Study of the Solar Sources of the 10 May 2024 Great Geomagnetic Storm

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The 10-11 May 2024 great geomagnetic storm (minimum *Dst*, Dst_{min} = -406 nT) is ranked as the 7th largest geomagnetic event on record. The solar source(s) of the May storm is still unsettled. It was associated with five halo coronal mass ejections (CMEs) erupting during May 8−9, but the Wind spacecraft only recorded an interplanetary shock at 16:32 UT on May 10 and a likely second one at 21:36 UT on the same day. In addition, the five CMEs were associated with moderate X-ray flares (M8.7−X2.2) and initial speeds of only ~530−1280 km/s, yet they produced a very intense geomagnetic storm. The present study employs a global magnetohydrodynamic simulation model [Wu et al. 2020] to address this puzzle. The CMEs, simulated with pressure pulses, were injected into the inner boundary (18 Rs) of simulation domains with speeds estimated from the white-light coronagraph images. An error range of 1.0−18.5 hours is found for the shock arrival time (SAT) when individual CMEs are simulated, and an error range of 0.2−6.0 hours for the SAT when the five CMEs are simulated together. The latter simulation reproduces the radial velocity profile in much better agreement with the Wind observations than any individual one does, suggesting that merging of the CMEs is responsible for the May geomagnetic storm.

MOTIVATION

1) 2024 May grand storm was associated with 6 moderate halo-CMEs and solar X-ray flares (M8.7-X2.2). CMEs' initial speed (V_{CME}) is relatively slow, 530-1280 km/s
2) Two Halloween storms (Dst_{min} = -353 & - 383 nT) occurred in October 2003, V_{CME} are 2125 and 1948 km/s; X-ray flares are X17 and X10 on Oct.ober28 and 29, respectively.
3) One would not expect that the 6 CMEs(May 2024) could have generated a storm with a Ds_{min} (= -406 nT) smaller than the Halloween storms.
4)It is important to understand how do multiple CMEs affect the near-Earth space weather leading to large geomagnetic storm and which CME is responsible for the SSE and initiation of the May 10 grand storm.
5)This subject has not been fully studied and the present study intends to solve the puzzle.

