Evolution of a Coronal Mass Ejection from 2.5 Solar Radii to the Earth and Beyond

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ABSTRACT

Currently, there are two general approaches in magnetohydrodynamic (MHD) simulations of the global solar wind (with or without a coronal mass ejection, CME) in the heliosphere: (1) initiating a coronal model from the surface of Sun and merging the model result with a solar wind model at ~0.1 AU and (2) initiating the solar wind MHD model at ~0.1 AU with empirical and theoretical boundary conditions. The first approach can be cumbersome and impractical in space weather operation, whereas the second approach does not provide information about the CME and its driven shock within 0.1 AU (e.g., first ~4 hours, assuming V_{cme} = 1000 km/s). Here, we present a new modeling capability aiming for space weather. The model propagates a flux-roped coronal mass ejection from the source surface (2.5 solar radii, $R_\odot$) to ~1 AU in a single model. This model is based on our G3DMHD solar wind model with three improvements: (1) extending the inner boundary from 18 Rs to 2.5 $R_\odot$, (2) adding the characteristic-based boundary treatment (Nakagawa et al., 1987; Wu and Wang, 1987) at the inner boundary to improve the model stability, and (3) injecting a self-contained magnetic flux-rope model (Chen, 1996) into the system at 2.5 $R_\odot$. We will demonstrate this new capability by simulating background solar wind in July 2007, and the CME event on July 12, 2012. Detailed results will be presented and compared with observation obtained at 1 AU.

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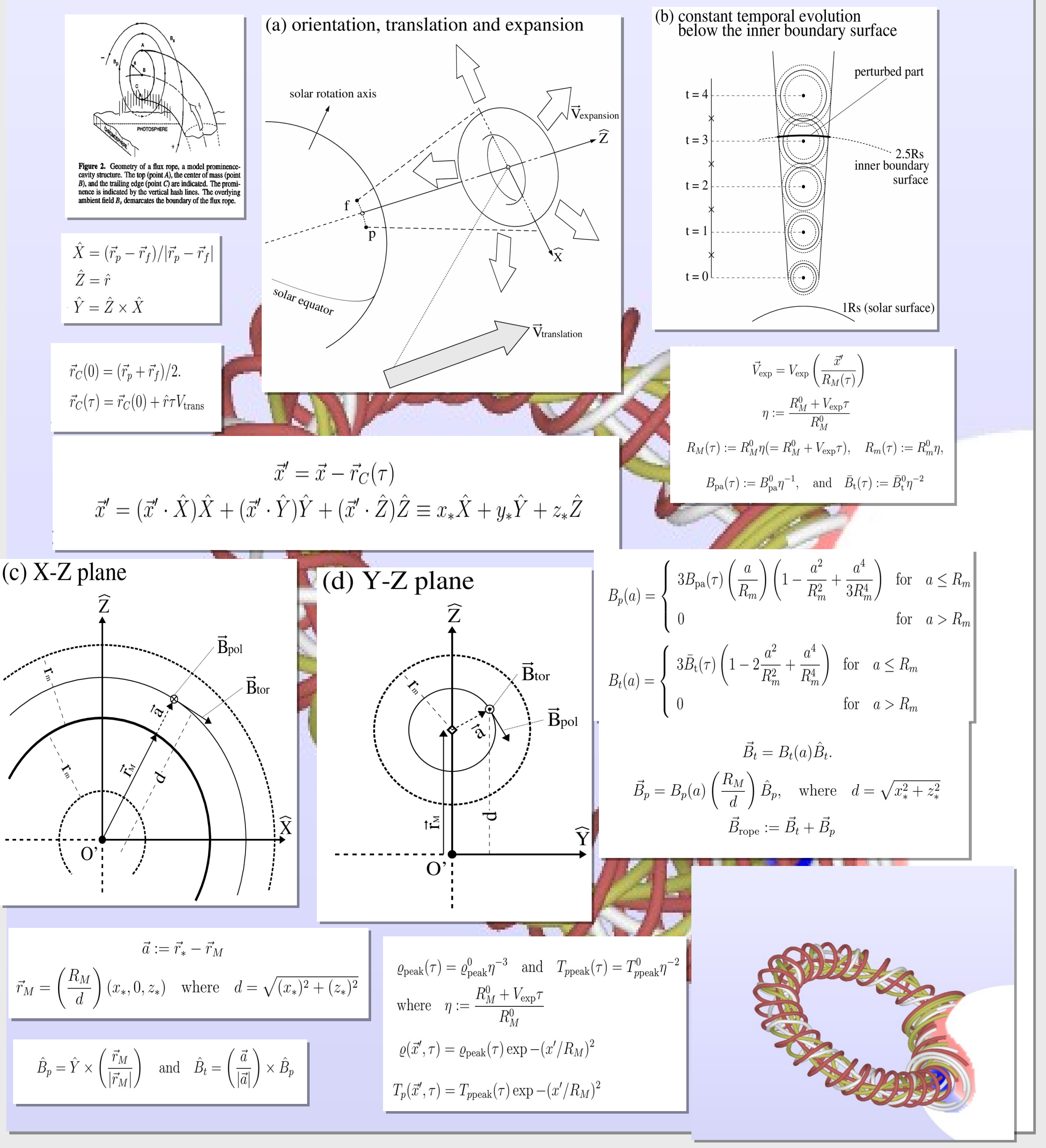
Flux Rope Model

