Space Weather Monitor at the L5 Point: A Case Study of a CME Observed with STEREO B

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Abstract

An important location for future space weather monitoring is the Lagrange point 5 (L5) of the Sun-Earth system. We test the performance of L5 for space weather monitoring using STEREO B observations of an Earth-directed coronal mass ejection (CME), seen as a partial halo by SOHO at L1. STEREO B (located close to L5) continuously tracked the CME. By using these data in combination with methods to calculate the CME arrival time at the Earth (extrapolation, drag-based model, and a magnetohydrodynamic model), we demonstrate that the estimation of the CME arrival time can be drastically improved by adding L5 data. Based on the L1 data alone, one could predict that the CME would arrive at the Earth. Using only the L5 data, one would not expect an arrival, as the estimations of the CME 3-D configuration is uncertain. The combination of L1 and L5 data leads to an ambiguous prediction of the CME arrival due to low CME brightness in L1 data. To obtain an unambiguous prediction, one needs its 3-D configuration, from observing the CME material close to the plane of the sky.

1. Introduction

Coronal mass ejections (CMEs) are huge eruptive events observed in the solar corona, in which magnetized solar plasma is expelled into interplanetary space. As the ejected material traverses interplanetary space, CMEs become known as interplanetary CMEs (ICMEs). When they arrive at the Earth with a favorable orientation of their magnetic field (i.e., a strong and long-lasting southward component), they may produce geomagnetic storms (e.g., Bothmer & Zhukov, 2007; Schwenn, 2006). In particular, ICMEs are responsible for the majority of the strongest geomagnetic storms recorded (Richardson et al., 2006; Zhang et al., 2007).

Halo CMEs (Howard et al., 1982) are a subset of CMEs that are of particular relevance for space weather. They are interpreted as CMEs propagating toward or away from the observer. Until the launch of the Solar–Terrestrial RElations Observatory (STEREO Kaiser et al., 2008), this was the direction along the Sun-Earth line. Full halo CMEs have an apparent (i.e., projected on the plane of the sky) angular width of 360° from the perspective of the observer, while partial halo CMEs have an apparent angular width ranging between 120° and 360°. Kwon et al. (2015) showed that the apparent width of a halo or partial halo CME is driven by the existence and the extent of the associated shock and does not represent an accurate measure of the CME ejecta size. The detection of a halo CME by the Large Angle and Spectrometric CORonagraph (LASCO Brueckner et al., 1995) on-board the SOlar and Heliospheric Observatory (SOHO Domingo et al., 1995) mission is currently used as the first indication of a possible CME eruption toward the Earth. The early determination of the direction of propagation of halo CMEs (toward or away from the Earth) is of vital importance for providing prompt warnings of possible geoeffectiveness. Another issue is that the speeds of halo CMEs measured by LASCO are plane-of-the-sky projected speeds and therefore do not always provide a good estimate of their radial speeds (e.g., Schwenn et al., 2005). Therefore, the placement of a spacecraft away from the Sun-Earth line can provide the crucial viewpoint needed for an early characterization of Earth-directed CMEs, in particular the CME propagation direction, measurement of the CME speed, and tracking of the CME propagation in the heliosphere.
The Lagrangian points (L points) of the Sun–Earth system are places in interplanetary space where the gravitational pull of the Sun balances that of the Earth, allowing an object placed there to remain in a fixed position with respect to these two objects. There are five L points (see Figure 1, left panel). The first three, L1, L2, and L3, fall on the Sun–Earth line. The L1 point is located directly between the Sun and the Earth (at \(1.5 \times 10^6\) km from the Earth), making it a good location for a Sun-watching spacecraft. The SOHO and the Wind (Ogilvie & Desch, 1997) spacecraft are located around the L1 point. The L2 point is situated behind the Earth, with respect to the Sun, and is better suited for astronomical studies away from the glare of the Sun. The L3 point is located behind the Sun as viewed from the Earth. The L5 and L4 points are located 60° behind and ahead, respectively, of the Earth on its orbit.

Placing an observatory at the L5 point has long been considered an important issue for monitoring the space weather conditions near Earth (see, e.g., Simunac et al., 2009; Vourlidas, 2015), but none of the previous studies have presented L5-based observations. Nevertheless, several previous studies have discussed the potential forecasting benefits of having an observer at L5 (e.g., Gopalswamy et al., 2011; Webb et al., 2010), some based on times when STEREO was near quadrature and estimated arrival times of events using data from this period in various ways (see Ravishankar & Michalek, 2019 and references therein). In particular, halo CMEs (as seen from L1) could be observed as limb CMEs from the L5 perspective, greatly improving the estimation of their characteristics, especially the propagation speed and direction. Furthermore, with the appropriate instruments, they can be tracked continuously during their travel from the Sun to the Earth, so any forecast of arrival times could be improved and updated. Another target of a space weather monitor at L5 are corotating interaction regions (CIRs; see, e.g., Richardson, 2018), which develop between fast and slow solar wind streams emerging from the Sun, generating shocks and compression regions that can be geoeffective (e.g., Kilpua et al., 2017; Richardson et al., 2006; Rouillard et al., 2008; Sheeley et al., 2008), particularly during solar minima (Echer et al., 2013; Verbanac et al., 2011). A satellite located at the L5 point would measure the properties of CIRs in situ several days in advance of their arrival at the Earth, allowing an early analysis of their structure.

The STEREO mission consists of two spacecraft that orbit the Sun leading (STEREO A) and trailing (STEREO B) the Earth in its orbit. The STEREO satellites, launched in 2006, have been slowly moving further ahead and behind the Earth in its orbit, and in October 2009, STEREO B was situated close to the L5 point behind the Sun-Earth line (Figure 1, right panel). On 17 October 2009, an Earth-directed partial halo CME was observed by SOHO from the L1 perspective. At that time, STEREO-A was only 2° away from the L4 position, while STEREO-B was less than 1° away from the L5 position. This was, to our knowledge, the only Earth-directed CME observed by STEREO B while it was located around the L5 point (that was at
the same time observed as a partial halo CME from Earth, triggering a space weather alert). Therefore, this represents an opportunity for testing, with a real event, the advantages of having a spacecraft located in this position to improve our space weather forecasting capabilities. Another indirect advantage of observations from L5 is that for Earth-directed CMEs and CIRs, the derivation of radial distance from elongation measurements (provided by heliospheric imagers) is simplified when the observer is located 60° away from the Sun-Earth line (Kahler & Webb, 2007), as will be shown in the next section. Furthermore, we used the 3-D magnetohydrodynamic (MHD) heliospheric model ENLIL (Arge et al., 2004; Odstrčil, 2003) in order to run simulations of the different possible scenarios using input data from L1, L4, and L5.

