



# Eruption and Interplanetary Evolution of a Stealthy Streamer-Blowout CME Observed by PSP at ~0.5AU

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Streamer-blowout coronal mass ejections (SBO-CMEs) are the dominant CME population during solar minimum. Although they are typically slow and lack clear low-coronal signatures, they can cause geomagnetic storms. With the aid of extrapolated coronal fields and remote observations of the off-limb low corona, we study the initiation of an SBO-CME preceded by consecutive CME eruptions consistent with a multi-stage sympathetic breakout scenario. From inner-heliospheric Parker Solar Probe (PSP) observations, it is evident that the SBO-CME is interacting with the heliospheric magnetic field and plasma sheet structures draped about the CME flux rope. We estimate that  $18 \pm 11\%$  of the CME's azimuthal magnetic flux has been eroded through magnetic reconnection and that this erosion began after a heliospheric distance of ~0.35 AU from the Sun was reached. This observational study has important implications for understanding the initiation of SBO-CMEs and their interaction with the heliospheric surroundings.

**Keywords:** coronal mass ejection (CME), heliosphere, reconnection, interplanetary magnetic field, interplanetary magnetic cloud

## 1 INTRODUCTION

Coronal mass ejections (CMEs) are huge expulsions of magnetised solar plasma into interplanetary space. They were first discovered in the early 1970s (Tousey, 1973; Gosling et al., 1974) and initially assumed to be always associated with solar flares and/or filaments. Based on improved coronagraphic and multi-wavelength low-coronal observations, a class of CMEs emerging from streamers having signatures of flux ropes (FRs) was identified and named as “streamer-blowout” (hereafter SBO; Sheeley et al., 1982; Vourlidas et al., 2002; Vourlidas and Webb, 2018) CMEs (SBO-CMEs). Their evacuation may take hours to days and their location mostly follow the tilt of the heliospheric current sheet (HCS; Vourlidas and Webb, 2018)—a boundary between open and oppositely directed heliospheric field lines (Smith, 2001). Having no direct association with solar active regions, flares, and/or filaments, SBO-CMEs often lack classic low-coronal signatures (Robbrecht et al., 2009; Ma et al., 2010; Kilpua et al., 2014; Lynch et al., 2016) and are hence characterised as “stealth CMEs” (Robbrecht et al., 2009; Howard and Harrison, 2013). Recent high-resolution, multi-wavelength, and multi-viewpoint coronal observations have revealed weak low-coronal dynamics associated with stealth CMEs, in some cases enabling study of their formation and lift-off (Korreck et al., 2020; Palmerio et al., 2021b; O’Kane et al., 2021). Stealth CMEs may also cause significant magnetic storms at Earth that are problematic for space weather forecasting (Nitta et al., 2021).

CMEs are preceded by a gradual accumulation of free magnetic energy and subsequent triggering of plasma instabilities in the energized magnetic structure. The accumulated free energy can power consecutive sympathetic eruptions in multipolar flux systems (Li et al., 2008). In this configuration, a CME may initiate via the breakout mechanism (Antiochos et al., 1999), where the breakout reconnection at an overlying, stressed null point gives rise to an increasing expansion of the energized streamer arcade that eventually triggers explosive flare reconnection below the rising sheared/twisted flux rope field lines. Under certain conditions, this multipolar topology has been shown to support consecutive eruptions from the same flux system (homologous eruptions; e.g., DeVore and Antiochos, 2008) and consecutive eruptions from adjacent flux systems (sympathetic eruptions; e.g., Török et al., 2011; Lynch and Edmondson, 2013; Dahlin et al., 2019). Shen et al. (2012) and Zhou et al. (2021) studied sympathetic filament eruptions in quadrupolar and tripolar magnetic field regions, respectively, and proposed that the magnetic implosion mechanism might be a possible link between the successive flux rope eruptions.

Although typically observed to be slow, an SBO-CME's interplanetary counterpart (ICME) may deflect and compress the ambient plasma ahead of it. This causes draping of the interplanetary magnetic field (IMF) about the ICME, where the pattern of draping depends on the overall size and shape of the ICME as well as its speed relative to the upstream plasma (Gosling and McComas, 1987; McComas et al., 1988). The draped IMF may interact with an ICME via magnetic reconnection (McComas et al., 1994; Dasso et al., 2006), which may significantly erode its original magnetic flux and helicity (Dasso et al., 2006; Ruffenach et al., 2015; Pal et al., 2020, 2021; Pal, 2022).

During its fifth orbit around the Sun, Parker Solar Probe (PSP; Fox et al., 2016) crossed an SBO-CME at a heliospheric distance of 0.52 AU. Along with PSP, the CME was also observed by BepiColombo and Wind (Möstl et al., 2022). The CME was a stealth event that followed consecutive eruptions initiated from the Earth-facing solar disk. In this study, by multi-vantage point remote-sensing, white-light, and *in-situ* observations, we discuss the initiation and launch of this SBO-CME and its interaction with its surroundings in the heliosphere. In **Section 2**, we describe the satellite data sets utilized in this study. **Section 3** provides an overview of the event at its origin and in the interplanetary medium. In **Section 4**, we present our analysis of the remote-sensing EUV and white light coronagraph data to describe the SBO-CME eruption and its coronal dynamics. In **Section 5**, we present our analysis of the *in-situ* plasma and magnetic field observations by PSP to describe the SBO-CME's heliospheric evolution. Finally, in **Section 6**, we discuss our results and present our conclusions.

## 2 DATA SETS

To perform this study, we use remote-sensing white-light data from the inner (COR1) and outer (COR2) coronagraphs (field of views or FOVs: 1.5–4  $R_{\odot}$  and 2.5–15  $R_{\odot}$ , respectively), part of the

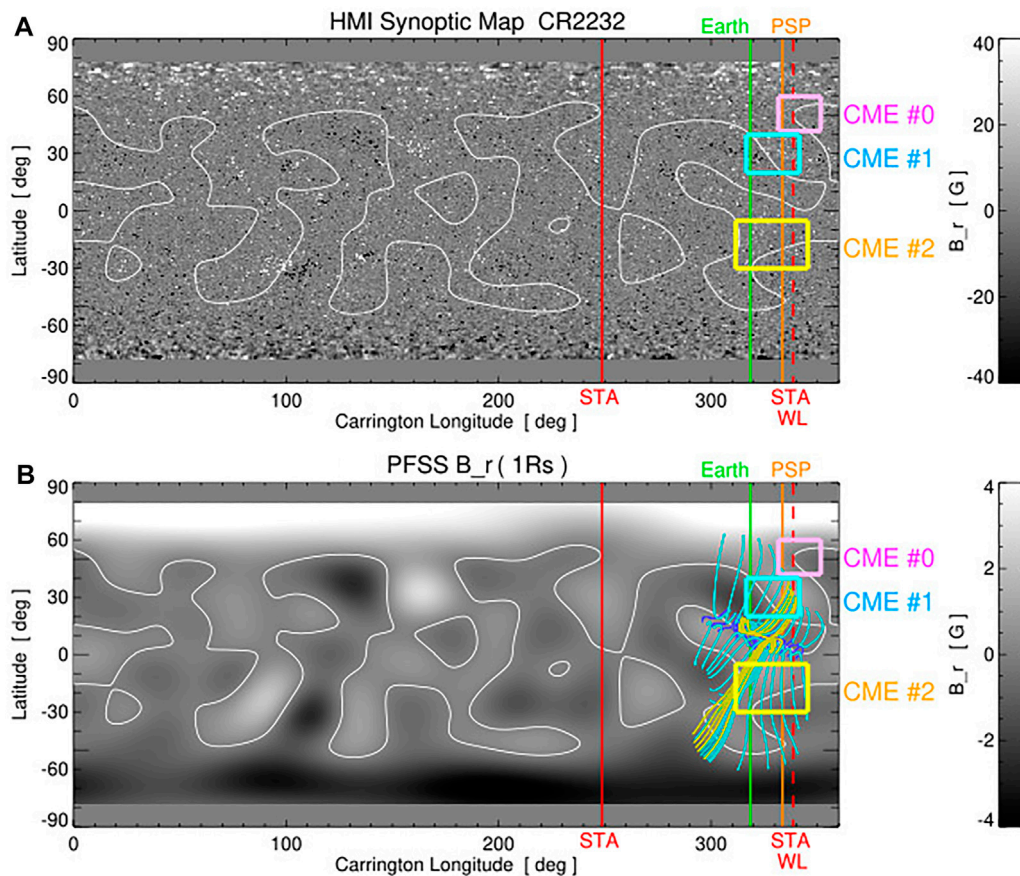
Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008) onboard the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al., 2008) Ahead (STEREO-A) spacecraft, and the C2 camera (FOV: 1.6–6  $R_{\odot}$ ) part of the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al., 1995) onboard the Solar and Heliospheric Observatory (SOHO; Domingo et al., 1995). We use extreme ultra-violet (EUV) imagery of the solar disk from the Extreme UltraViolet Imager (EUVI) camera onboard STEREO-A and the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) instrument onboard the Solar Dynamics Observatory (SDO; Pesnell et al., 2012), and photospheric radial synoptic magnetograms from the Heliospheric Magnetic Imager (HMI; Scherrer et al., 2012) onboard SDO. *In-situ* solar wind measurements are obtained from the fluxgate magnetometer, a part of the PSP's FIELDS (Bale et al., 2016) investigation, as well as the Solar Probe Cup (SPC; Case et al., 2020) and the Solar Probe Analyzers-Electron (SPAN-E; Whittlesey et al., 2020) instruments, part of PSP's Solar Wind Electrons Alphas and Protons (SWEAP; Kasper et al., 2016) investigation.