Based on Chen [JGR (1996) 101(A12):27499]

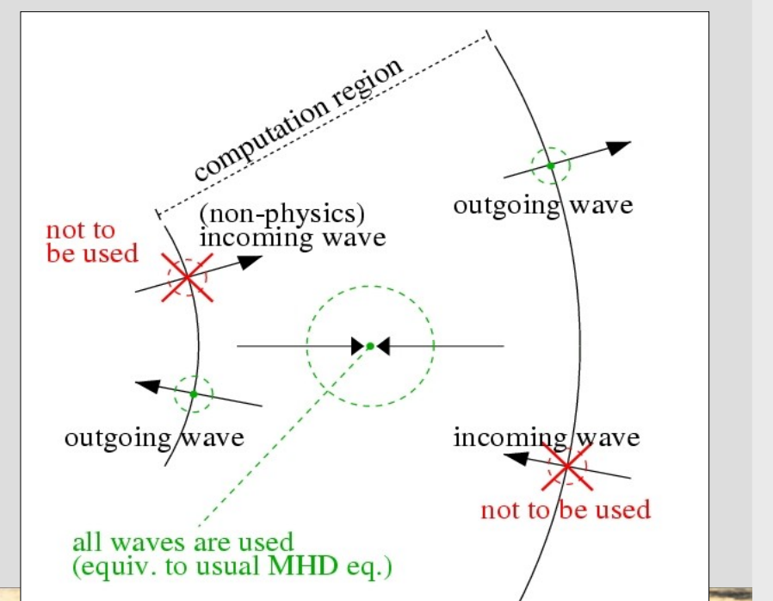


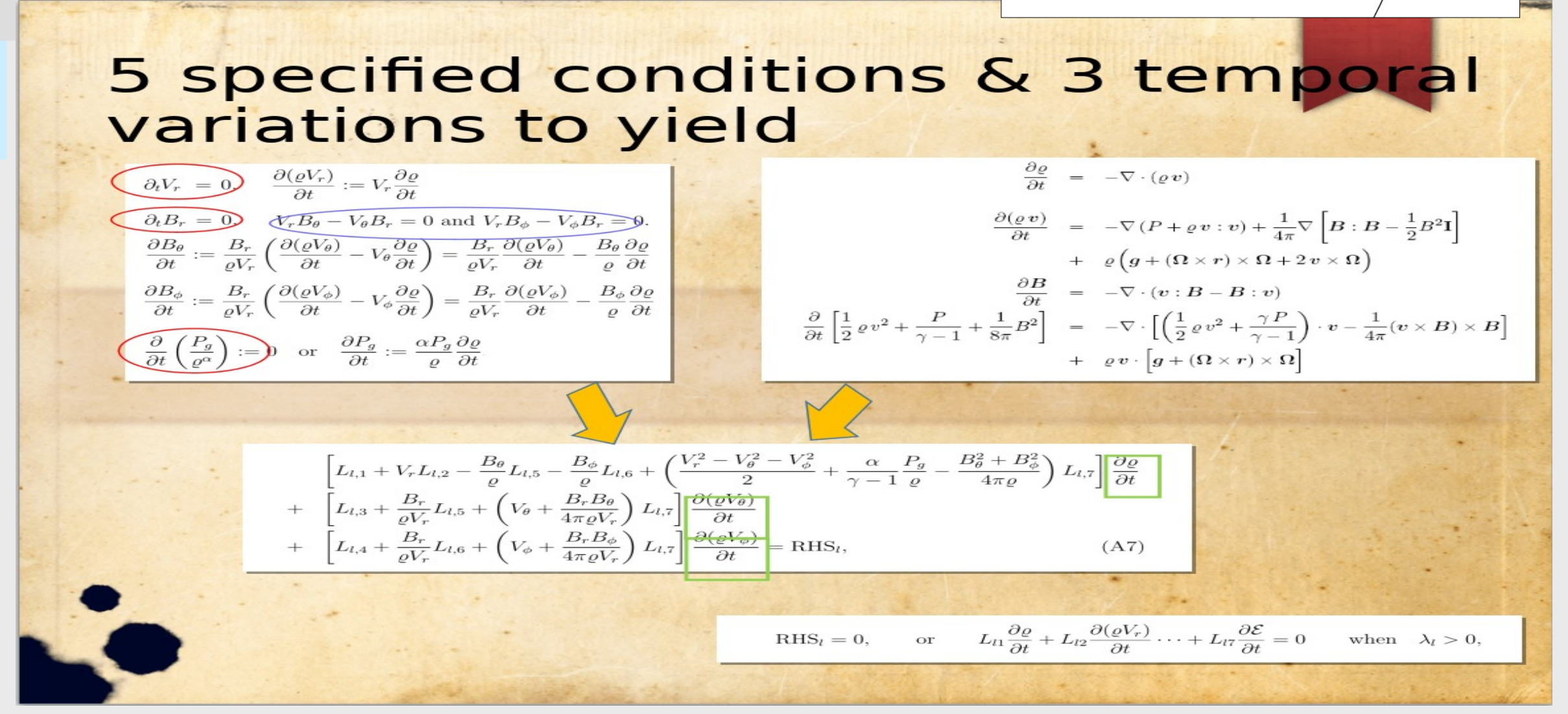
CharM: Boundary Treatment at 2.5 Rs

Characteristic Method (CharM) [Hayashi+ 2023 (under review/revision)]

- Based on the characteristic-based boundary treatment [Nakagawa+ (1987) A&Ap 197:354; Wu & Wang (1987) CMAME 64:267].
- Offers numerical stability on and near the sub-magnetosonic boundary surfaces.
- Determines unspecified temporal variations on the sub-sonic/Alfvenic boundary surface; the number of specified variables is equal to the number of (non-physical incoming) MHD wave modes.

- **Specification of boundary condition at 2.5 Rs:**
  - Vr and Br are held constant
  - Assume polytropic fluids ($\rho^{n-1}/T = C$)
  - V and B are parallel to each other
  - The number of specified (unspecified) variables is 5 (3)