CMEs' Evolution during May 08-10 2024

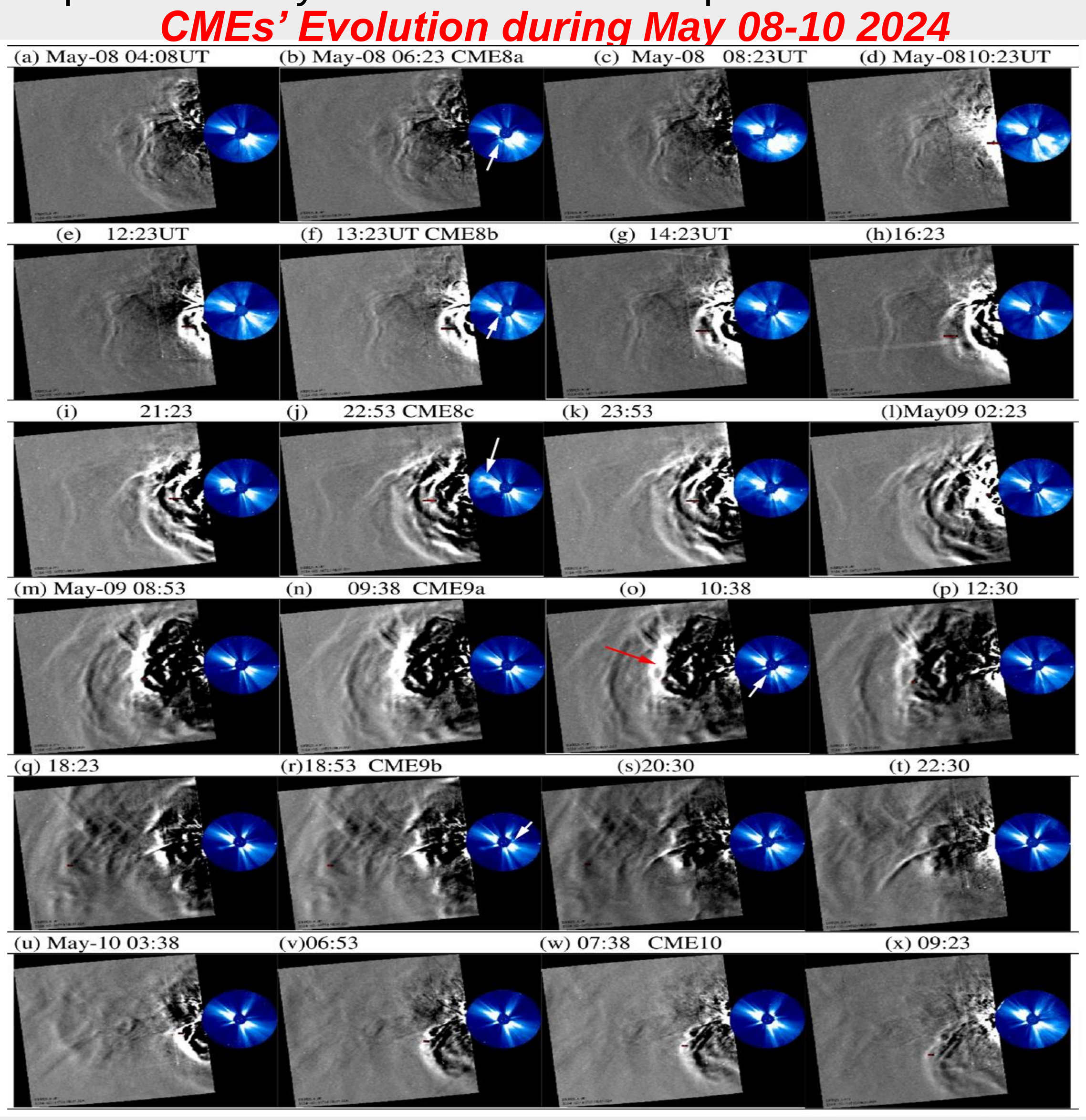

Figure 1. Selected white-light images recorded by STEREO/SECCHI Cor2(blue) and CHI1(grey scale) on May 8-10, 2024. The time tags indicate the date and time of the center of the images as well as the CME events first emerged in the FOV.

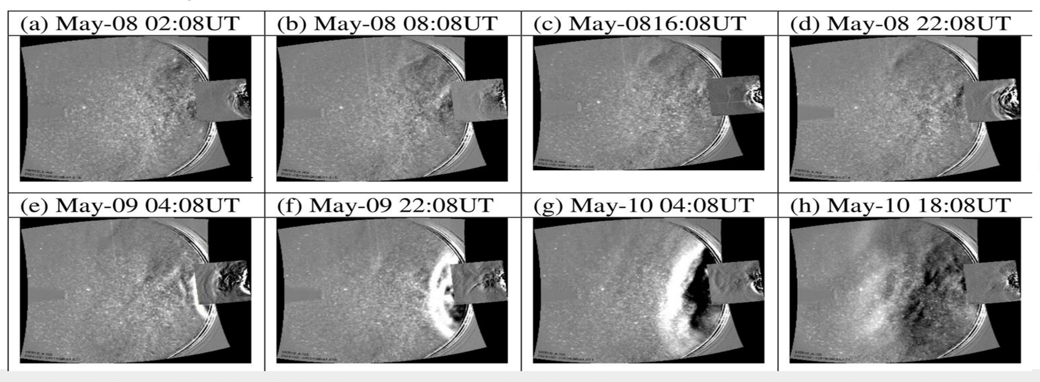

Figure 2. Selected white-light images recorded by STEREO/SECCHI Hi1 and Hi2 telescopes on May 8-10, 2024. Earth was located at edge of left side.