The paper is organized as follows. In section 2, the observations of the CME and the corresponding ICME are presented, together with different estimations of the ICME arrival times to Earth. In section 3, we model the propagation of the CME from the Sun to the Earth using a physics-based heliospheric model. We then compare the predictions obtained with in situ observations and with predictions derived from empirical and semiempirical models. In section 4, we compare the real space weather forecast reports issued by two space weather forecasting centers (in the United States and Belgium), in relation to this event. These reports were done using data from the L1 point only (SOHO and Wind). We then proceed to show how the space weather forecasts could have been improved if the data from STEREO B had been used. In section 5, a discussion is presented and conclusions are drawn.

2. Observations of the CME on 17 October 2009

2.1. CME and Its Source Region in the Solar Corona

The 17 October 2009 CME was seen from the perspective of the L1 point by the LASCO coronagraph on-board SOHO, as well as from the L5 perspective by the COR-1 and COR-2 coronagraphs included in the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008) instrument suite on-board STEREO B. The CME was first observed by LASCO C2 at 20:58 UT on 17 October. In the LASCO C2 field of view, the CME appeared as a partial halo with angular width of 145° and with a plane-of-sky projected speed of 220 km s\(^{-1}\) (from the CDAWeb LASCO CME catalog, https://cdaw.gsfc.nasa.gov/CME_list/; Yashiro et al., 2004), with the bulk of the material propagating toward the southwest (see Figure 2, left panel). The CME was also seen as a very faint partial halo CME from the L1 perspective by the LASCO C3 coronagraph. This event was later classified as a “very poor event” in the LASCO CME catalog. From the L5 perspective, the CME was visible in COR-2 B starting from 17 October at 21:54 UT, where it appeared as a west-limb CME (Figure 2, right panel) characterized by an angular width of 39° and a plane-of-the-sky projected speed of about 368 km s\(^{-1}\) (from the SEEDS COR2 CME catalog Olmedo.
et al., 2008; https://spaceweather.gmu.edu/seeds/secchi.php). In both instruments, the CME was faint, so the use of the running difference technique is necessary to enhance the visibility of the CME in the images, as seen in Figure 2, where the previous image has been subtracted from each image. Note that while this technique is highlighting the bright leading edge ahead of the CME, it does introduce some ambiguity in the structure within the body.

Low-coronal signatures of the CME were seen from L1 by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al., 1995) on-board SOHO and from L5 by the Extreme UltraViolet Imager (EUVI; Wueller et al., 2004) on STEREO B, in the Fe XII passband centered at 1.6 × 10^6 K. A good indication of the CME source region in the low corona is provided by the detection of EUV dimmings, which often trace the evacuation of the coronal material during a CME (Harrison et al., 2003; Zhukov & Auchère, 2004). There were clear dimmings associated with the CME as detected by EIT and EUVI around 19:20 UT on 17 October 2009 (Figure 3), with the dimming center located at θ = −27° and ϕ = 0° in Stonyhurst coordinates (Thompson, 2006). No significant flares were observed close to the CME launch time.

2.2. CME Propagation into the Heliosphere

As the CME propagated farther out from the Sun, it was possible to observe it from the L5 perspective with the SECCHI Heliospheric Imager (HI) on-board STEREO B (Eyles et al., 2009), allowing the CME to be tracked along the Sun-Earth line in the interplanetary space. Each HI-1 camera has a 20° × 20° field of view, the boresight of which is, in nominal operations, aligned at 14° elongation (angle from Sun-center) in the ecliptic plane, covering elongation angles in the range 4–24°, approximately corresponding to 15–84 solar radii, hereafter \( R_\odot \). The CME was seen in the HI-1 field of view starting around 03:00 UT on 18 October (see Figure 4, left panel). The CME later propagated through the HI-2 field of view (covering elongation angles in the range 19–89°, approximately corresponding to 66–318 \( R_\odot \)) starting from around 18:00 UT on 19 October (see Figure 4, right panel).

In this work, we tracked the position of the CME leading edge in HI images using the J-map tracking method. A J-map (Davies et al., 2009) is made of slices extracted from COR-2 and HI images along a given position angle (PA) and stacked in time. The result is an intensity map having elongation (i.e., the angle between the observed feature and the Sun, as seen from the spacecraft) as the y axis and time in the x axis. In this method, the position of the CME front was tracked directly on the J-map, as shown in Figure 5.

We tracked the leading edge of the CME at a PA = 275°, corresponding approximately to the direction of the ecliptic plane in the observations made by the COR-2, HI-1, and HI-2 instruments on-board STEREO B,
so that we could measure the CME trajectory and velocity from ∼3 to ∼150 R⊙, corresponding to ∼45° in elongation. Beyond this distance, the features became too faint to be tracked. We note that the bright stripe seen ahead of the tracked feature in the HI-2 portion of the J-map does not appear to have clear counterparts in COR-2 and HI-1 elongations. It is most probably not associated with the CME under study but rather related to a previous CME that erupted from the same AR on 16 October 2009.

**Figure 4.** Running difference images of the CME propagating from the Sun to the Earth on 19–20 October 2009 taken by HI-1 (left panel, adapted from the HELCATS HICAT catalog Harrison et al., 2018; https://www.helcats-fp7.eu/catalogues/wp2_cat.html) and by HI-2 (right panel, from the STEREO Science Center, https://stereo-ssc.nascom.nasa.gov) on-board STEREO B. In the left panel, a red line marking the position angle in the direction of the Earth (PA = 275°) has been added to guide the eye. In the right panel, the Earth is located at the vertical stripe in the middle, at an elongation of about 56° from the Sun.