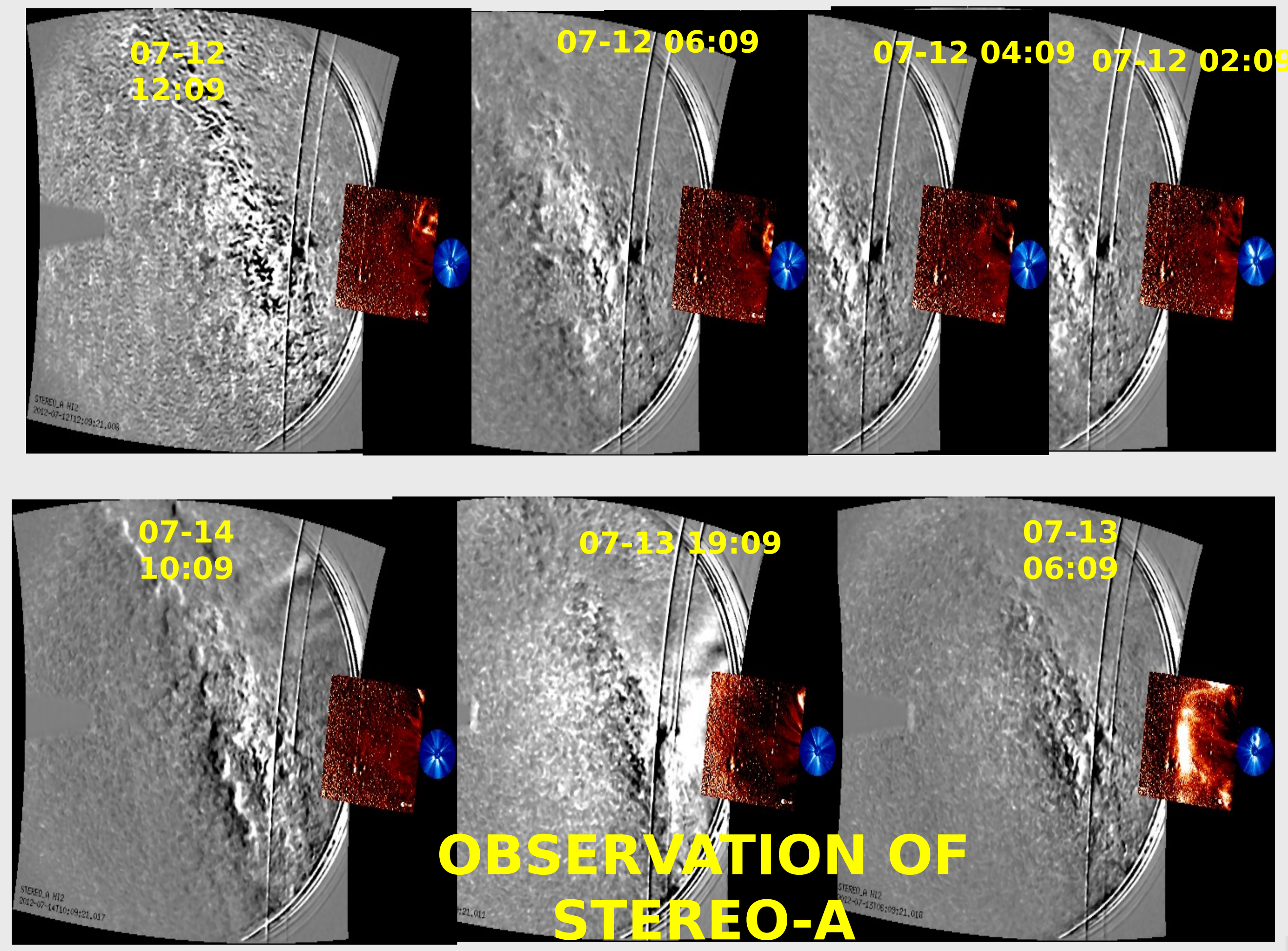



5 specified conditions & 3 temporal variations to yield

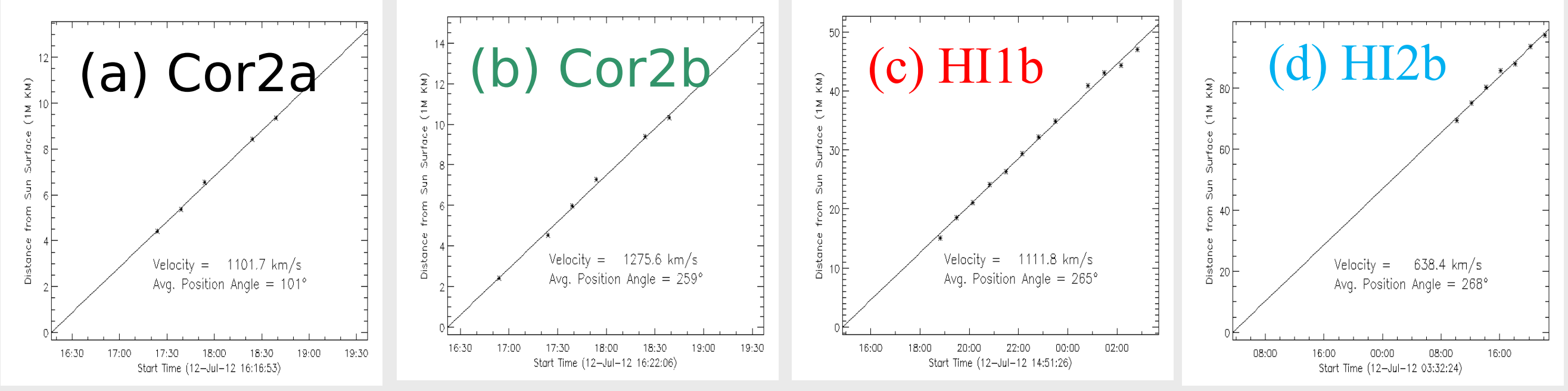
Global Three-Dimensional MHD Simulation Model (G3DMHD)

- **A global, fully three-dimensional (3D), time-dependent, magnetohydrodynamic (MHD) simulation model G3DMHD (Wu et al., 2007, 2020) is modified and is capable to simulate solar wind evolution from 2.5 $R_\odot$ to 250 $R_\odot$ (Hayshi et al., 2023, APJS in revision).**
- **G3DMHD is a modified version of Han code (Han 1977; Han, Wu, and Dryer, 1988). Han code is also a fully 3D, time-dependent, MHD simulation code. Han code is not able to study the realistic solar wind.**
- **The 3DMHD model solves a set of ideal-MHD equations using an extension scheme of the two-step Lax–Wendroff finite-difference method (Lax and Wendroff, 1960).**
- **An ideal MHD fluid is assumed in the Han model, which solves the basic conservation laws (mass, momentum, and energy) as shown with the induction equation to take into account the nonlinear interaction between plasma flow and magnetic field.**
- Simulation domain: $2.5 R_\odot \le r \le 250 R_\odot$; $-87.5° \le \theta \le 87.5°$; $0° \le \phi \le 360°$.
- Open boundary (no reflective disturbances) at θ = 87.5°, θ = -87.5°, and $r = 250 R_\odot$
- Constant grids $\Delta r = 0.15 R_\odot$, $\Delta\theta = 5°$, and $\Delta\phi = 5°$ (results in 1650 x 36 x72 = 4,276,800 grids).