## 3 EVENT OVERVIEW

The SBO-CME first appeared over the west limb with a “classical” three-part structure, i.e., a bright front followed by a dark cavity containing a bright core Illing and Hundhausen (1983), in STEREO-A/COR2 images (from  $\sim 70^{\circ}$  East of the Sun–Earth line at  $\sim 1$  AU) around  $t_{\text{start}} = 16:30$  UT on 22 June 2020. STEREO-A/COR1 and COR2 observations of a gradual swelling of the overlying streamer before the eruption and a depleted corona afterward are the characteristic signatures used to identify this eruption as a slow SBO-CME. We also identified two preceding eruptions that significantly distorted and/or disrupted the overlying coronal helmet streamer leading up to and enabling the third, slow eruption of the SBO-CME.

**Figures 1–3** show remote observations summarizing the source region of the stealth SBO-CME event (hereafter CME #2) and the two preceding eruptions (hereafter CMEs #0 and #1). **Figure 1A** shows the HMI synoptic magnetogram for Carrington Rotation (CR) 2,232 where the red, green, and orange vertical lines indicate the Carrington longitude of the STEREO-A, SOHO, and PSP spacecraft positions at the time of the SBO-CME, respectively. In the LASCO/C2 coronagraph, CME #2 appeared as a faint event on the western side of the solar disc. Although the appearance of CME #2 in the coronagraphs indicates its origin to be from the Earth-facing side of the Sun, no clear eruptive signatures were observed in SDO/AIA imagery. Therefore, we classify CME #2 as a stealth event.

It is apparent from EUV imagery that CME #2 lifted off from the southern hemisphere. By modeling the coronal evolution of the CME using the Forecasting a CME's Altered Trajectory (ForeCAT; Kay et al., 2015) model and confirming its results with the output of the graduated cylindrical shell (GCS; Thernisien et al., 2006) model applied to coronagraph data, Palmerio et al. (2021a) found that the CME deflected towards the HCS. In the upper corona, we obtain a de-projected speed for the CME of  $\sim 220$  km/s through forward



**FIGURE 1 | (A)** Synoptic magnetogram of photospheric  $B_r$  from SDO/HMI. The blue, green, and red vertical lines denote the Carrington longitude of STEREO-A, SOHO/Earth, and PSP on 21 June 2020, respectively. **(B)** Synoptic magnetogram of the PFSS  $B_r$ , showing the large-scale flux distributions with representative magnetic field lines of the multipolar flux system on STA's west limb (WL; red dashed vertical line). In both panels the average magnetic PILs are shown as the white contours and the three CME source regions are indicated.

modeling with the GCS technique. The obtained speed is very similar to the typical values for stealth CMEs (Ma et al., 2010) and consistent with the results in Section 4.3. The CME arrived at PSP, located at 0.52 AU and  $\sim 20^\circ$  west of the Sun–Earth line, on 25 June, approximately 3 days after its detection in STEREO/COR2. At PSP the event featured a smoothly rotating magnetic field direction, high-intensity magnetic field, and low plasma- $\beta$  ( $< 1$ ) during most of its interval. No signature of a CME-driven interplanetary shock was found in the *in-situ* observations.

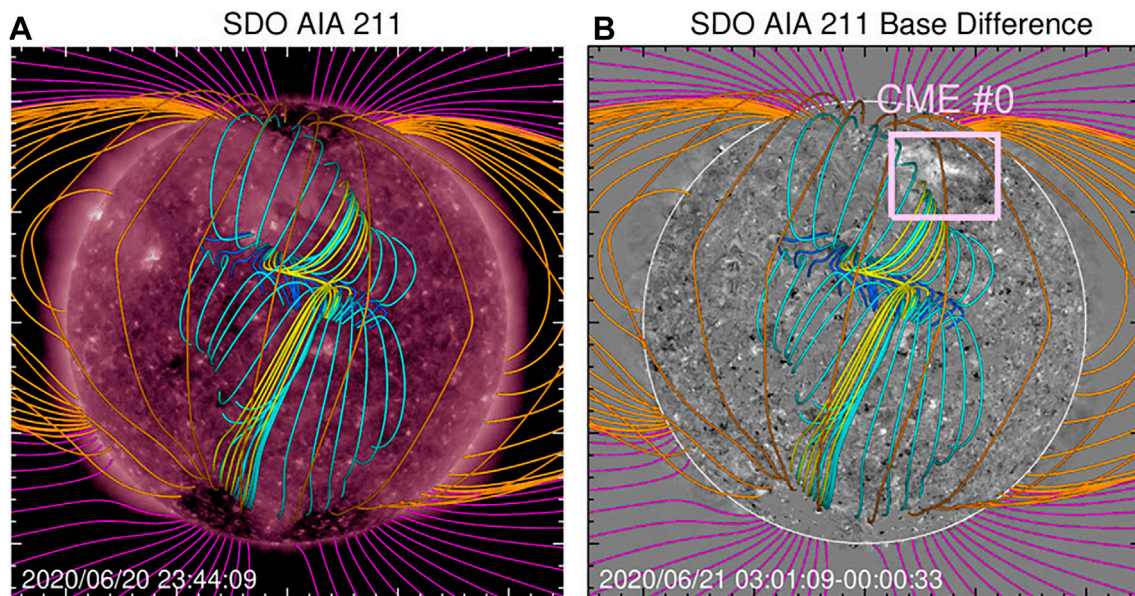
## 4 REMOTE-SENSING OBSERVATIONS AND ANALYSIS OF THE SBO-CME

Off-limb STEREO-A/EUV, COR1, and COR2 imagery reveal that the SBO-CME eruption was part of a multi-stage, sequential (and most likely sympathetic) eruption scenario (e.g., Török et al., 2011; Lynch and Edmondson, 2013; Schrijver et al., 2013). In this Section, we identify the coronal source regions and analyse the coronal dynamics of each of the sequential eruptions leading up to and including the SBO-CME.