**Figure 5.** STEREO B J-map starting on 18 October 2009. The red points mark the elongation of the CME leading edge in time at position angle 275° in COR-2, HI-1, and HI-2 images. The vertical black stripe represents missing data.
Furthermore, we verified the results obtained from the J-map tracking method with results obtained by tracking a point belonging to the CME front in COR-2 and HI full images. As the results from the two methods were consistent with each other, in the following analysis, we consider the results of the J-map tracking technique only. Since J-maps alone often do not provide enough information to understand the actual connection of each bright feature with different coronal and heliospheric transients (e.g., CME-driven shock fronts, CME structures, or CIRs), the support of COR-2 and HI full images also helped us in verifying the tracking of the correct feature in J-map data.

### 2.2.1. Converting Elongations to Radial Distances

In HI images, the distance of an object from the Sun is measured in terms of the elongation angle. The elongation values have therefore to be converted to radial distances from the Sun. In order to do this, several methods can be used. The Point-P (PP) and the Fixed-φ (FP) methods are the simplest ones (Howard et al., 2006; Kahler & Webb, 2007; Sheeley et al., 1999). For the PP method, the CME is assumed to be expanding spherically from all around the Sun, and the distance \( r_{PP} \) can be calculated in the following form:

\[
r_{PP} = d \sin \epsilon,
\]

where \( r \) is the radial distance from the Sun to the observed structure, \( d \) is the distance from the Sun to the observer (STEREO B in this case), and \( \epsilon \) is the elongation angle measured in the HI field of view. The use of this method is favored for inferring the radial propagation of wide CMEs but can yield large errors for narrower ones (Kahler & Webb, 2007). On the other hand, the FP method is better suited for narrower eruptions as it considers that a CME propagates radially away from the Sun in a fixed direction. In this method, the radial distance \( r_{FP} \) can be derived from \( d \), \( \epsilon \), and \( \phi \) (the angle between the Sun-observer line and the trajectory of the transient), as

\[
r_{FP} = \frac{d \sin \epsilon}{\sin(\epsilon + \phi)}.
\]

The difference between the radial distances calculated using these two methods is largely dependent on the angle \( \phi \). According to Kahler and Webb (2007), if the angle \( \phi \) is close to 60°, then the difference between the two methods is minimized for elongation angles between 20° and 40° (the range used in this study): It amounts to less than 5% (see Figure A3 of Kahler & Webb, 2007 for a full comparison). For the CME under study, the propagation angle \( \phi \) is estimated to be around 60° based on the position of the CME source region seen in EUV observations from both the L1 and L5 perspectives (Figure 3). Therefore, the distances calculated using the PP and FP methods are expected to be within 5% of each other. Lugaz et al. (2009) introduced another method for estimating the radial distance of CMEs from the elongation angle: the harmonic mean (HM) method. This technique represents the CME as a radially expanding circle anchored at the Sun center, with its apex traveling in a fixed radial direction. The distance \( r_{HM} \) calculated using this method is the harmonic mean of the distances obtained from the PP and the FP methods and is defined as

\[
r_{HM} = 2 \frac{d \sin \epsilon}{1 + \sin(\epsilon + \phi)}.
\]

Finally, the self-similar expansion (SSE Davies et al., 2012) technique assumes a circular CME frontal shape with variable half width propagating in a self-similar manner so to maintain a constant half angular width during propagation. Since it provides the capability to estimate the transient’s angular extent in the plane orthogonal to the field of view, this method can be regarded as intermediate between the FP and HM models. In this method, the radial distance \( r_{SSE} \) of the observed structure can be derived using the following relation:

\[
r_{SSE} = \frac{d \sin \epsilon (1 + \sin \omega/2)}{\sin(\epsilon + \phi) + \sin \omega/2}.
\]

where \( \omega/2 \) is the half angular width of the observed structure, that is, of the CME. Differently from Equations 1–3, Equation 4 includes the parameter \( \omega/2 \), which corresponds to the CME half angular width subtended at the center of the Sun, which is a parameter related to the curvature of its front (Davies et al., 2013).
To convert elongation to radial distances, we used the four different methods described above, that is, the PP, the FP, the HM, and the SSE. As seen from Equations 2–4, the FP, HM, and SSE methods require as input the angle $\varphi$, corresponding to the direction of propagation of the transient with respect to the observer. Additionally, the SSE method also requires the transient angular width $\omega/2$ as an input parameter for Equation 4. To constrain each of these parameters, we fitted the CME in LASCO C2 and COR-2 B images using the graduated cylindrical shell (GCS; Thernisien, 2011; Thernisien et al., 2006, 2009) model. This model is designed to reproduce the large-scale 3-D structure of flux rope-like CMEs using a croissant-like shape. It consists of a tubular section forming the main body of the structure attached to two cones that correspond to the “legs” of the CME. Only the surface of the CME is modeled; there is no rendering of its internal structure. This gives us information mostly on the propagation of the leading edge of the CME. The GCS reconstruction of the event using running-difference LASCO C2 and COR-2 B images taken on 17 October