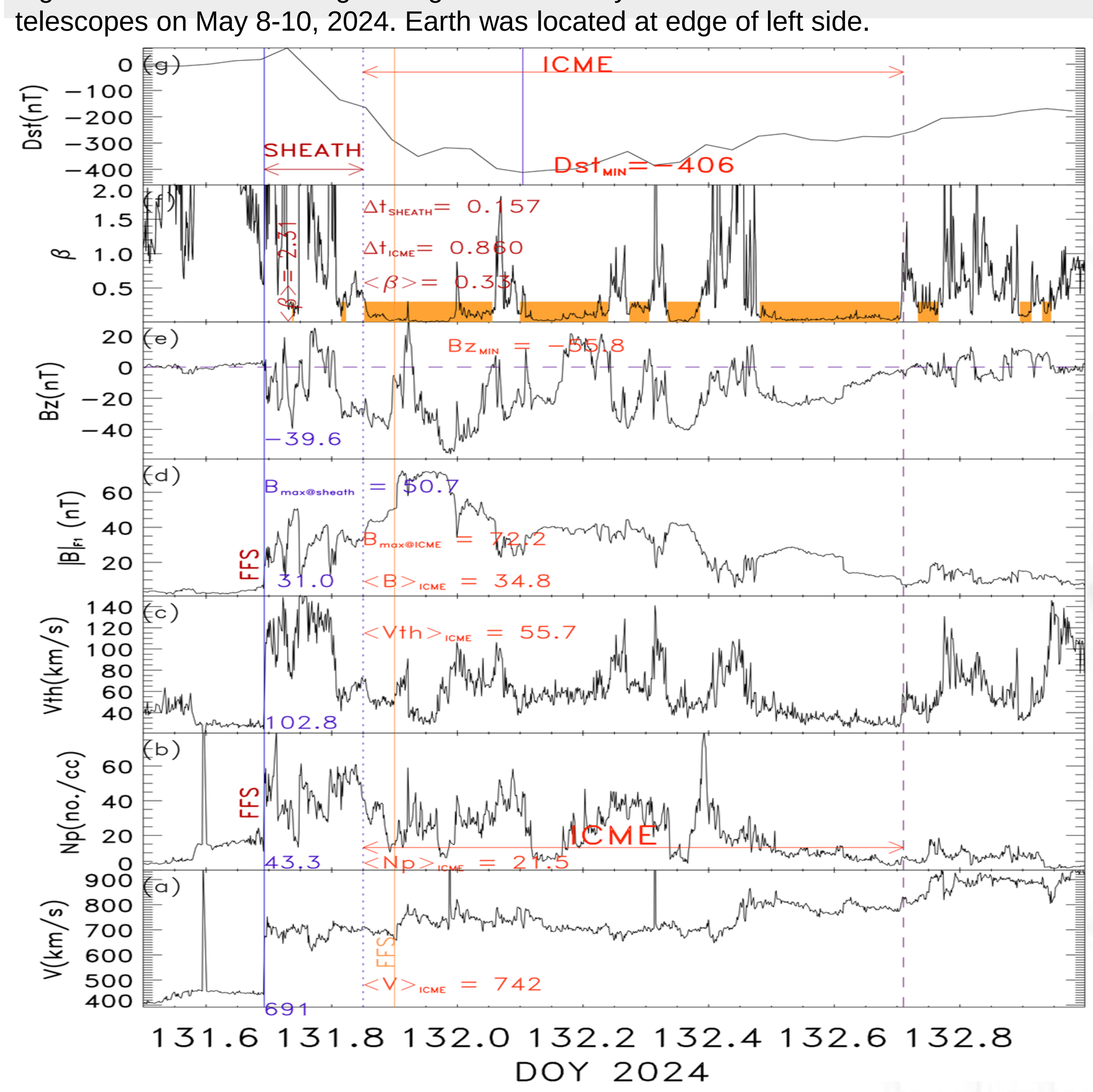

Fig. 3. In situ measurements of the solar wind parameters: proton (a) speed (V), (b) density (Np), (c) temperature, (d) magnetic field intensity (|B|F1), (e) magnetic field Bz component, (f) proton beta (β), and the geomagnetic storm index (Dst).

METHODOLOGY

- A fully three-dimensional (3-D), time-dependent, magnetohydrodynamic simulation code (Han 1977; Han, Wu, and Dryer, 1988) was used to propagate solar wind parameters at the inner boundary to 1 AU to compare with *in-situ* measurements. Realistic Global 3-D MHD was developed by Wu et al. [2020]
- The MHD model solves a set of ideal-MHD equations using an extension scheme of the two-step Lax–Wendroff finite-difference methods (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.