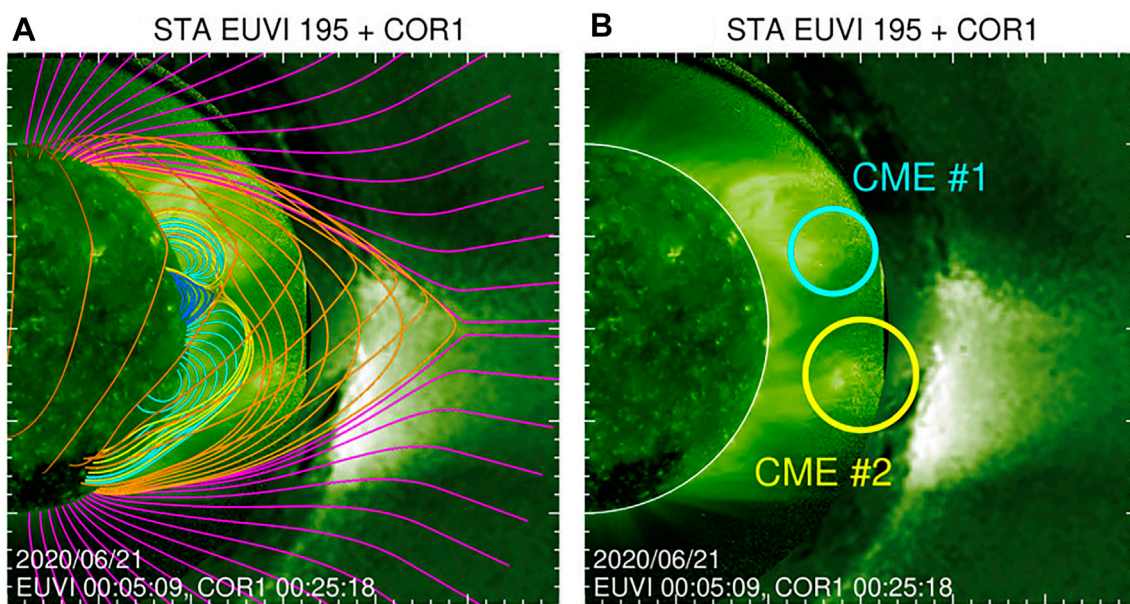
### 4.1 Solar Sources of the Sequential Eruptive Events

The HMI synoptic map shown in **Figure 1A** depicts a typical solar minimum/quiet-Sun corona. **Figure 1B** shows a low-order potential field source surface (PFSS; Wang and Sheeley, 1992) representation of the global magnetic field during CR2232. In both panels, the PFSS global polarity inversion lines (PILs) are plotted as white contours. Representative PFSS field lines are shown in **Figure 1B** over the synoptic map. At the longitudes of Earth and PSP (green and orange vertical lines, respectively), the latitudinal distribution of the radial field show a sequence of +, −, +, − polarities from north to south with three main PILs on the Earth-facing disk, resulting in a multipolar configuration beneath the helmet streamer (i.e. the topology required for the magnetic breakout CME initiation of Antiochos et al., 1999). **Figures 2A,B** show SDO/AIA 211 Å EUV image and the AIA 211 Å image in base-difference to highlight the location of the on-disk signature associated with the first of the sequential eruptions, CME #0. This region (the  $\sim 20^\circ \times \sim 15^\circ$  area marked in pink) is located





**FIGURE 2 | (A)** SDO/AIA 211Å emission and representative PFSS magnetic field lines illustrating the different flux systems on the Earth-facing solar disk. **(B)** The same PFSS field lines plotted over the base-difference 211Å image. The on-disk eruption signatures (and source region) for CME #0 (pink) are to the northwest of the multipolar flux system.



**FIGURE 3 | (A)** Composite image showing the limb-enhanced STA/EUVI 195Å emission together with the processed STA/COR1 white light observations. Representative PFSS magnetic field lines are also shown to identify the (approximate) positions of the different flux systems on the west limb. **(B)** The same composite image as panel **(A)** with annotation to show the pre-eruption (flux rope) progenitors for CME #1 (cyan) and CME #2 (yellow) at  $r \sim 1.3R_{\odot}$  in the northern and southern side-lobe arcades, respectively. An animation of the limb-enhanced STA/EUVI data is included as **Supplementary Video S1** in the supplementary materials.

outside and to the northwest of the equatorial multipolar flux system. Representative PFSS field lines are also shown in SDO/AIA 211 Å images (Figures 2A,B), and in a composite of STEREO-A EUVI 195 Å and COR1 data

(Figure 3A). Figure 3A shows the side-lobe flux systems in cyan, the central flux system in blue, the overlying flux system in orange, and open field lines in magenta. Figure 3B indicates the off-limb EUVI emission features identified as the

progenitors for the second (CME #1) and third (CME #2) eruptions of the event sequence. The comparison of the PFSS topology in **Figure 3A** and the locations of the high-altitude progenitors for CMEs #1 and #2 in **Figure 3B** clearly indicate that CMEs #1 and #2 originate in the (energized) northern and southern side-lobes of the streamer flux system, respectively. An animation of the limb-enhanced STEREO-A EUVI 195 Å imaging data is included as **Supplementary Video S1** in the supplementary material. In the animation, all three sequential eruptions (CMEs #0, #1, and #2) are indicated using arrows, although for the animations, we recommend viewers manually sweep the slider/progress bar quickly back and forth to more easily identify the evolutionary dynamics.

## 4.2 STEREO-A/COR1 Image Processing and Height-Time Profiles

To understand the eruption dynamics we analyse STEREO-A/COR1 and COR2 data and fit the height-time points calculated from the COR2 J-maps. The J-maps are time-elongation maps created following the method explained in Sheeley et al. (1999). We utilise processed COR1 data available at STEREO Science Center which gives an image every  $\Delta t \sim 5$  min (i.e.,  $t_n = n \Delta t$ ). The first step is to read in all the files ( $N$ ) and make a *minimum background* image from the data sequence.

$$I_{\text{bkg}}(i, j) = \min[I_{\text{COR1}}(i, j, t_n)] \quad \text{for } n \in [0, N-1]. \quad (1)$$

We note this is essentially the same procedure that is used to construct (and remove) the F-corona background component in the standard processing of SOHO/LASCO or STEREO/SECCHI coronagraph data. Our application to the previously processed COR1 data represents the removal of a minimum K-corona background. Next, we loop through image sequence data and 1) subtract the  $I_{\text{bkg}}$  minimum, 2) multiply by a (weak) radial function  $(r_{ij}/R_\odot)^\alpha$  with  $\alpha = 1.2$  and  $r_{ij} = \sqrt{x_i^2 + y_j^2}$ , and 3) average nine total images per frame ( $\pm 4$  images on either side) to obtain a  $\sim 45$  min averaging window. This yields

$$\tilde{I}_{\text{proc}}(i, j, t_n) = \frac{1}{9} \sum_{n=-4}^{+4} \left( \frac{r_{ij}}{R_\odot} \right)^\alpha (I_{\text{COR1}}(i, j, t_n) - I_{\text{bkg}}(i, j)). \quad (2)$$

In the final step, we saturate the intensity range from the resulting image to enhance the contrast. This results in a type of base-difference image sequence where the (averaged) difference  $\tilde{I}_{\text{proc}}$  is above the intensity minimum values over a temporal interval rather than from the intensity at an initial time. In general, base-difference processing has demonstrated an advantage in the identification of larger-scale, slowly-varying signatures of eruptive transients, such as the EUV dimmings and/or brightenings, associated with stealth or stealthy CME eruptions (e.g., Palmerio et al., 2021b; Nitta et al., 2021).