Figure 6. The top panel shows a distance-time plot of the CME leading edge propagation in the corona and in the heliosphere, obtained from the STEREO B J-map analysis for a PA of 275°. The four different methods used to convert from elongation to radial distance give very similar results when applied to COR-2 and HI-1 data, making some of the dots not visible due to superposition. This was not the case for HI-2 data. The CME half width used was $\omega/2 = 22°$ for SSE$_\text{min}$ and $\omega/2 = 37°$ for SSE$_\text{max}$. In addition to the recovered distance values (marked by the dots), error bars corresponding to 1% of the distance values are also shown. The solid lines in the top panel show the linear regression obtained by fitting COR-2, HI-1, and HI-2 data points separately. The bottom panel shows the instantaneous speeds calculated from the points in the top panel, together with the range of speeds derived from linear regression (colored shaded areas) for each of the three instruments. The error bars on the instantaneous speed points (propagated from the errors on the distance values shown in the top panel) for each method are also indicated. For instantaneous speeds estimated in the HI-2 field of view, the values from different methods are not always consistent within error bars. The fact that they do not always overlap reflects the large spread in the distance estimations obtained from different methods. In both panels, the CME arrival time and CME speed at Earth have been indicated as black diamonds.
2009 at 23:54 UT indicated that the CME structure was propagating at a longitude of $\phi = 30^\circ$, corresponding to a $\phi \approx 90^\circ$ with respect to an observer located at L5. Since the recovered $\phi$ was $\neq 60^\circ$, it was not possible to determine a priori the discrepancy between the PP and FP methods. For this reason, both methods have been considered in the following analysis, using a $\phi = 90^\circ$ as reconstructed from the GCS model above. Based on the GCS reconstruction, the croissant aspect ratio (i.e., a measure of the thickness of the croissant loop Thernisien et al., 2006) was $\kappa = 0.25$, and the half angle between the croissant legs $\alpha = 30^\circ$. Based on the $\kappa$ and $\alpha$ parameters above, we obtained two extreme values for the CME half angular width (i.e., the edge-on and face-on half angular widths; see Table 1 in Thernisien, 2011): a minimum half angular width of $\omega_{\text{min}}/2 = 22^\circ$ (edge-on) and a maximum one of $\omega_{\text{max}}/2 = 37^\circ$ (face-on). In the following, the SSE method is therefore applied to both the aforementioned half angular width values.

Figure 6 reports the results obtained from the application of the above methods to convert elongations based on the J-map tracking technique, into radial distances from the Sun. The error bars for the distance and speed points are calculated considering a 1% relative error in the distance measurements (that corresponds to about 20 pixels on average in the HI-1 field of view), which we have propagated to instantaneous speed values using the general formula for error propagation (e.g., Taylor, 1982). The lack of points on 19 October is due to a data gap in the corresponding J-map (Figure 5). The top panel shows the distance-time plot, while the bottom panel shows the instantaneous speeds calculated from the data points above. The range of speeds of the CME leading edge determined in each instrument field of view (i.e., COR-2 B, HI-1 B, and HI-2 B) by fitting the data points with a linear function are indicated in both panels.

From Figure 6, we see how the PP, FP, HM, and SSE methods provide very similar results when applied to elongations derived in COR-2 B and HI-1 B detectors. For this reason, in the following, we do not differentiate among different methods when discussing the results obtained from the J-map tracking on COR-2 B and HI-1 B images. However, this is not the case for the conversion of elongations extracted from the J-map tracking method on HI-2 B images. In this case, results differ significantly between the different methods. The upper and lower limits to the converted distances are provided by the FP and the PP methods, respectively, while the HM and SSE methods provide values in between. By fitting the data points for each instrument using a linear function, we recover CME speeds equal to 445 km s$^{-1}$ in COR-2 B, 350 km s$^{-1}$ in HI-1 B, and between 450 and 815 km s$^{-1}$ in HI-2 B. Results based on the J-map tracking therefore show a consistent trend in the evolution of the CME speed as it propagates throughout the heliosphere only if we consider the speeds derived from HI-2 B observations combined with the PP method. On the other hand, the upper limit of the CME speed in HI-2 B is the one estimated using the FP method, that is, 815 km s$^{-1}$. This value greatly exceeds the CME speeds estimated by all the other reconstruction techniques employed and at all range of distances from the Sun, and it should therefore be considered as unrealistic. Furthermore, Liu et al. (2013) find that CMEs fitted with the FP method show a late phase acceleration that can lead to large overestimations in speeds, an effect that is reduced when increasing the angular width of the CME used in the method. A similar effect was found by Barnes et al. (2020), who analyzed a large set of CMEs observed by STEREO/SECCHI HI, finding that the use of methods that consider narrow CMEs show more acceleration than those using wider ones. Figure 6, bottom panel, shows the same effect, that is, the use of narrower CME angular widths led to higher speeds at larger radial distances from the Sun.

### 2.2.2. Propagation to 1 AU

From the radial distance and speed values above, we further estimate the CME arrival time at 1 AU by employing two different techniques. The first technique consists in applying a linear fit to the distance-time data points and extrapolating the results to 1 AU. The second, more sophisticated method used is the drag-based model (DBM; Vršnak & Žic, 2007, http://oh.geof.unizg.hr/DBM/dbm.php), an analytical model of the CME propagation describing the CME dynamics in the heliosphere as governed by the interaction between the CME and the ambient solar wind in the form of a drag force (Vršnak et al., 2013). As input for the DBM model, we use a background solar wind speed of 300 km s$^{-1}$ (consistent with the speeds observed before the ICME arrival at the Wind spacecraft, as shown in Figure 8) and the default drag parameter value ($\Gamma = 0.2 \times 10^{-7}$ km$^{-1}$). The other input parameters (i.e., the CME speed and time of passage at a given heliocentric distance) are determined using the results obtained from the J-map tracking above. Figure 7 shows the CME arrival times at Earth/1 AU obtained with these two different methods (i.e., simple extrapolation and DBM), as well as by running heliospheric simulations using ENLIL (as discussed in section 3). For comparison, the arrival time of the CME-driven shock at L1 (i.e., 21 October at 23:15 UT,
from the Wind spacecraft) is indicated by the black dashed line (see also section 2.3). The arrival times estimated using the different combinations of observational and propagation methods are listed in Table 1. Furthermore, predictions of the CME arrival time obtained using projected CME properties as observed in LASCO C2 and COR-2 B images are also included in order to quantify the advantage of having one viewpoint at L5 as an alternative to/in addition to a viewpoint at L1. Results are discussed in detail in section 2.3.

