submitted to A&A

Modelled geoeffectiveness from simulation data

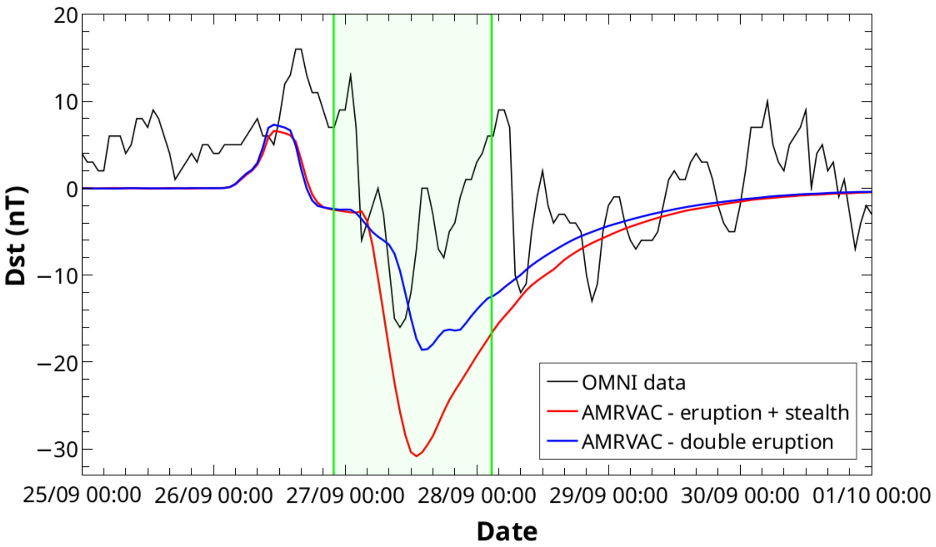
- Dst calculation with the model of O'Brien & McPherron (2000):

$$VB_s = \begin{cases} |VB_z|, \text{if } B_z < 0 \\ 0, \text{if } B_z \geq 0 \end{cases} \qquad Q = \begin{cases} -4.4 * (VB_s - 0.49), \text{if } VB_s > 0.49 \\ 0, \text{if } VB_s \leq 0.49 \end{cases}$$

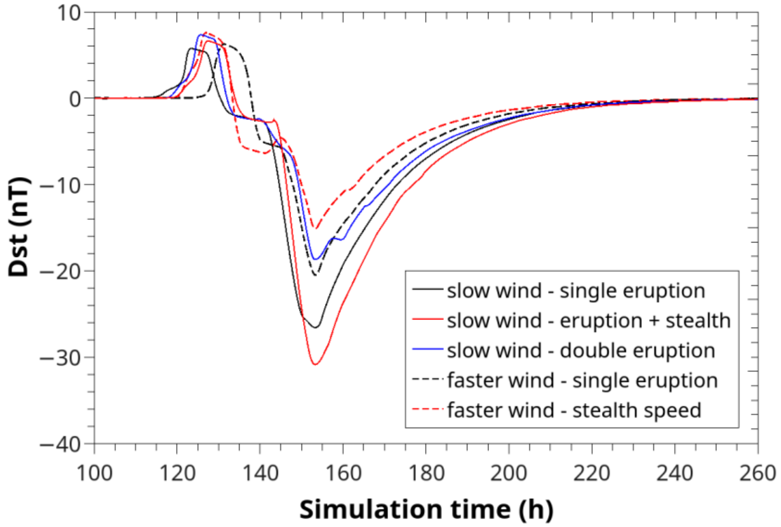
$$Dst^* = Dst - b\sqrt{P_{dyn}} + c, \text{ with } b, c = \text{constants}$$

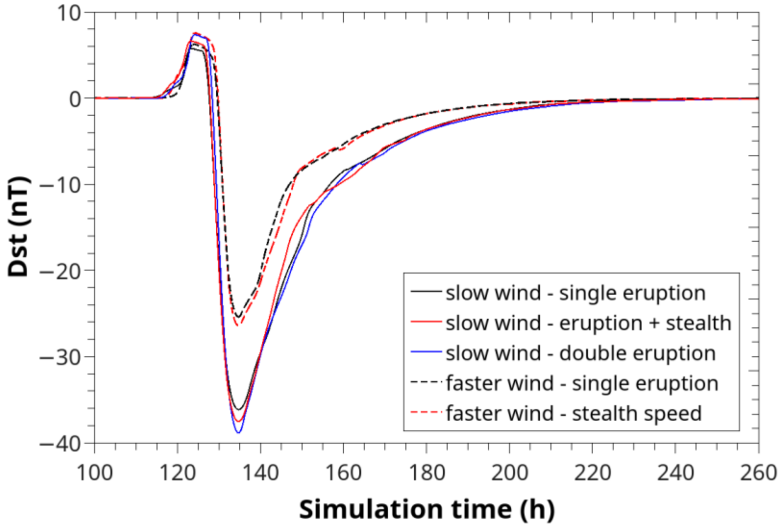
$$Dst^*(t + \Delta t) = Dst^*(t) + \left[Q(t) - \frac{Dst^*(t)}{\tau}\right]\Delta t, \ \tau = 2.4 exp\left[\frac{9.74}{4.69 + VB_s}\right]\Delta t$$