## 4.3 Height-Time Fit Parameters

To fit the points in the height-time “J-maps” derived from the STEREO-A/COR1 and COR2 measurements, we use the Sheeley et al. (1999) formulation given by,

**TABLE 1** | Best-fit parameters for the height-time profiles of the three sequential eruptions.

Event	$t_0$ (day)	$r_0$ ( $R_\odot$ )	$r_a$ ( $R_\odot$ )	$v_a$ (km/s)	$v(r = 20R_\odot)$ (km/s)
CME #0	-21.12	2.47	1.26	350.17	350.17
CME #1	-21.58	1.67	1,321.0	1,472.8	172.90
CME #2	-22.51	2.07	16.54	302.96	246.48

$$h(t) = r_0 + 2r_a \ln \left[ \cosh \left( \frac{v_a(t + t_0)}{2r_a} \right) \right] \quad (3)$$

that results in an analytic expression for the velocity as a function of radial distance,

$$v(r) = v_a \sqrt{1 - \exp \left[ \frac{-(r - r_0)}{r_a} \right]}. \quad (4)$$

This functional form has four free parameters,  $(r_0, t_0, r_a, v_a)$ . The initial position is given by  $r_0$  at time  $t_0$ . The parameter  $v_a$  is the asymptotic velocity (as  $r \rightarrow \infty$ ) and  $r_a$  is the radial distance that  $v(r)$  achieves 80% of its asymptotic value.

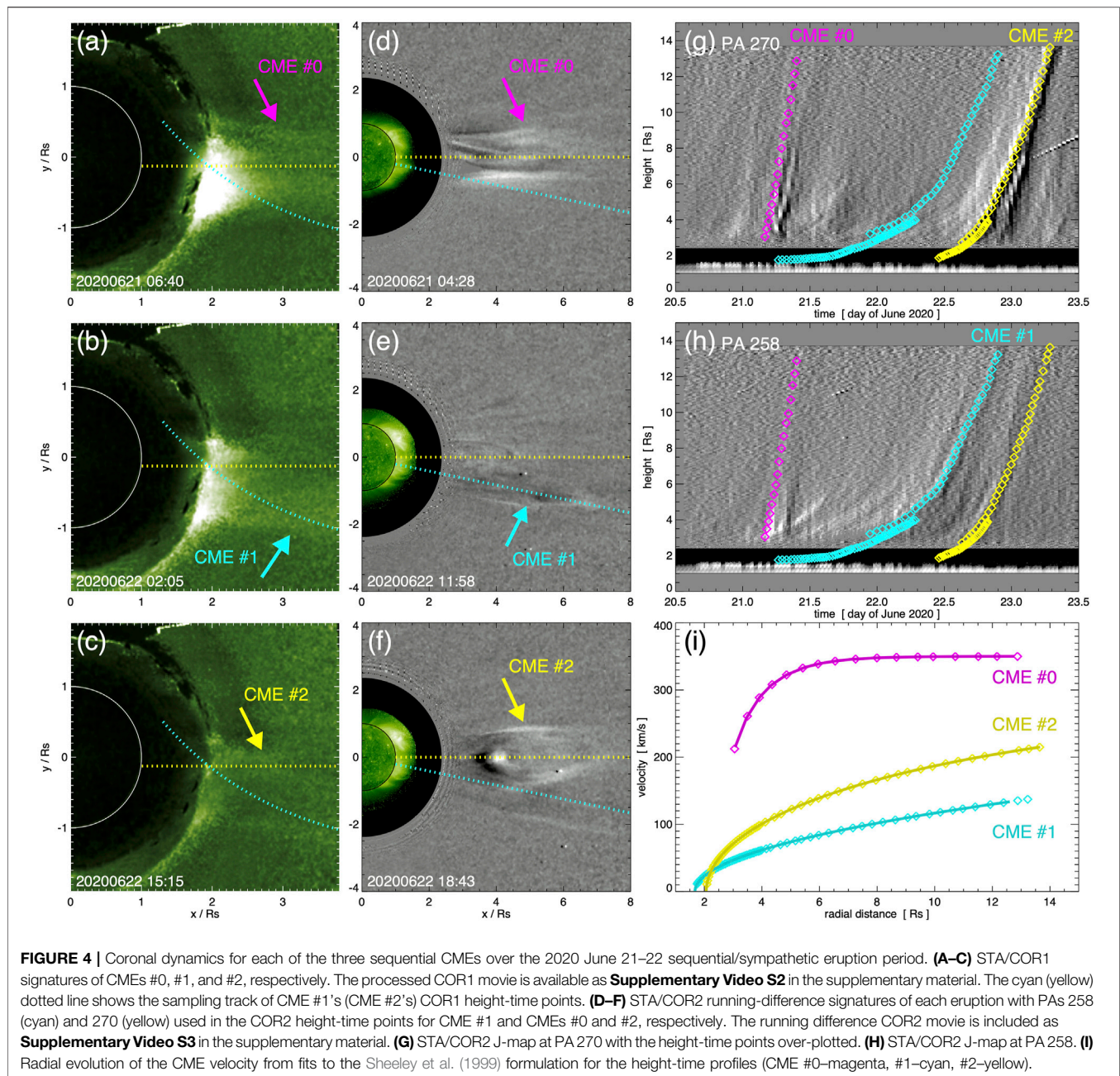
We use the IDL function `curvfit.pro` to minimize the  $\chi^2$  error between the observed height-time points and the model values from **Eq. 3**. The weights given to each point  $h(t_i)$  for the fitting procedure are uniform, i.e.  $w_i = 1$  for each  $i$ . The best-fit parameter values for each profile are listed in **Table 1** along with the velocity  $v(r)$  evaluated at  $r = 20R_\odot$ . The height-time points are shown in **Figures 4G,H** while the corresponding velocity profiles are shown in **Figure 4I**.

## 4.4 Eruption Scenario and Coronal Dynamics

In the following section we report the low-coronal signatures of each of the three sequential CMEs and their dynamics through the FOVs of the coronagraphs. Herein, we localize features in the EUV and coronagraph images using the position angle (PA), i.e., the counter-clockwise angle from  $0^\circ$  pointing up (solar north).

CME #0 is the only eruption that had easily recognizable on-disk signatures in SDO/AIA data. **Figure 2B** shows that these signatures are largely outside of the multipolar flux system. Despite CME #0's source region being behind the limb (from the STEREO-A view), the upper edge of the northern side-lobe arcade does brighten in the off-limb EUVI 195 Å data, beginning on 21 June at 00:54 UT and followed by an apparent loop opening at  $\sim 1.3 R_\odot$  and PA  $308^\circ$ . The EUVI off-limb activity continues through  $\sim 03:30$  UT. The AIA 211 Å dimming shown in **Figure 2B** begins on 21 June at  $\sim 03:00$  UT, followed immediately by a brightening that expands northward until it reaches the coronal hole boundary. The first indication of CME #0 in the COR2 running-difference data occurs at 03:24 UT as a brightening at the northern edge of the helmet streamer. The top portion of the streamer is apparently blown out (detaches) and has a concave-up morphology in the running-difference COR2 movie (**Figure 4D**, **Supplementary Video S3**). By 04:54 UT, the





leading edge of the CME #0 ejecta has reached  $\sim 6 R_{\odot}$  (at PAs 265–280°) while the trailing edge is at  $\sim 2.7 R_{\odot}$ . **Figure 4** (top row) shows the CME #0 streamer detachment eruption in STEREO-A COR1 data, COR2 running-difference data, and in the J-map height-time plot at PA 270° as panels **Figures 4A,D,G**, respectively. **Figure 4I** shows that CME #0 quickly reaches a constant, 350 km/s radial velocity for  $r \geq 6 R_{\odot}$ .