2.3. In Situ CME Observations

On 21 October, 4 days after the CME left the Sun, a shock was detected in the Wind data at 23:15 UT (from the Heliospheric Shock Database, http://ipshocks.fi/database; Kilpua et al., 2015). It exhibited all the standard shock characteristics (see, e.g., Kilpua et al., 2015), namely, the jumps in the magnetic field intensity, solar wind speed, plasma density, and temperature. The shock was driven by an ICME. The plasma and magnetic field data taken by Wind are shown in Figure 8. The ICME (start time: 22 October 2009 around 06:00 UT, end time: 23 October 2009 around 12:00 UT) showed weak signatures, mainly evident from the elevated magnetic field intensity and the low plasma $\beta$. We note, however, that the position of the rear ICME boundary is difficult to determine exactly, and apart from the one marked in Figure 8, it could also be placed on 24 October, where a large peak in density is seen. This ICME was not a magnetic cloud as there was no smooth rotation of the magnetic field vector present. The average ICME speed as measured by Wind was about 400 km s$^{-1}$. Normally, slow CMEs like this one are not expected to produce a shock. In this case, the shock was created because of the even slower solar wind in front of the CME ($\sim$300 km s$^{-1}$). The shock normal had an
orientation of 36° with respect to the ecliptic plane (i.e., geocentric solar ecliptic [GSE] latitude) and 170° angle with respect to the Earth-Sun line. This angle corresponds to the bulk of the ICME passing to the south of the Earth. This is well in agreement with the CME source region position in the Southern Hemisphere (Figure 3) and with the observation of the bulk of the CME material propagating to the south of the ecliptic plane as seen by the LASCO C2 and COR-2 B coronagraphs (Figure 2).

2.3.1. Prediction of the CME Arrival Time at Earth

Applying a simple extrapolation technique to results obtained from the J-map tracking, the best prediction of the CME arrival time at Earth is obtained when COR-2 data are used. We believe this is a fortuitous result, as J-map COR-2 observations provided only three data points which were all very close to the Sun and as such are not representative of the CME dynamics in the heliosphere. In this case, the CME arrival is predicted on 21 October at 20:16 UT, that is, 3 hr earlier than observed in situ. HI-1 data predict the CME arrival on 22 October at 19:36 UT, that is, about 20 hr later than observed. Predictions based on HI-2 data range between 21 October at 04:14 UT (FP) and 22 October at 03:24 UT (PP), with the PP method giving the best prediction.
of the CME arrival time at L1 for the specific event considered. Overall, predictions from COR-2 data and HI-2 data for the HM and SSE methods are all within \pm 10 hr from the actual arrival time (indicated by the gray dashed lines in Figure 7), that is, within typical uncertainties associated with the prediction of the CME arrival time at Earth (e.g., Riley et al., 2018). As simple extrapolation neglects the effect of the interaction with the ambient solar wind on the CME dynamics, the results obtained from this propagation method are considered to be subject to higher uncertainties than the ones obtained by employing a more realistic tool such as the DBM (discussed below). For comparison, the HEliospheric Cataloguing, Analysis and Techniques Service (HELCATS; https://www.helcats-fp7.eu) project provides a list of CMEs detected by the HI-1 instruments on board the STEREO spacecraft. In particular, the CME considered in this work is listed in the HiGeoCAT CME list (Barnes et al., 2019) with a speed of 471 km s\(^{-1}\), estimated by applying the SSE method to elongations obtained from the J-map tracking in the HI-1 B and HI-2 B field of view. The predicted CME arrival time at Earth contained in the HELCATS catalog is 21 October at 14:54 UT, that is, about 9 hr earlier than actually observed, consistent with the prediction obtained in this work using a similar approach.

Predictions obtained applying the DBM to J-map tracking results are more clustered (i.e., the predicted arrival times are scattered over a smaller range of values) and are shifted toward later times compared to the predictions obtained from extrapolation. This is the result of the more sophisticated treatment of the CME-solar wind interaction in DBM, where a CME initially faster than the ambient wind is progressively slowed down until asymptotically reaching the solar wind speed. In this case, the best prediction is given by the HM and SSE\(_{\text{max}}\) methods applied to HI-2 data analyzed with the J-map tracking. Such methods predict CME arrival times on 21 October at 19:22 UT and 16:23 UT, respectively (i.e., 3 and 6 hr earlier than observed). The predicted impact CME speeds are 460 and 480 km s\(^{-1}\), respectively, that is, higher than the observed impact speed which was about 400 km s\(^{-1}\). For comparison, COR-2 and HI-1 data predict the CME to arrive on 22 October at 06:22 UT and 22:39 UT, respectively. The predicted impact CME speeds are 371 and 336 km s\(^{-1}\), respectively. The most reliable predictions of the CME arrival time are therefore given by HI-2 data in combination with the HM and SSE methods and by COR-2 data regardless of the specific methods used to convert elongations into radial distance. The FP and HM geometries are special cases of SSE, with half-widths of 0° and 90°, respectively (Davies et al., 2012). Four of the five HI-2 methods presented are therefore SSE using \(\omega/2 = 0°, 22°, 37°, \text{and } 90°\). From these four, the HM model gives the closest arrival
Table 2
List of ENLIL Runs Performed in This Work, With the Relative CME Input Parameters Used

| Run | Observational method | Viewpoint | \(v_{\text{CME}}\) at 0.1 AU | \(\theta_{\text{CME}}\) | \(\phi_{\text{CME}}\) | \(w_{\text{CME}}/2\) | Arrival at Earth |
|-----|----------------------|-----------|-------------------------|-----------------|-----------------|-----------------|-----------------|
| 01  | SOHO (EIT and LASCO C2) | L1        | Oct 18 13:38 UT | 220 km s\(^{-1}\) | \(-27^\circ\) | 0° | 72° | Y (Oct 23, 04:30 UT) |
| 02  | STEREO B (EUVI, COR-2) | L5        | Oct 18 06:56 UT | 368 km s\(^{-1}\) | \(-27^\circ\) | 0° | 20° | N  |
| 03  | J-map on COR-2 B (all) | L5 (with input from L1) | Oct 18 08:00 UT | 445 km s\(^{-1}\) | \(-21^\circ\) | 30° | 22° | N  |
| 04  | J-map on COR-2 B (all) | L5 (with input from L1) | Oct 18 06:56 UT | 445 km s\(^{-1}\) | \(-21^\circ\) | 30° | 37° | G (Oct 21, 20:00 UT) |
| 05  | J-map on HI-1 B (all) | L5 (with input from L1) | Oct 18 09:40 UT | 350 km s\(^{-1}\) | \(-21^\circ\) | 30° | 22° | N  |
| 06  | J-map on HI-1 B (all) | L5 (with input from L1) | Oct 18 09:40 UT | 350 km s\(^{-1}\) | \(-21^\circ\) | 30° | 37° | G (Oct 22, 04:00 UT) |
| 07  | GCS (2 viewpoints)    | L1, L5    | Oct 18 07:50 UT | 320 km s\(^{-1}\) | \(-21^\circ\) | 30° | 22° | N  |
| 08  | GCS (2 viewpoints)    | L1, L5    | Oct 18 07:50 UT | 320 km s\(^{-1}\) | \(-21^\circ\) | 30° | 37° | G (Oct 22, 04:00 UT) |
| 09  | GCS (2 viewpoints)    | L5, L4    | Oct 18 08:32 UT | 282 km s\(^{-1}\) | \(-13^\circ\) | 7° | 20° | G (Oct 22, 00:00 UT) |
| 10  | GCS (2 viewpoints)    | L5, L4    | Oct 18 08:32 UT | 282 km s\(^{-1}\) | \(-13^\circ\) | 7° | 35° | Y (Oct 22, 00:00 UT) |