$$\frac{D\rho}{Dt} + \rho\nabla\cdot V = 0 \quad (1)$$

$$\rho\frac{DV}{Dt} = -\nabla p + \frac{1}{\mu o}(\nabla\times B)\times B - \rho\frac{GM_s(r)}{r^2}r \quad (2)$$

$$\frac{\partial}{\partial t}\left[\rho\rho + \frac{1}{2}\rho|V|^2 + \frac{|B|^2}{2\mu o}\right] + \nabla\cdot\left[V\left\{\rho e + \frac{1}{2}\rho|V|^2 + p\right\} + \frac{B\times(V\times B)}{\mu o}\right] = -v\cdot\rho\frac{GM_s(r)}{r^2}r \quad (3)$$

$$\frac{\partial B}{\partial t} = \nabla\times(V\times B) \quad (4)$$

Simulation Domain and Setup

- The MHD equation set is solved in the Sun-center spherical coordinate system (r, θ, ϕ)
- The domain covers -87.5° ≤ θ ≤ 87.5°; 0° ≤ ϕ ≤ 360°; 18 $R_\odot$ ≤ r ≤ *345* $R_\odot$ (~0.08 – 1.6 AU; $R_\odot$: Solar radius)
- Open boundary conditions at θ = 87.5°, θ = -87.5°, and *r* = 1518 $R_\odot$ are used, so there are no reflective disturbances.
- A constant grid size of Δr = 3 $R_\odot$, Δθ = 5°, and Δϕ = 5° are used, which results in 501 x 36 x72 grid sets.
- At the inner boundary r = 18 Rs, plasma and field parameters are taken from the modified WS model $V = V_1 + V_2 f_s^{-\alpha}$, where f_s is the magnetic expansion factor, V_1 = 150 km/s, V_2 = 500 km/s, and α = 0.4. [*Wu et al.*, 2020, *Solar Physics* **295:** 25; JASTP,

- *Wu et al., 2020, Solar Physics* ***295:*** *25; doi: 10.1007/s11207-019-1576-6*
- *Wu et al., 2020, JASTP, https://doi.org/10.1016.j.jastp.2020.105211*