The next two CMEs (#1 and #2) originate from the northern and southern side-lobes of the equatorial multipolar flux system. These eruptions occur much closer in time, with the upper part of the northern side-lobe EUVI enhancement in **Figure 3B** apparently

to disconnect on 21 June at 09:24 UT (at  $1.3 R_{\odot}$ , PA  $\sim 270^{\circ}$ ), and disappearing from the EUVI field of view by 11:54 UT. Signatures of CME #1 in the COR1 field of view follow an overall southwestern trajectory (dotted cyan line in **Figures 4A–C**). A narrow, dark cavity appears at the inner edge of the COR1 occulter on 21 June at  $\sim 08:00$  UT ( $1.75 R_{\odot}$ , PA  $280^{\circ}$ ), just after the opening of the northern flank of the helmet streamer by CME #0 in **Figure 4A**. The cavity expands to the southwest and an extremely faint, circular leading edge becomes visible at  $\sim 16:00$  UT. As this front expands, the streamer swells and deflects towards the south. This front fades with distance, becoming indistinguishable from the streamer by 23:40 UT. A faint, circular arc structure is seen at the inner boundary of COR2 ( $3\text{--}3.3 R_{\odot}$ , PA

255–275°) at 20:54 UT on 21 June and a bright edge that is wider than the helmet streamer is seen to be moving along the streamer stalk at 3.6–3.8  $R_\odot$  by 22 June 01:54 UT. The streamer continues its southward deflection in the COR2 data from 22 June 02:00–10:00 UT. A streamer blob-like enhancement begins to form/pinch-off at 11:54 UT ( $\sim 5.5 R_\odot$ , PA 258°; **Figure 4E**). The tail end of the blob reaches  $\sim 7 R_\odot$  by 13:54 UT. CME #1's height–time points along the cyan dotted lines are shown on the J-maps of **Figures 4G,H**. The CME #1 is the slowest of the sequential eruptions, reaching  $\sim 140$  km/s by 13  $R_\odot$ .

The remainder of the remote-sensing analysis focuses on the third sequential/sympathetic eruption, CME #2, i.e., the SBO-CME. The circular, pre-eruption EUVI enhancement labeled in **Figure 3B** occurs over PA 255–265° at an altitude of 1.3–1.6  $R_\odot$  and may correspond to CME #2's pre-eruption flux rope core/central axis. This feature shows a slow, rolling motion, beginning at 05:40 UT on 21 June (see **Supplementary Video S1**). There are other dynamic features also seen in the southern side-lobe arcade before CME #2's eruption. For example, a bright loop begins to contract/shrink in response to CME #1's activity in the northern side-lobe arcade which occurs simultaneously with CME #2's flux rope progenitor beginning to rise with a slight northwestern trajectory. This EUV structure disappears from the EUVI field of view at 17:54 UT. By 19:55 UT, there is a slight enhancement of a Y-shaped feature with the vertical segment at PA 256° and the V-shaped split at 1.27  $R_\odot$ , PA 260°. In COR1, the remaining helmet streamer material diminishes in brightness between CME #1 and the eruption of CME #2. Another V-shaped emission structure becomes visible at 11:15 UT on 22 June, at  $\sim 2 R_\odot$ , PA 270°. The COR1 V-shape shows rapid acceleration and leaves the frame by 22 June at 19:25 UT. The leading edge of CME #2 becomes visible in COR2 data at 14:13 UT. By 14:55 UT, the circular core appears at the inner boundary (2.6–3.2  $R_\odot$ , PA 264–278°). The 3-part CME structure is clearly visible in **Figure 4F** and its kinematics are captured in the J-maps and velocities of **Figures 4G–I**. CME #2 shows a larger acceleration than CME #1, reaching a speed of  $\sim 220$  km/s by 14  $R_\odot$ .

## 5 IN-SITU OBSERVATIONS AND ANALYSIS OF THE SBO-CME

**Figure 5** shows PSP *in-situ* observations of the solar wind during 24–27 June 2020. On 25 June, the PSP magnetometer recorded a steady enhancement in magnetic field magnitude  $B$ , the initiation of a smooth rotation in the magnetic field vector (as indicated by the  $B_T$  and  $B_N$  variation), and an increment in the plasma velocity  $V_{sw}$ . Based on the *in-situ* signatures, we estimate that the leading-edge of the ICME encountered the spacecraft at  $t_{in} = 16:00$  UT on 25 June. The coherent rotation in the magnetic field longitude angle  $\phi_B$  (measured between  $\mathbf{B}$  projected onto the  $R$ – $T$  plane and  $\hat{R}$ ) lasted for approximately 18 h, until  $t_{out} = 09:54$  UT on 26 June. The black solid vertical lines in **Figure 5** indicate  $t_{in}$  and  $t_{out}$ . A drop in proton temperature  $T_p$ , a dip in plasma density  $N_p$ , and plasma- $\beta$  (specifically in the flux rope core) during this interval indicate the presence of a confined plasma structure, i.e., a magnetic cloud (MC). The MC was expanding as it passed

PSP, the front-to-rear speed difference being  $\approx 22$  km/s. Inside the MC, the electron pitch angle distribution (PAD) at 283.9–352.9 eV remains unidirectional, indicating the abundance of outward field lines at the front and inward field lines at the rear part of the MC (Carcaboso et al., 2020).

## 5.1 Minimum Variance Analysis and ICME Magnetic Flux Erosion

We employ nested-bootstrap minimum variance analysis (MVA; Sonnerup and Cahill, 1967; Kawano and Higuchi, 1995) method and a self-similarly expanding linear force-free FR (LFF) model having cylindrical cross-section (Burlaga, 1988; Lepping et al., 1990; Hidalgo et al., 2000; Marubashi and Lepping, 2007) to the *in situ* observations of the magnetic profile of MC. Following Ruffenach et al. (2015), we perform 1,000 random data re-sampling and repeat this for seven nested time intervals separated by 10 min within the MC. Here, each time interval starts 10 min after and ends 10 min before the previous time interval. Utilising these methods to MC *in situ* observations, we determine the MC axis orientation ( $\theta_{ax}$ ,  $\psi_{ax}$ ) in RTN coordinates.

The bootstrap method (Kawano and Higuchi, 1995) with random data re-sampling helps assessing the impact of the intrinsic variability inherent in the magnetic field data on the axis determination and the nested time intervals within the MC mitigates the uncertainty involved in defining the MC boundaries on the determination of its axis. After obtaining the MC frame ( $\hat{x}_{cloud}$ ,  $\hat{y}_{cloud}$ ,  $\hat{z}_{cloud}$ ) using MVA and the LFF model, the magnetic field components  $B_{x,cloud}$ ,  $B_{y,cloud}$ ,  $B_{z,cloud}$  in the MC frame are obtained and the closest distance  $p_0$  (normalised to the MC radius  $R_{mc}$ ) between the MC center and PSP crossing path is approximated. In MVA,  $p_0$  is approximated as  $p_0 = \langle B_{x,cloud} \rangle / \langle B \rangle$  (Démoulin and Dasso, 2009; Ruffenach et al., 2015).