\(^a\text{Note: The rightmost column lists the type of CME encounter predicted at Earth in each simulation (Y, yes; N, no; G, glancing blow), together with its arrival time, where relevant.}\)

time of the ICME to the Earth. These results confirm what was mentioned for Figure 6, and regarding the findings of Liu et al. (2013) and Barnes et al. (2020), that is, narrower CMEs show artificial acceleration at large radial distances, which produce earlier arrival times. The arrival times of the different methods displayed in Figure 7 show this effect systematically.

It is important to mention that, even though the most accurate predictions could be done by using the HI-2 data, the lead time of the predictions was in this case the smallest. In terms of space weather forecasts, it can be more valuable to have lower accuracy in the time of arrival but larger lead time in order to take mitigation actions. For the case studied here, HI-2 predictions give a lead time of around 1 day, whereas (less accurate) HI-1 observations allow for about 3 days notice.

For both propagation methods (i.e., extrapolation and DBM), the worst prediction of the CME arrival time at Earth is given by single viewpoint observations from L1. Using projected CME properties based on LASCO C2 observations alone, we report an error of more than 3 days compared to the observed CME arrival time. This is the result of the very low speed estimated from the observations in the LASCO C2 field of view (i.e., 220 km s\(^{-1}\)), combined with the low ambient solar wind speed used as input for DBM. Observations only from the COR-2 instrument on board STEREO B (i.e., from the L5 perspective), on the other hand, are able to predict the CME arrival time at Earth with an error of less than 18 hr. Although less satisfactory than predictions based on the J-map tracking technique, this result highlights how even the single L5 viewpoint allows to perform a significantly better estimate of the arrival time of Earth-directed CMEs compared to a view limited to L1.

3. Prediction of the CME Arrival by WSA-ENLIL

In section 2, we discussed the possible prediction of the CME arrival time at 1 AU based on empirical propagation models. Together with more realistic predictions of the CME arrival time at 1 AU, it is also important to determine if a CME would arrive at the Earth at all. The 3-D configuration of the CME needs to be investigated for this purpose. We use the WSA-ENLIL model (Arge et al., 2004; Odstrčil, 2003) to simulate the propagation of the CME from the Sun to the Earth in three dimensions. The WSA-ENLIL model was employed for operational forecasting purposes at the time of the event under study, but it was not used to model the propagation of the CME to 1 AU.

ENLIL (Odstrčil, 2003) is a time-dependent 3-D MHD model of the heliosphere designed to model the ambient solar wind as well as CMEs propagating through it. In this work, we use ENLIL version 2.8f, running at the NASA Community Coordinated Modeling Center (CCMC) and available for runs on request (https://ccmc.gsfc.nasa.gov/requests/SH/E28/enlil_options.php), in combination with the Wang-Sheeley-Arge (WSA) semiempirical coronal model (Arge & Pizzo, 2000; Arge et al., 2004). We run all simulations using a heliospheric computational domain spacing between 0.1 and 2.1 AU in the radial direction, and covering ±60° in latitude and ±180° in longitude. In our simulations, we use a low resolution (i.e., 384 grid cells in the radial direction, 30 grid cells in the latitudinal direction, and 90 grid cells in the longitudinal direction)
consistent with the resolution used for operational forecasting of the solar wind conditions and CME properties at NASA/CCMC and the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration (NOAA/SWPC, https://www.swpc.noaa.gov/products/esa-enlil-solar-wind-prediction). As input for the WSA coronal model, we use a standard magnetogram generated by the Global Oscillation Network Group (GONG, https://gong.nso.edu/data/magmap/QR/bqs/) on 17 October 2009 at 05:54 UT.

We model the CME using the cone model (Odstrčil, 2003). As input to our simulations, we use different set of CME parameters, derived from the various observational methods described in section 3.1, performing a total of 10 simulations (all the simulation results discussed in this paper can be accessed online via the NASA/CCMC website). The complete list of CME input parameters used is presented in Table 2, and their determination based on CME observations at the Sun is discussed below.

### 3.1. CME Input Parameters for ENLIL

In this section, we describe in detail the various methods, based on observations from the L1 and L5 perspectives, employed to determine the parameters later used as input for ENLIL heliospheric simulations of the CME event under study. A summary of the CME input parameters used in ENLIL simulations is presented in Table 2.

Coronagraphic observations taken from different viewpoints are crucial to determine the CME input parameters for heliospheric simulations reliably (e.g., Lee et al., 2015). In particular, we note that while the determination of the CME angular size and direction of propagation in 3-D are the most critical parameters to determine whether a CME would arrive at the Earth at all, the CME speed is the parameter that most affects the prediction of the CME arrival time at Earth.

As the aim of the paper is assessing the importance of L5 observations to provide improved predictions of the CME arrival at the Earth compared to the L1 data, we start by performing one simulation using CME parameters determined uniquely from L1 observations. To do that, we make use of data contained in the CDAWeb LASCO CME catalog. In particular, we make use of the distance measurements from L1 observations. To do that, we make use of data contained in the CDAWeb LASCO CME catalog. In particular, we make use of the distance measurements from L1 observations.