G3DMHD Simulation Results

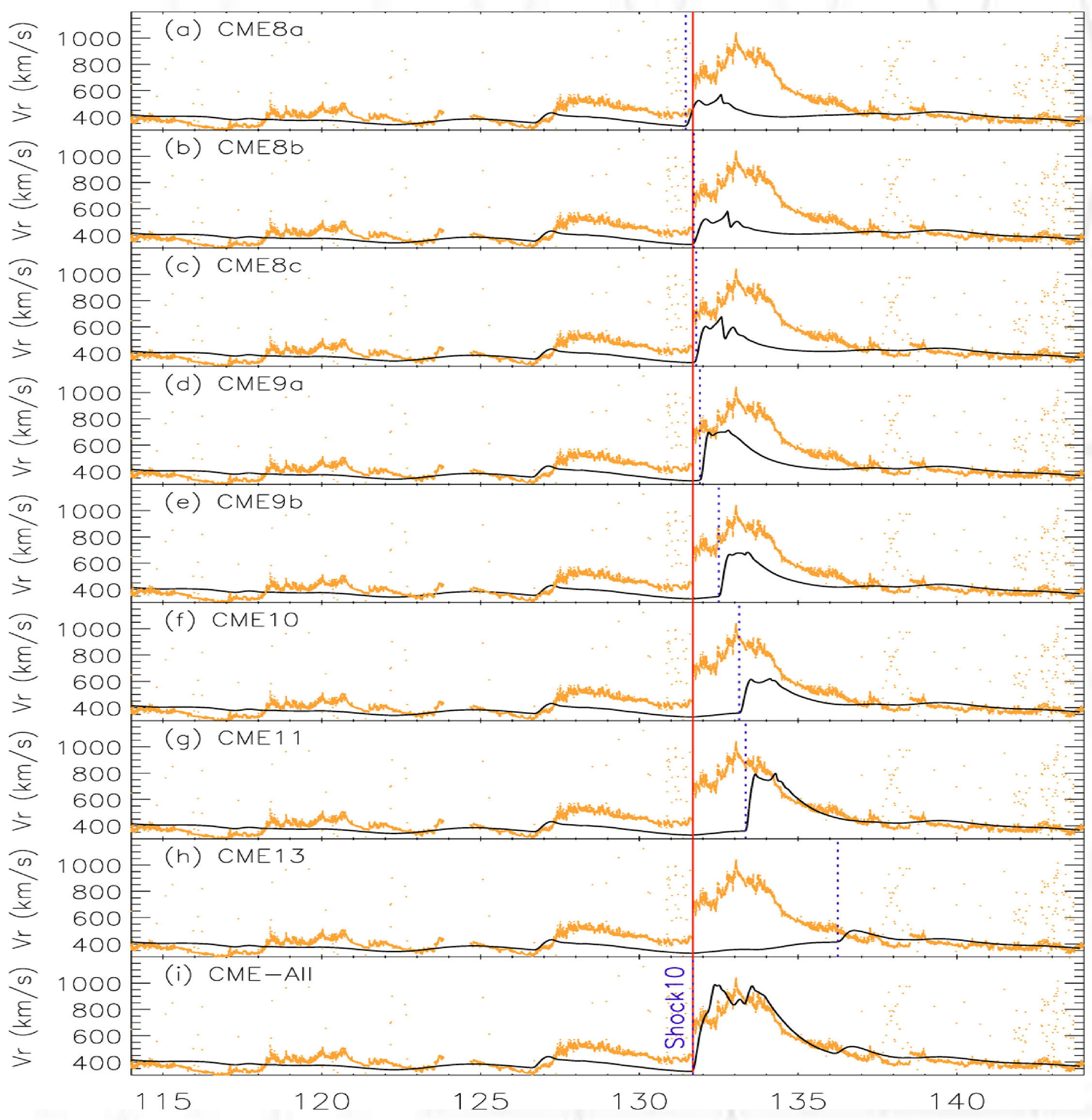

Figure 4. Simulated solar wind radial velocity profiles (black curves) for (a-h) 8 separated CMEs and (i) combined 8 CMEs. The overlapped traces (dotted orange lines) are in situ measurements from Wind. The red vertical line indicates the arrival time of Shock10, whereas the dotted vertical lines represent the simulated shock arrival times.