- when $\mathrm{Dst}^*(\mathrm{t} + \Delta\mathrm{t}) = \mathrm{Dst}^*(\mathrm{t})$ (steady state), constant c varies with the background solar wind: $\begin{cases} c = 10.44 \text{ nT, for the slow wind} \\ c = 15.77 \text{ nT, for the faster wind} \end{cases}$

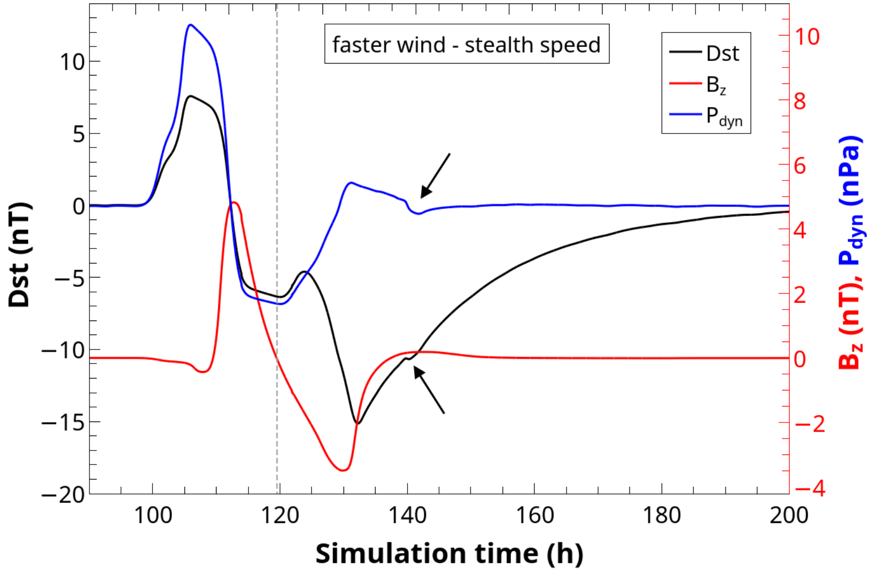


Comparison of hourly Dst index from observed database (black line) with modelled Dst using simulation data (red and blue lines).





Modelled Dst using simulation data (left) and using the Bz component with reversed sign (right). The minima of the curves have been aligned onto that of the last occurring minimum, which was the case of the single eruption in the slow wind.



Modelled Dst using simulation data (black line, left axis), Bz component of the magnetic field (red line, right axis) and dynamic pressure (blue line, right axis).

Conclusions

Slow solar wind

- Shearing speed → extremely important for CME eruption and structure;
- 3 different scenarios investigated;
- Good correlation with in-situ signatures at MESSENGER and Earth; major trends in observed magnetic field variations and arrival time are reproduced;
- The second CME merges with its precursor during the propagation to 1 AU;
- Several plasma blobs occur in the trailing current sheet.

Faster solar wind

- The temperature of the background solar wind influences the structure of the initial configuration, separating the southern pseudostreamer from the northern streamer;
- Even when the same shearing speed is applied, the dynamics of the eruption is very different, no longer creating a stealth CME;
- The negative B_z component of the magnetic field is highly influenced (reduced), possibly due to the change in the initial configuration;
- The arrival time at Earth is shifted earlier by approx. half a day;
- No plasma blobs in the aftermath of the CMEs.

Geoeffectiveness

- The geoeffectiveness of a CME can be influenced by a secondary eruption: given the current magnetic configuration, the released CME arrives at Earth with a leading positive B_z, and the second CME reconnects with the negative trailing part, reducing the absolute value of the induced Dst;
- Reversed sign of B_z:
    - The leading negative B_z would be unaffected, and the geoeffectiveness is increased.
    - The minima happen faster than with the initial B_z, and the Dst decrease is sharper.
    - The biggest difference is observed in the double eruption case, which now results in a weak geomagnetic storm.
- Qualitative and quantitative fit between the modelled Dst in the double eruption case (slow wind) and measured values;
- Contributions to Dst from both B_z and dynamic pressure, even in the recovery phase.