Observation of CME on 2012-07-12



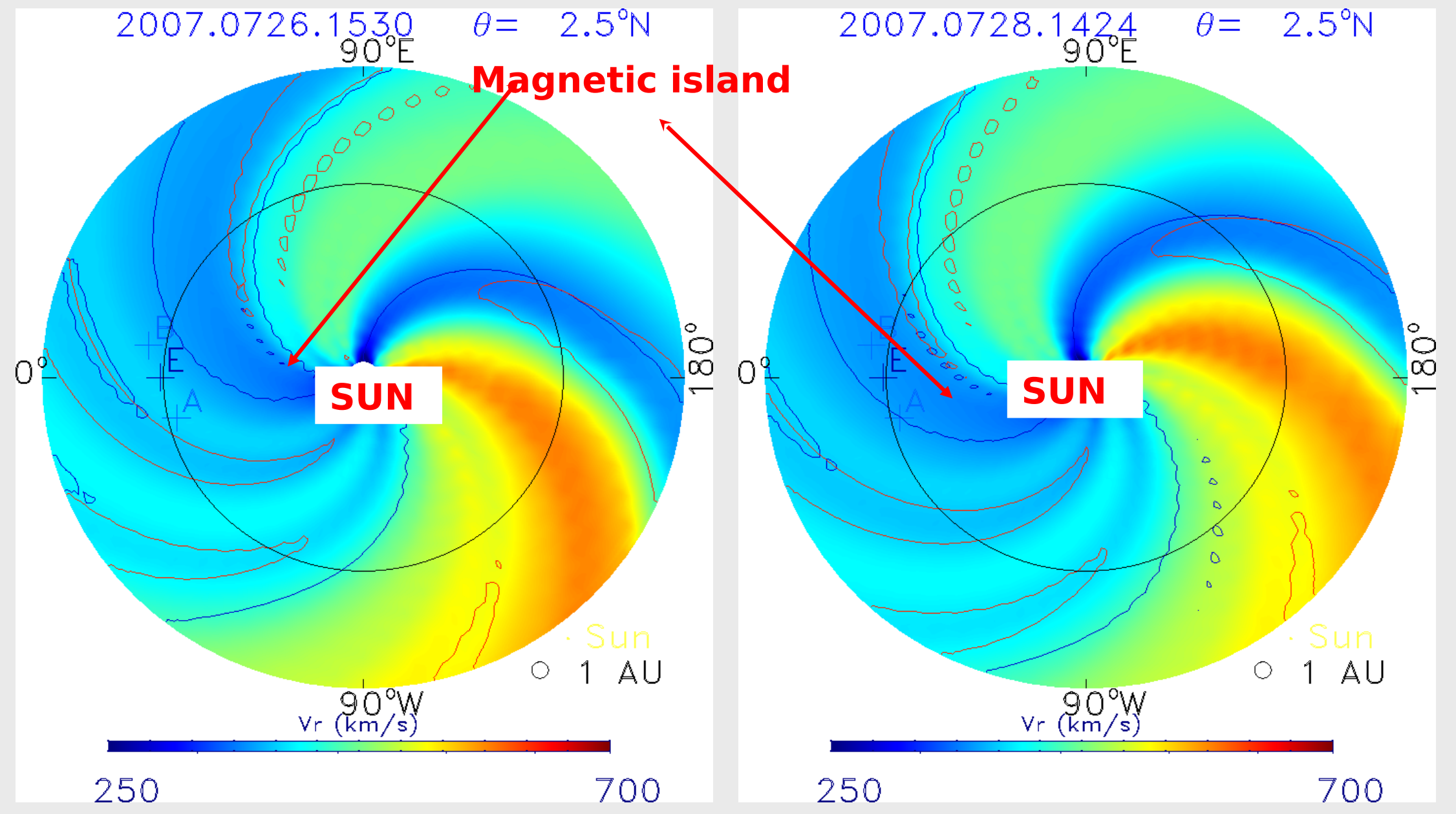
Propagation speed of CME12



Average propagation speed of CME12: (a) 1102, (b) 1276, (c) 1111.8, and (d) 638.4 km s^{-1} estimated with *Cor2a*, *Cor2b*, **HI1b** and **HI2b**, respectively.