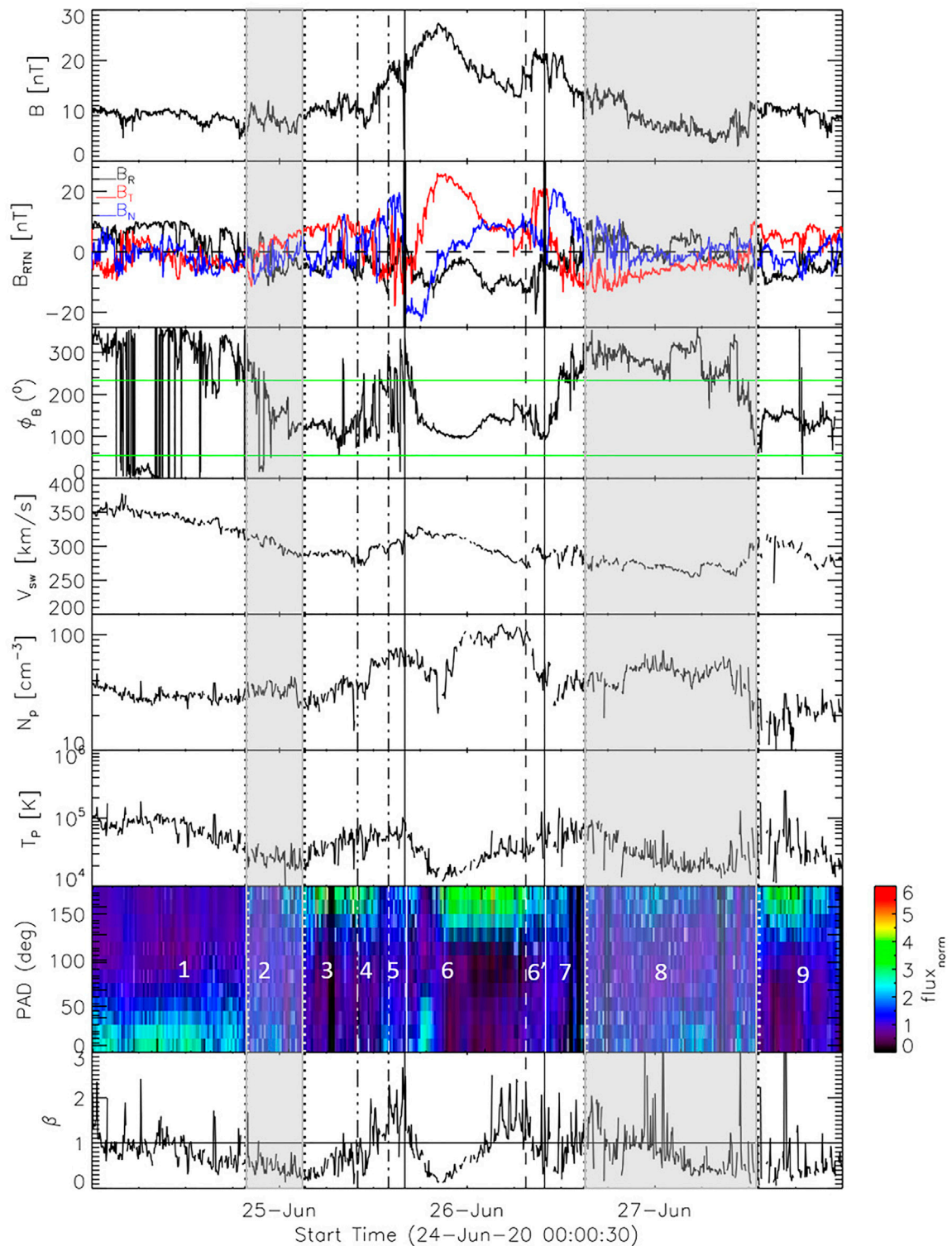
We apply the model-independent “direct method” (Dasso et al., 2005b) that estimates MC flux accumulated in the azimuthal plane,  $\phi_{dir,acc}^p$ , directly from the observed magnetic field and plasma speed profiles in MC, assuming cylindrical symmetry for the magnetic field configuration in the MC's cross-section. This method computes azimuthal flux in the outbound path (from the MC center at  $t = t_c$  to its boundary at  $t = t_{out}$ ) as

$$\frac{\phi_{dir,out}^p}{L_{mc}} = \int_{t_c}^{t_{out}} B_{y,cloud}(t) \frac{L'_{mc}(t)}{L_{mc}} v_{x,cloud}(t) dt, \quad (5)$$

where  $L'_{mc}(t)$  is the axial length of the FR,  $L_{mc} = L'_{mc}(t_{in})$ , at the time of the spacecraft encounter,  $t = t_{in}$  (Dasso et al., 2005a, 2006, 2007). To calculate  $\phi_{dir,out}^p / L_{mc}$ , we utilise MC axis orientation ( $\theta_{ax}$ ,  $\psi_{ax}$ ) from the nested-bootstrap MVA and LFF fitting (and their mean). To perform the azimuthal flux  $\phi_{dir,in}^p$  calculation for the inbound path (when PSP approaches the MC center), the integration limits ( $t_c$ ,  $t_{out}$ ) are replaced by ( $t_{in}$ ,  $t_c$ ). In Eq. (5), the ratio  $L'_{mc}(t) / L_{mc}$  can be approximated as

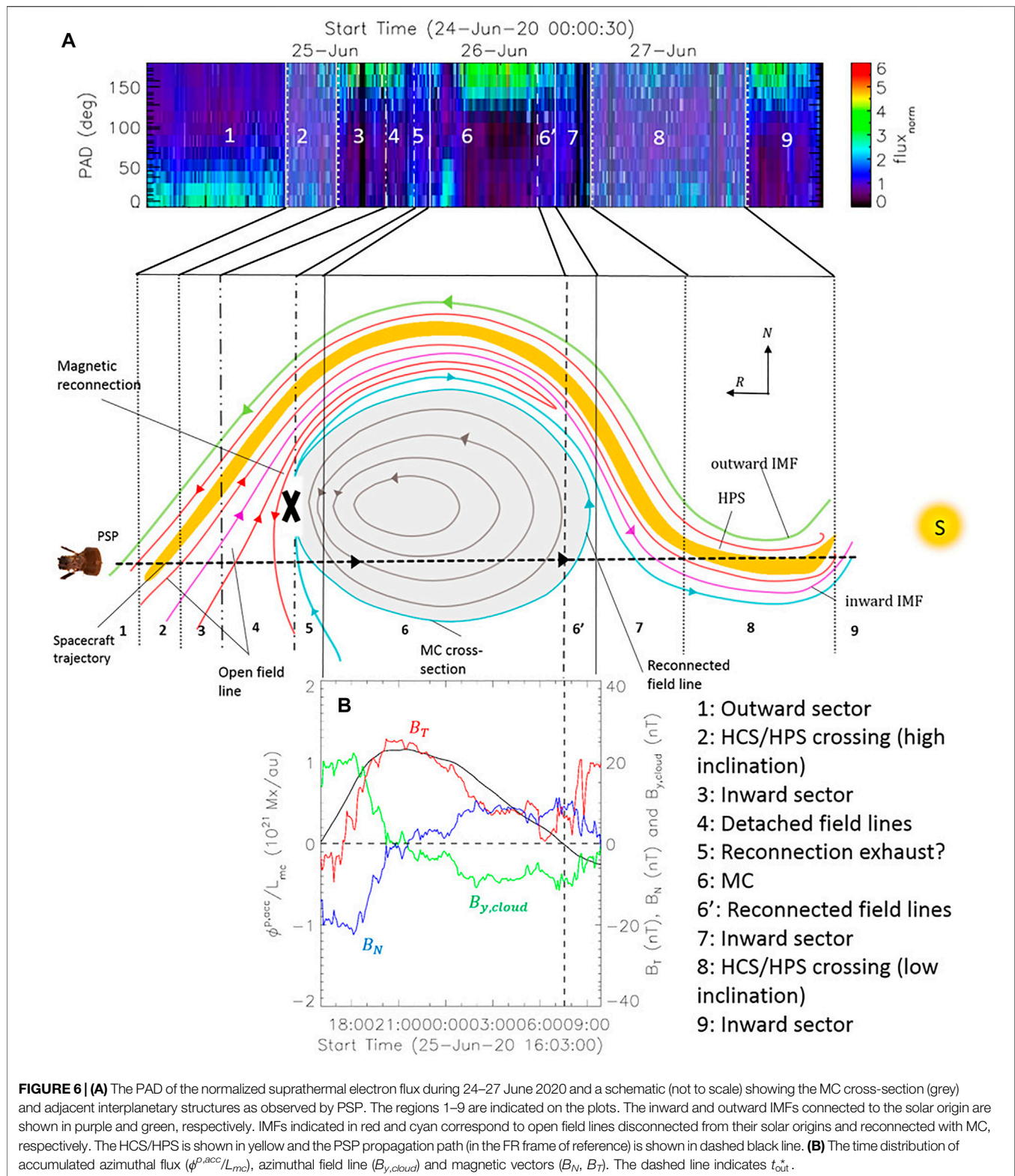
$$\frac{L'_{mc}(t)}{L_{mc}} \approx 1 + \frac{(t - t_{in})V_{mc}}{r_{psp}}, \quad (6)$$