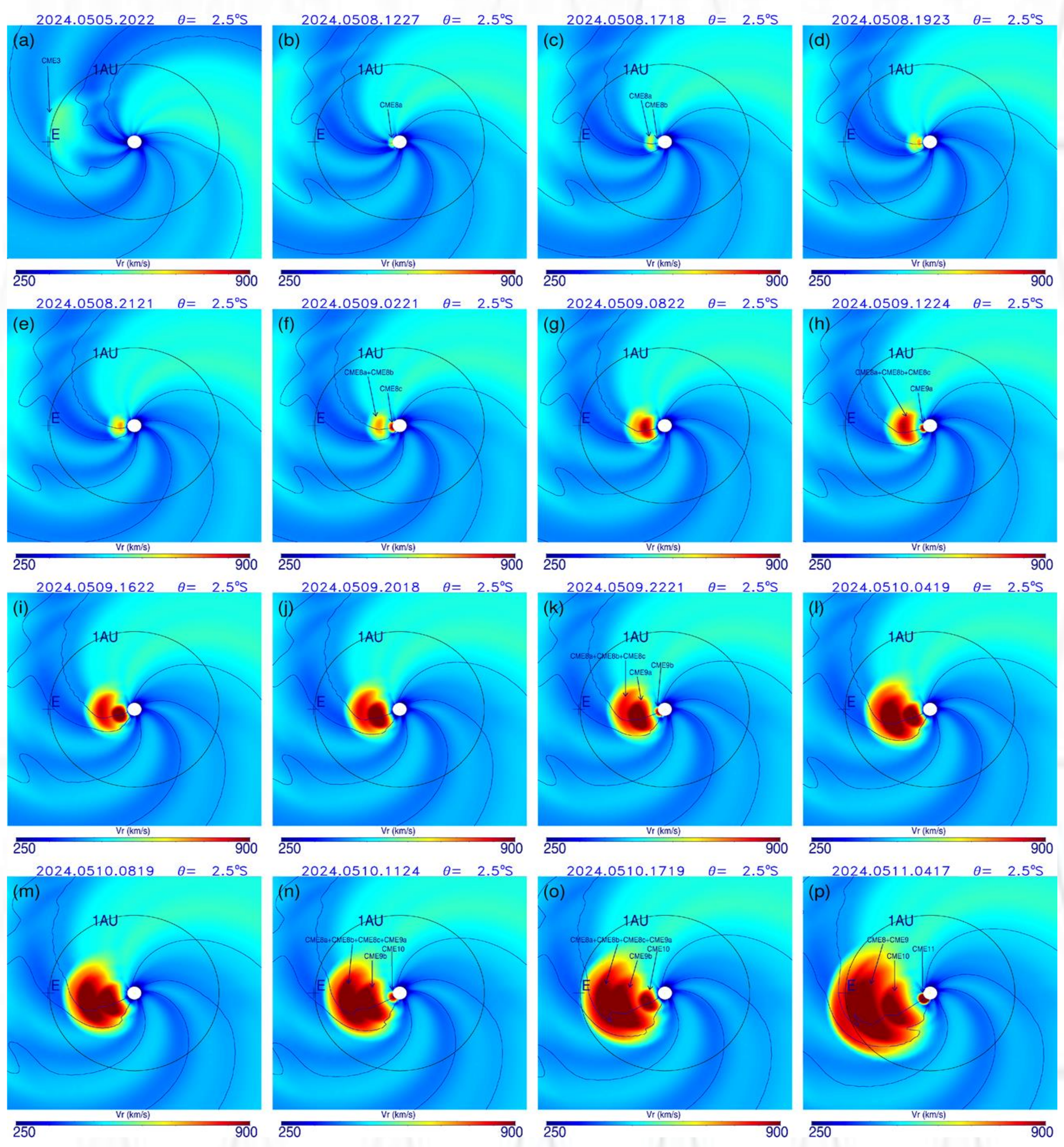

Figure 5. Cross-sectional view of the color-coded solar wind radial velocity for selected intevals from May 5 to May 11 of 2024. The black circle marks r = 1 AU and the blue contours are the heliospheric current sheet (Bφ = 0). The locations of the Wind spacecraft and the Earth are marked by a "+" sign and "E", respectively. The color bar for the solar wind speed is provided to the bottom of each panel