To assess the advantage of having two viewpoints (i.e., L1 and L5) to perform a reconstruction of the CME properties in 3-D, we also perform a total of four simulations using the results from the J-map tracking technique in COR-2 and HI-1 field of views in combination with the PP, FP, HM, and SSE methods introduced in section 2.2 (3-D data obtained from one viewpoint at L5, with limited input from L1 observations). In this case, the parameters that could not be derived from the J-map tracking technique (i.e., the CME direction of propagation in 3-D space and the CME half width) were initialized using the results from the GCS reconstruction applied to COR-2 B and LASCO C2 images (see section 2.2.1). The CME longitude and latitudes...
recovered from the GCS reconstruction at low-coronal heights are $\theta_{CME} = -21^\circ$ and $\phi_{CME} = 30^\circ$, respectively. The GCS-based upper and lower limits for the CME half width ($\omega_{CME}/2 = 37^\circ$ and $\omega_{CME}/2 = 22^\circ$) are both tested, while the CME speeds and passage times at 21.5 $R_\odot$ are derived from the linear fitting and extrapolation of the distance-time data points presented in Figure 6(Runs 03–06 in Table 2).

Additionally, we perform two simulations using only results from the GCS fitting of the CME structure in LASCO and COR-2 B coronagraphs (3-D data obtained from two viewpoints, L1 and L5; Figure 9). As the CME was too faint to be observed in LASCO C3, the GCS fitting using two viewpoints was only possible using COR-2 B images combined with LASCO C2 ones. In order to make a more reliable estimation of the CME direction of propagation and half width, which is not possible using observations from a single viewpoint, we therefore use the results from the GCS fitting on COR-2 B and LASCO C2 images performed during the early propagation of the CME (introduced in section 2.2.1). We note that we deliberately did not attempt to fit the COR-2 A data. By doing so, we simulated a possible forecasting scenario where data were only available from L1 and L5 monitors. Also, the resulting fit re-projected on the COR-2 A image does not fit the data well (see the right panels of Figure 9). As for the previous sets of simulations, we use a CME longitude and latitude of $\theta_{CME} = -21^\circ$ and $\phi_{CME} = 30^\circ$ based on the GCS reconstruction, and we test both the upper and lower limits for the CME half width (i.e., $\omega_{CME}/2 = 37^\circ$ and $22^\circ$). In this case, the CME speed and passage time at 21.5 $R_\odot$ were estimated by applying the GCS model at later times using COR-2 B images only, that is, when the CME was as close as possible to 21.5 $R_\odot$, corresponding to the inner boundary of the ENLIL heliospheric model (using a total of four images taken by COR-2 B between 00:39 UT and 01:54 UT on 18 October). The GCS fitting at these later times provided $v_{CME} = 320$ km s$^{-1}$ and a passage time of the CME at 21.5 $R_\odot$ on 18 October around 07:50 UT (Runs 07 and 08 in Table 2).

Finally, to assess the quality of the GCS reconstruction obtained from two viewpoints (L1 and L5), we also perform two ENLIL simulations using the results from the GCS fitting including COR-2 A data (Figure 10) as input. We find that using three viewpoints (L1, L5, and L4) does not lead to a good fit for all the three
data sets due to the very weak appearance of the CME in the LASCO C2 and C3 field of views. As a consequence, we made the GCS fit for the two viewpoints (L5 and L4) that allowed us to observe the CME with sufficient clarity. In this case, we obtain a CME direction of propagation of $\theta_{\text{CME}} = -13^\circ$ and $\phi_{\text{CME}} = 7^\circ$, a croissaint aspect ratio $\kappa = 0.25$, and a half angle between the croissant legs $\alpha = 20^\circ$. In this case, the CME half width ranges between $\omega_{\text{CME}}/2 = 20^\circ$ and $\omega_{\text{CME}}/2 = 35^\circ$ depending on the view angle (i.e., edge-on or face-on, respectively). The recovered CME speed was $v_{\text{CME}} = 282 \text{ km s}^{-1}$ and its passage at 21.5 $R_\odot$ estimated on 18 October at 08:32 UT. Runs 09 and 10 in Table 2 correspond to these parameters.

It has to be pointed out that the results of the GCS reconstruction using the L1 and L5 viewpoints are very different from those obtained using the L5 and L4 viewpoints. In the latter case, the CME latitude $\theta_{\text{CME}} = -13^\circ$ and longitude $\phi_{\text{CME}} = 7^\circ$ place its propagation direction significantly closer to the Sun-Earth line than the coordinates obtained from the STEREO B and SOHO data (i.e., L5 and L1). For comparison, the maximum uncertainties on the CME longitude and latitude reconstructed from the GCS model are estimated to be about 17$^\circ$ and 4$^\circ$, respectively (Thernisien et al., 2009); that is, they are smaller than the difference in the direction of propagation estimated using either the L5 + L1 or L5 + L4 viewpoints ($\Delta \phi = 23^\circ$, $\Delta \theta = 8^\circ$). We believe that the 3-D configuration reconstructed using COR-2 A and COR-2 B images (L4 and L5 viewpoints) is closer to the true configuration, as the CME in the LASCO C2 data was very faint and its angular extent was difficult to determine based on COR-2 B and LASCO C2 images only. On the contrary, the CME in the COR-2 A data was sufficiently

Figure 10. GCS fitting results for the CME under study, based on COR-2 B (left column) and COR-2 A (right column) data on 18 October 2009 at 01:24 UT. The top panels show the multipoint coronagraph observations of the CME in running-difference images, while the lower panels show the same images with the corresponding GCS fits overlaid. The reconstruction does not fit the LASCO C2 data at all (not shown).
bright, thus allowing a more reliable GCS reconstruction from COR-2 A and B data. The consequences of this important point will be discussed in section 4.