**FIGURE 5** | Solar wind magnetised plasma measurements (from top to bottom:  $B$ ,  $B_{RT}$ ,  $\phi_B$ ,  $V_{sw}$ ,  $N_p$ ,  $T_p$ , PAD of normalised suprathermal electron flux, plasma- $\beta$ ) during 24–27 June 2020. The  $\phi_B$  between horizontal green lines correspond to sunward IMF. The solid black lines show  $t_{in}$  and  $t_{out}$  and the dashed vertical line indicates  $t_{out}^*$ . The shaded regions correspond to HCS/HPS crossings. The annotated regions indicate the regions 1–9 described in text.





where  $r_{psp}$  and  $V_{mc}$  denote the Sun–PSP distance and the central speed of the MC, respectively (Dasso et al., 2007).

To quantify the azimuthal flux eroded due to reconnection, we calculate the inbound–outbound flux asymmetry. If reconnection

occurs at the front of the MC, the reconnected flux that still remains part of the MC causes an outbound asymmetry in  $\phi_{p,acc}$ . Therefore, the azimuthal flux contained in the FR before the erosion is  $\phi_{dir,out}^p$  and the eroded flux is  $\phi_{erod}^p = (\phi_{dir,out}^p - \phi_{dir,in}^p)$ .

We determine the percentage of erosion as  $\phi_{er} = (\phi_{erod}^p / \phi_{dir,out}^p) \%$ . We determine a new FR boundary at  $t = t_{out}^*$  by excluding the piled up, reconnected flux at the MC rear. The region between  $t_{out}^*$  and  $t_{out}$  represents the back region of MC (e.g., Dasso et al., 2006; Kilpua et al., 2013) that expands due to velocity difference between the solar wind velocity  $V_{sw}$  at  $t_{out}$  and  $V_{mc}$ , and any additional flux that may have resulted from continued reconnection in the trailing eruptive flare/CME current sheet. Considering only the first factor, we estimate the time  $t_{rec} = t_{in} - \delta t$  after which the ongoing flux erosion starts. Here the elapsed time is given by

$$\delta t = \frac{(t_{out} - t_{out}^*) V_{sw}(t_{out})}{V_{mc} - V_{sw}(t_{out})}. \quad (7)$$

## 5.2 SBO-CME Adjacent Interplanetary Structures

In **Figure 6A**, we present a schematic of the MC and its adjacent interplanetary structures along with the PAD of normalised suprathermal electron flux as observed by PSP. Here and in the following discussion, the segments indicated by numbers 1–9 correspond to the annotated regions of **Figure 5**.

The continuous probing of solar wind preceding and following the MC indicates the presence of large-scale interplanetary structures around the MC. PSP came across an outward field line sector 1) until 19:42 UT on 24 June, when it encountered a true sector boundary (TSB; 2)—a boundary between the magnetic field lines of true opposite polarity at their solar source (Kahler and Lin, 1994; Crooker et al., 1996; Kahler et al., 1996). It is identified by a switch in direction of suprathermal electrons from field-aligned to anti-field-aligned. The values of  $\phi_B$  between the horizontal green lines (i.e.,  $54^\circ < \phi_B < 234^\circ$ ) in the third panel of **Figure 5** correspond to the inward-directed field with respect to the Parker spiral field with a local spiral angle of  $36^\circ$ . During 2,  $\phi_B$  displayed a  $\sim 180^\circ$  change across one of the nominal sector boundaries (green lines). Also, the suprathermal electron PAD becomes isotropic, indicating a drop in heat flux (McComas et al., 1989) during that time. Thus, 2 (19:42 UT 24 June – 03:11 UT 25 June) shown by the first shaded region in **Figure 5**, contains the HCS crossing (e.g., Crooker et al., 2004; Lavraud et al., 2020). The coincidence of the TSB, current sheet, and elevated plasma  $\beta$  at scales from minutes to few hours indicates the presence of a steady-state heliospheric plasma sheet (HPS; Crooker et al., 2004) encasing the HCS. The front of two coincides with a minor  $\sim 25$  min  $\beta$  peak. This confirms the presence of the HPS in that region. Also, two corresponds to a high  $N_p$  and low  $T_p$  compared to the surroundings as well as a negative velocity gradient, which generally characterize the isotropic PAD region (McComas et al., 1989). Magnetic reconnection across the HCS above a coronal streamer may generate detached magnetic structure and isotropize the suprathermal electron PAD (McComas et al., 1989; Crooker et al., 2003; Gosling et al., 2005b; Chollet et al., 2010; Carcaboso et al., 2020). Due to the lack of good-quality,

high-resolution data, we are unable to locate reconnection exhaust signatures (Gosling et al., 2005a; Phan et al., 2020) at the front and rear boundary of 2. We employ MVA to the magnetic field data over two and estimate the absolute latitude angle  $\theta_n$  of the direction normal to the local current sheet (Lepping et al., 1996a,b). We obtain  $\theta_n$  as  $49^\circ$ , indicating that the HCS surface was inclined to the spacecraft orbital plane. This was likely resulting from the IMF draping about the MC, which may lead to MC erosion via magnetic reconnection.

After 2, there exists an inward field line sector 3) followed by a short interval of isotropic PAD region (4). Just before the MC front boundary, during 13:55–16:00 UT on 25 June (5), we locate a region with an accelerated  $V_{sw}$ , higher  $N_p$ , higher  $T_p$ , and reduced  $B$  than the surrounding solar wind. These indicate a possibility of the presence of reconnection exhaust (Gosling et al., 2005a). However, due to the insufficient resolution of plasma data this cannot be confirmed. The dash-dotted line in **Figure 5** indicates the start time of 5. After the passage of the MC (6 and 6'), there exists an inward IMF region 7) followed by region 8 (15:03 UT 26 June–13:11 UT 27 June; second shaded region in **Figure 5**) with enhanced  $N_p$ , reduced  $T_p$  than the surroundings, and isotropic distribution of solar wind electrons, where  $\phi_B$  hovered near the boundary between the outward and inward sectors until it made a definite turn towards the inward sector at 10:50 UT on 27 June accompanied by a sharp peak in  $\beta$ . Taken together, these signatures suggest that once again PSP encountered the HCS and HPS. During 8,  $\theta_n$  is found to be  $61^\circ$ , indicating a low inclination of region eight to the PSP orbital plane. After 8, there exists a region 9) of inward IMF.

## 5.3 ICME Interaction With the Draped Interplanetary Magnetic Field

To determine whether the IMF draping evident from the *in-situ* observations resulted in erosion of MC flux via reconnection, we further analyse the MC's magnetic flux profile. We only focus on its azimuthal flux, because erosion mainly affects the MC's outer part where azimuthal flux dominates. After obtaining the MC's axis orientation using nested-bootstrap MVA and LFF fitting, we derive the MC's accumulated azimuthal flux  $\phi_{dir,out}^p/L_{mc}$ , its eroded azimuthal flux  $\phi_{erod}^p$ , percentage of erosion  $\phi_{er}$  and the time  $t_{rec}$  after which the ongoing flux erosion might have started. Both the MVA and LFF fitting techniques yield a right-handed ICME flux rope, with  $p_0$  being approximately half and the flux rope axis almost parallel to the spacecraft orbital plane and perpendicular to the Sun–PSP line ( $\hat{r}$ ).