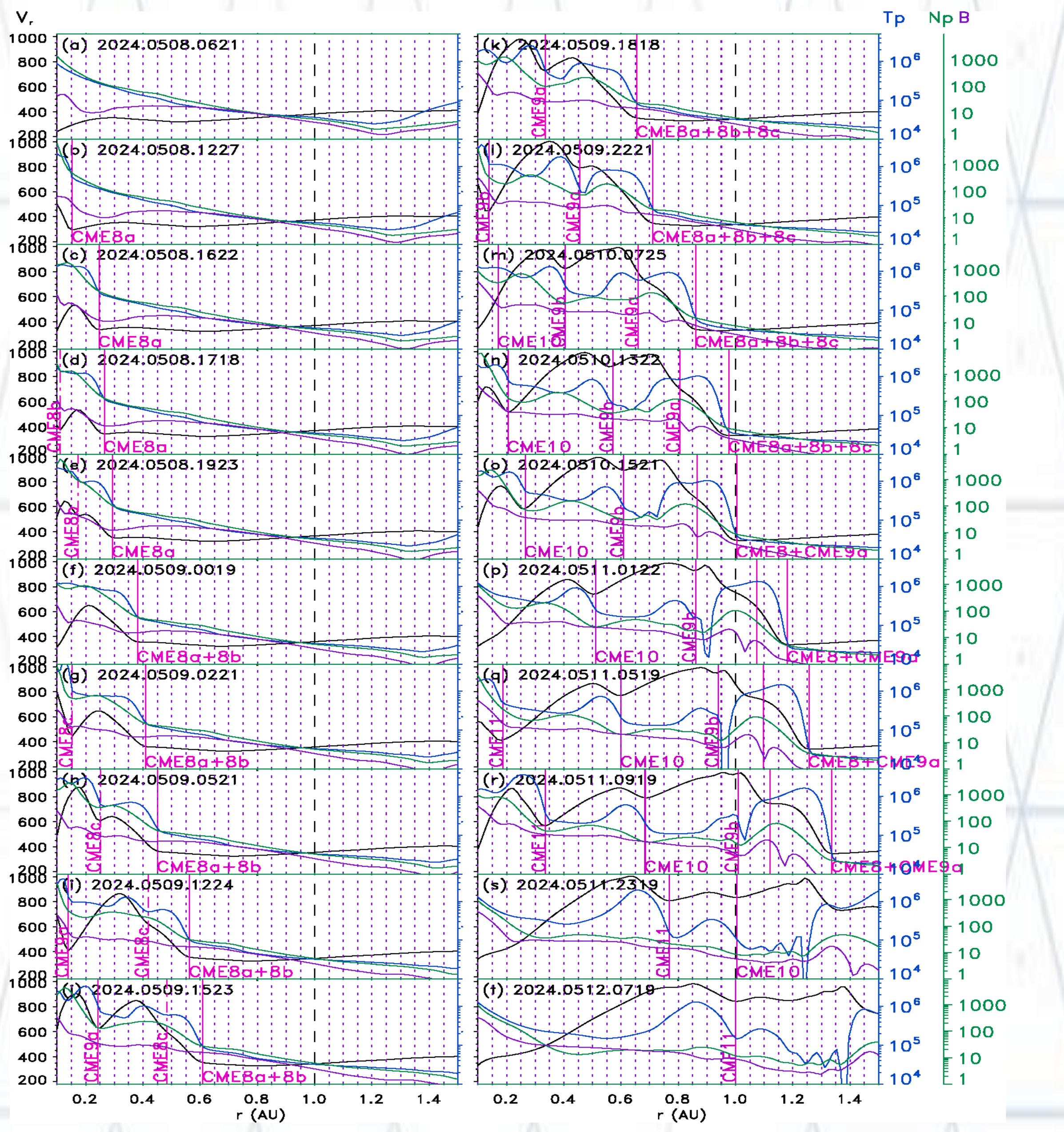

Figure 6. Selected sequence of simulated solar wind parameter (Vr: black, Tp: blue, Np: green, and B: purple) radial profiles toward Earth (0.08 – 1.5 AU) showing the time evolution of the 8 CMEs. The blue and purple vertical lines mark the locations of shocks.

DISCUSSION

Source location and propagation speed of CMEs occurred on 3-11 May 2024.

	CME[a]			Flare[a]		Δt_{EST}[b]	SAT_{EST}[b]			SAT_{MHD}[c]
	Date	UT	V_{CME}	Class	Lat, Lon	hrs	DOY	Date	UT	DOY
CME3	05/03	02:48	808	X1.6	N25E07	50.8	126.236	05/05	05:34	
CME8a	05/08	05:36	530	X1.0	S18W17	77.6	132.466	05/11	11:12	131.48
CME8b	05/08	12:24	677	M8.7	S20W11	60.7	132.045	05/11	01:06	131.68
CME8c	05/08	22:24	952	X1.0	S20W17	43.1	131.729	05/10	17:30	131.75
CME9a	05/09	09:24	1280	X2.2	S20W26	32.1	131.730	05/10	17:30	131.94
CME9b	05/09	18:52	1024	X1.1	S14W28	40.2	132.461	05/11	11:04	131.75
CME10	05/10	07:12	953	X3.9	S17W34	43.1	133.088	05/12	02:18	133.34
CME11	05/11	01:36	1614	X5.8	S15W45	25.4	133.126	05/12	03:01	136.21
CME13	05/13	08:48	1690	M6.6	S20W81	24.3	135.616	05/14		
ΣCME[d]										131.68

[a]CME and flares information adapted from SOHO/LASCO Halo CME Catalog
[b]Estimated shock arrival time at L1 with V_{CME}
[c]Estimated with the G3DMHD model
[d]All CMEs combined.

CONCLUSION

The solar sources of the extremely large (Dst ~ -406 nT) geomagnetic storm on May 10, 2024 were studied. We focused on the propagation of multiple CMEs with an intention to answer the question about how do multiple CMEs affect the near-Earth space weather leading to large geomagnetic storms and which CME is responsible for the SSC and initiation of the May 10 geomagnetic storm? The propagation of the multiple CMEs was studied by both analyzing the white-light CME images and numerically simulating the multiple CMEs. It is shown that merging of multiple (4) CMEs within 1 AU are most likely the cause for May storm. Our simulation also suggests that when a fast CME catch up a slow CME from behind, it does not pass through each other; instead, the two CME become merged and move together. This is the reason why only one major shock is observed by *Wind* prior to the storm onset.

ACKNOWLEDGMENT

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