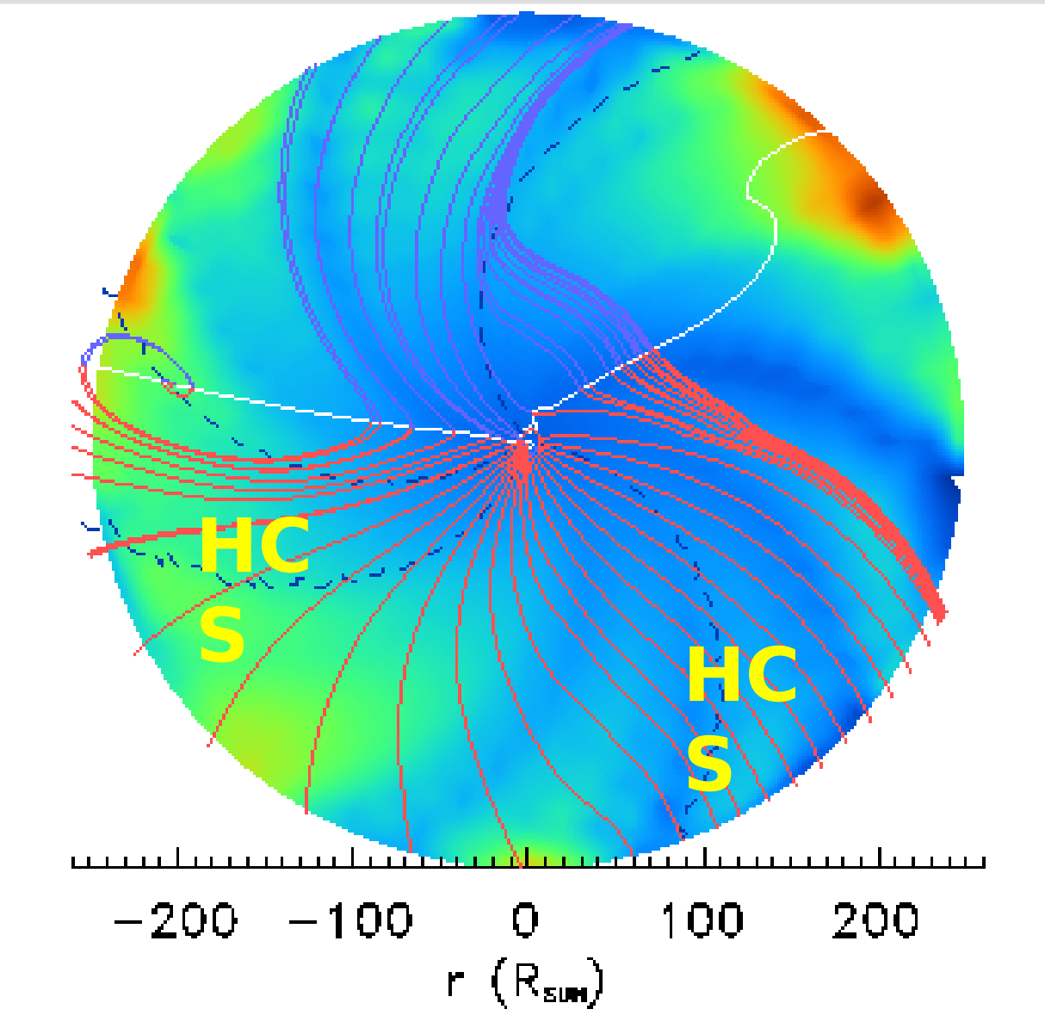
Simulation Results

Background Solar wind in 2007-July



LoS integrated density

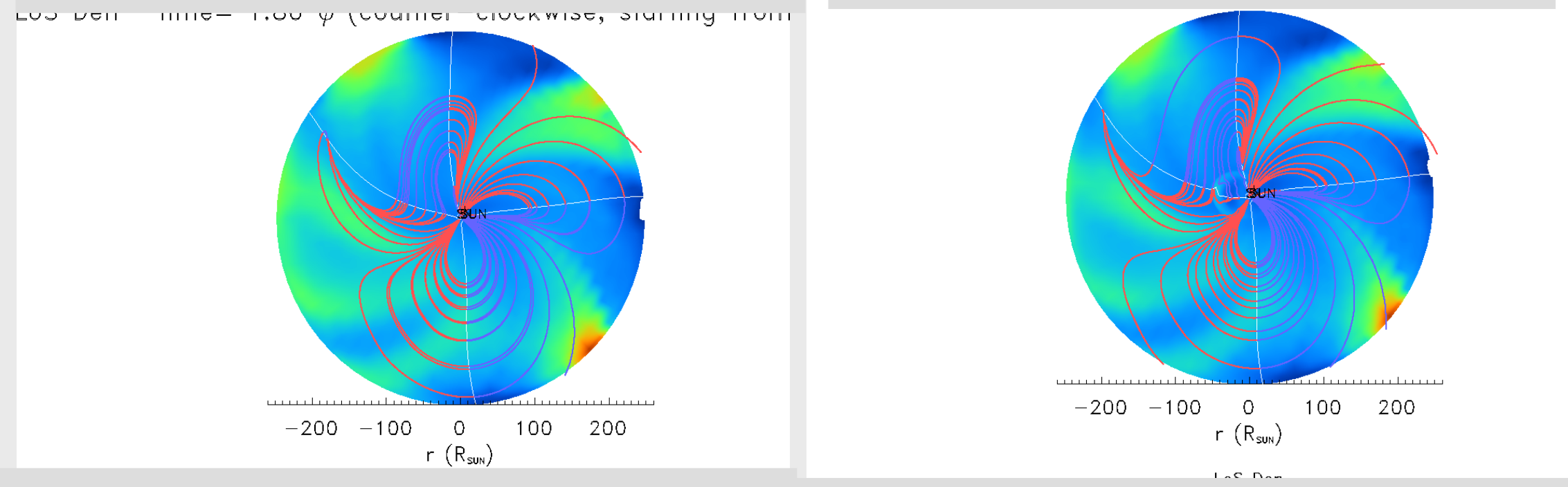
2007-07-29



CME occurred on 2012-July 12

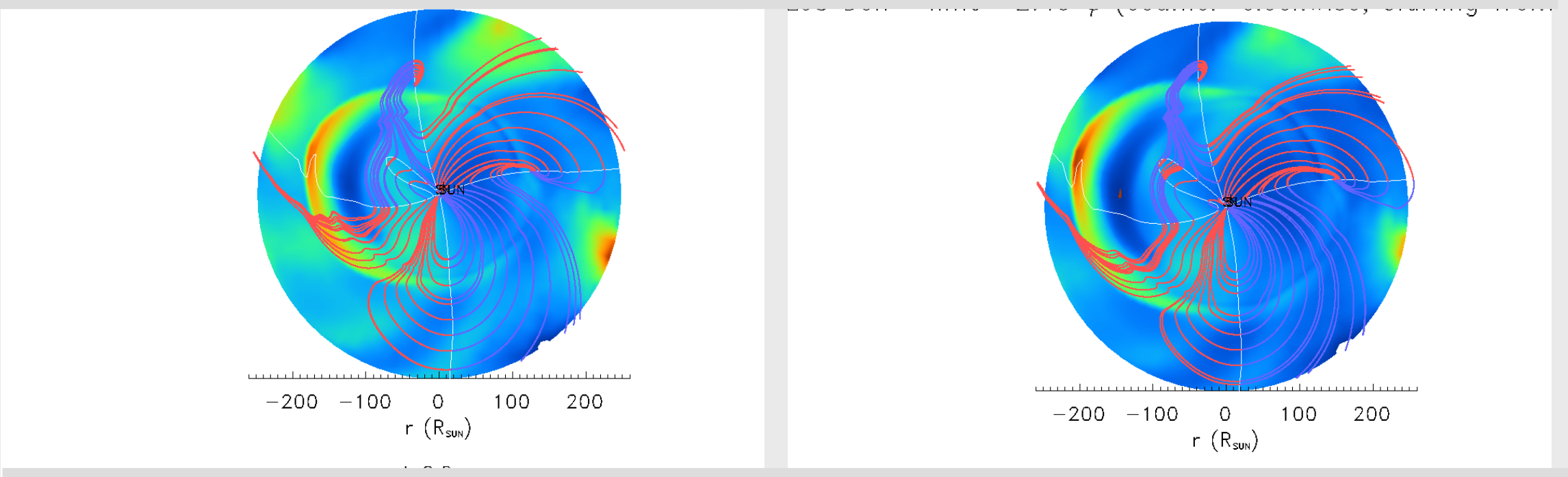
(a) Before CME12 eruption

(b) After CME eruption

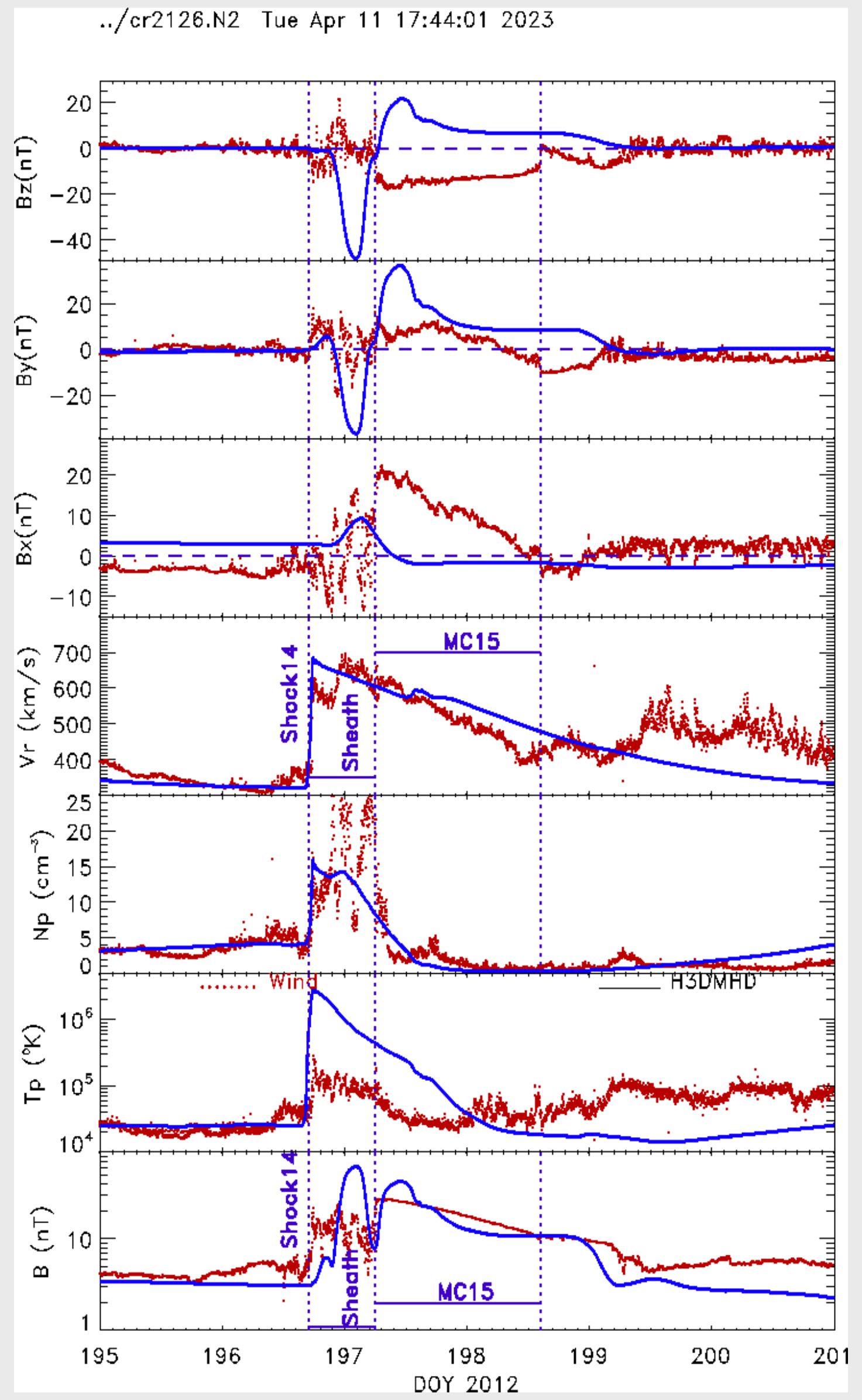


(c) CME (flux-rope) arrived at the Earth

(d) CME (flux-rope) passed the Earth



Comparison of Simulation Results vs. *Wind in-situ observation*



- Temporal profile is similar
- Sheath duration is almost same size
- Driver (flux-rope) size is same
- Shock velocity jump is similar
- B-profile is similar
- Density jump is similar
- Tp jump is too high

CONCLUSIONS

We have demonstrate the improvements & capabilities of the global 3D MHD simulation:

- Inner G3DMHD boundary is extended from 18 solar radii to 2.5 radii.
- G3DMHD is able to simulate a CME event with a flux-rope structure.
- The new G3DMHD model is not only able to simulate the CME driven shock but also the CME (flux-rope) structure.
- Thus the new G3DMHD model is suitable for space weather operation.

Acknowledgment

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