In **Table 2**, we summarise the results obtained from the *in situ* observation analysis of the MC. We provide nested-bootstrap MVA and LFF fitting results and MC's azimuthal flux balance-related analysis. Utilising the ICME's Sun-to-PSP transition speed  $V_{tr} \sim 300$  km/s and  $t_{rec}$ , we obtain the heliospheric distance  $r_{rec} = V_{tr} (t_{rec} - t_{start})$  after which the ongoing flux erosion might have started. We provide the result in **Table 2**. Note that erosion of the original flux rope might have started closer to the Sun, with the corresponding back region having lost identifiable CME properties (and having

**TABLE 2** | Summary of results obtained from the ICME *in-situ* flux analysis at PSP.

Quantity	<i>In-situ</i> reconstruction method		
	LFF	MVA <sup>a</sup>	mean (LFF, MVA)
Time interval of MC	16:00 UT 25 June – 09:54 UT 26 June		
MC axis orientation ( $\theta_{ax}$ , $\psi_{ax}$ )	(2°, 83°)	(5 ± 6°, 64 ± 2°)	(4°, 74°)
Impact parameter ( $\rho_0$ ) <sup>b</sup>	−0.45	−0.65	−0.50
Eigenvalue ratio ( $\lambda_2/\lambda_3$ ) <sup>c</sup>	—	2.3 ± 0.2	—
Root-mean-square error ( $E_{rms}$ ) <sup>b</sup>	0.32	—	—
Azimuthal flux ( $\phi_{dir,out}^p/L_{mc}$ )	$1.35 \times 10^{21}$ Mx/au	$1.5 \pm 0.2 \times 10^{21}$ Mx/au	$1.4 \times 10^{21}$ Mx/au
Percentage of flux erosion ( $\phi_{er}$ )	8%	29 ± 13%	18 ± 11%
Time of accumulated azimuthal flux imbalance <sup>e</sup>		$t_{out}^* = 07:30$ UT 26 June	
Estimated <i>start time</i> of the flux erosion <sup>e</sup>		$t_{rec} \sim 17:00$ UT 24 June	
Estimated <i>start distance</i> of the flux erosion <sup>e</sup>		$r_{rec} \sim 0.35$ au	

<sup>a</sup>Nested-bootstrap MVA (see Ruffenach et al., 2015).

<sup>b</sup>A negative value means the spacecraft crosses south of the MC, axis.

<sup>c</sup>The intermediate ( $\lambda_2$ ) to minimum ( $\lambda_3$ ) eigenvalue ratio determined from MVA.

<sup>d</sup>Defined as  $E_{rms} = (\sum_{i=1}^N |\mathbf{B}^{obs}(t_i) - \mathbf{B}^{LFF}(t_i)|^2)^{1/2} / (N \max |\mathbf{B}^{obs}|)$  in Marubashi and Lepping (2007).

<sup>e</sup>Calculated using the mean(LFF, nested-bootstrap MVA) values.

become fully detached from the CME) by the time of observation at PSP. In **Figure 5**,  $t_{out}^*$  is indicated using a dashed vertical line. Here, the region 6' between  $t_{out}^*$  and  $t_{out}$  corresponds to the MC's back region. We notice that some of the MC characteristics such as high  $B$  with low variance, coherent rotation in the field vector and a low  $T_p$  continued well after  $t_{out}^*$ . **Figure 6B** shows the  $B_T$  (red),  $B_N$  (blue), azimuthal field component  $B_{y,cloud}$  (green), and accumulated azimuthal flux  $\phi^{p,acc}/L_{mc}$  (black) of the MC as functions of time. Here, The dashed vertical line indicates  $t_{out}^*$ .

## 6 DISCUSSION AND CONCLUSION

The primary focus of this work was to investigate the initiation and formation of a stealth CME and its interaction with surrounding interplanetary structures. The spatiotemporal proximity between the sequence of three eruptions observed over STEREO-A's west limb, combined with the large-scale geometry of the PFSS coronal field extrapolation, strongly suggest a direct and causal magnetic coupling between the eruptions (Schrijver et al., 2013). In the Török et al. (2011) MHD simulation, their coupled, sympathetic eruptions from the adjacent flux systems of a coronal pseudostreamer were triggered by a prior eruption *external* to the pseudostreamer arcades. In our study, CME #0 plays an analogous role, removing a portion of the overlying (restraining) helmet streamer flux and disrupting the quasi-equilibrium force-balance of the energized, multipolar flux system. CMEs #1 and #2 then erupt sympathetically, in succession. CME #1 starts in the northern side-lobe arcade, is seen to deflect south, and given the orientation of the PFSS arcades in **Figure 1**, likely propagates toward STEREO-A. CME #2 starts in the southern side-lobe and is deflected northward (Palmerio et al., 2021a). As discussed in Lynch and Edmondson (2013), each of the sympathetic CMEs' non-radial deflections are toward their overlying breakout current sheet which corresponds to the local magnetic pressure minimum (path of least resistance).

More generally, there are many examples of mid-to high-latitude eruptions deflecting towards the HCS as they become SBO-CMEs (e.g., Kilpua et al., 2009; Panasenco et al., 2013; Zheng et al., 2020; Getachew et al., 2022). Further numerical modeling is needed to confirm this multipolar sympathetic eruption scenario and to characterize the reconnection flux transfer between arcades during this multi-stage, SBO-CME event.

At ~0.5 AU, PSP witnessed the draping of IMF that reconnected with the SBO-CME (CME #2) and eroded almost 20% of its azimuthal flux. Analysing the MC's back region populated with reconnected field lines, we estimate that the reconnection might have initiated after 17:00 UT on 24 June at a heliospheric distance of ~0.35 AU. A lower inclination (~29°) of plasma sheet behind the CME than the inclination (~41°) of plasma sheet in front of it indicates the draping of IMF about the MC having asymmetric, expanding, and non-circular FR structure. The asymmetry in magnetic field intensity has been quantified by  $C_{B,t}$  (Janvier et al., 2019) and  $C_{B,x}$  (Démoulin et al., 2020) in temporal and spatial coordinates, respectively, where a negative value of  $C_{B,t}$  and  $C_{B,x}$  indicates a non-circular, expanding cross-section of a FR. In our study we find  $C_{B,t} \sim C_{B,x} \sim -0.04$ .

With the aid of coronal field extrapolations as well as remote and *in-situ* observations, we explain in this study the formation of a classic slow SBO-CME and examine the interplay with its surroundings in the inner heliosphere. By analyzing the PFSS geometry and the dynamics in low-coronal EUV and white-light imagery, we show that the CME followed two prior eruptions from nearby source regions and suggest coronal reconnection played a significant role in the eruption process. The CME's inner-heliospheric propagation resulted in a draping of the heliospheric field adjacent to the HCS about the CME flux rope. It forced the HCS to be inclined to the spacecraft orbital plane with a moderate and low inclination angle ahead and behind the CME, respectively, at a ~0.5 AU heliospheric distance. Thus, this study provides



important implications for the origin and interactions of a slow eruptive flux rope in the interplanetary medium and highlights the necessity of continuous off-limb observations away from the Sun–Earth line leading to a better exploration of the dynamics of stealthy CMEs in the low corona and inner heliosphere.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://sdac.virtualsolar.org/>, <https://stereo-ssc.nascom.nasa.gov/>, <https://cdaweb.gsfc.nasa.gov/index.html/>.

## AUTHOR CONTRIBUTIONS

SP, BL, SG, EP, and EK contributed to conception and design of the study. SP, BL, SG, and EP performed the analysis. SP and BL wrote the first draft of the manuscript. MS organised the solar wind data. All authors contributed to manuscript revision, and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspas.2022.903676/full#supplementary-material>

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