3.2. WSA-ENLIL Predictions at Earth

In this section, we describe the results of the ENLIL runs made with the CME initial parameters described in Table 2. The type of CME encounter predicted at Earth in each simulation and its arrival time (where relevant) are provided in the rightmost column of Table 2. The CME arrival times estimated from ENLIL simulations are also compared to the results from other propagation methods used (i.e., simple extrapolation and DBM) in Figure 7.

First of all, we note that for all the runs, ENLIL significantly overestimates the ambient solar wind speed (around 400 km s\(^{-1}\)) in comparison with the speed measured by Wind prior to the CME arrival at Earth (around 300 km s\(^{-1}\)). Most likely because of the overestimation of the solar wind speed, in all the runs the CME speed is very close to that of the ambient solar wind, so the observed shock wave is not reproduced in the simulations. Therefore, even in the runs predicting the CME to arrive at Earth (as discussed below), it is difficult to distinguish the CME signal from the ambient solar wind. The CME is hardly detectable in modeled in situ time series at Earth, and the small difference between the CME and the ambient solar wind speeds and densities result, in all simulations, in a very weak pile-up at the CME front.

Run 01, based only on L1 data, predicts a head-on arrival of the CME at the Earth around 04:30 UT on 23 October. The predicted CME duration is around 36 hr, which provides an indication of the type of encounter (glancing blow or head-on encounter). The relatively long duration of the CME simulated in this run further confirms a head-on encounter.

Run 02, based only on the L5 data, predicts that the CME would miss the Earth, passing well below the ecliptic plane. This is most probably due to the CME half width (\(\omega_{\text{CME}}/2 = 20^\circ\)) being smaller than the latitude of the CME propagation direction (\(\delta_{\text{CME}} = -27^\circ\)).

Runs 03, 05, and 07 also predict that the CME would miss the Earth, passing significantly to the west. For these runs, this is due to the CME half width (\(\omega_{\text{CME}}/2 = 22^\circ\)) being smaller than the central longitude of the CME propagation direction with respect to the Earth (\(\phi_{\text{CME}} = 30^\circ\)).

Runs 04 and 06 are similar to Runs 03 and 05, with the bulk of the CME passing to the west of the Earth. However, in these runs, the CME has a larger half width (\(\omega_{\text{CME}}/2 = 37^\circ\)). Therefore, the model predicts a glancing blow of the CME arriving at the Earth around 20:00 UT on 21 October and around 04:00 UT on 22 October for Runs 04 and 06, respectively. In these runs, the predicted CME duration at Earth is 8 and 4 hr, respectively, consistent with a glancing blow. Run 08 is very similar to Run 06.

Runs 09 and 10 are based on what we consider the most precise information about the 3-D structure of the CME, derived from the L5 and L4 data sets. As mentioned in section 3.1, the COR-2 A and B coronagraphs observe the CME to be sufficiently bright to derive its 3-D structure reliably. Both runs predict the CME arrival at the Earth around 00:00 UT on 22 October, with a CME duration of 8 and 20 hr, respectively.

The ENLIL runs demonstrate that the arrival at the Earth and the type of encounter (head-on or a glancing blow) depend on the initial 3-D configuration of the CME. If the GCS reconstruction gives a too small CME half width or a too large longitudinal distance between the CME propagation direction and the Earth, then ENLIL predicts that the CME would miss the Earth or hit it with a glancing blow. The correct 3-D reconstruction is therefore a crucial task that is necessary for an accurate prediction of the CME arrival at the Earth. The CME is very weak as seen from L1. Due to this, the reconstruction based on L5 and L1 coronagraphic data does not lead to a consistent prediction of the CME arrival at the Earth, with half of the runs leading to a miss and the other half to a glancing blow. A more realistic reconstruction based on the L5 and L4 vantage points probably gives a better estimate of the CME structure and its propagation direction in three dimensions; it also consistently predicts the CME arrival at the Earth. This is discussed in more detail in the next section.

4. Discussion on the Operational Space Weather Forecasts

The observation of the partial halo CME was announced on 18 October 2009 by (at least) two Regional Warning Centers (RWCs), members of the International Space Environment Service (ISES). Both the
The ICME arrived at the Earth late on 21 October. On 22 October, reports of the ICME arrival were issued by both RWCs. Neither RWCs anticipated significant geoeffectiveness (to access the various forecasts and alert messages sent by both centers, see sidc.be/archive and ftp://ftp.swpc.noaa.gov/pub/warehouse). There were no estimations of arrival times made in these reports. NOAA estimated a CME speed of 230 km s\(^{-1}\) (referring to the plane-of-the-sky projected speed) using LASCO data. This would place the CME arrival on 25 October, that is, much later than in reality, if one uses the DBM for calculating the arrival time with a background solar wind speed at 300 km s\(^{-1}\) (taken upstream of the ICME from Figure 8), or at 02:00 UT on 21 October using the model from Gopalswamy et al. (2001) that considers constant acceleration up to 0.76 AU. Nothing more was said about the CME until it arrived at the Earth late on 21 October. On 22 October, reports of the ICME arrival were issued by both RWCs. The ICME arrived at Wind (Figure 8) and then at the Earth, producing active geomagnetic conditions, with \(K_p = 4\) and local \(K\) indices reaching 6 at high latitudes (these values can be obtained from ftp://ftp.swpc.noaa.gov/pub/indices/old_indices/2009_DGD.txt). These values show that the ICME had an impact on the geomagnetic field, albeit a weak one.

It is clear that if the data from STEREO B at the L5 point had been used, the arrival time forecast could have been improved to reach an error on the arrival time down to 2 hr only (Figure 7). This is similar to or better than the mean error of the predicted arrival times of 7–10 hr reached by current state-of-the-art models (Riley et al., 2018; Steenburgh et al., 2014) using L1 input data. On 17 October 2009, the CME could have been detected by both COR-2 and LASCO and classified as an Earth-directed CME, with an estimated true radial speed around 300 km s\(^{-1}\). On 19–21 October, the HI-1 data would have shown the propagation of the CME with an increasing speed reaching 400 km s\(^{-1}\). At that moment, it could have been predicted to arrive to the Earth within 3 days. Finally, by using HI-2 observations, the arrival of the ICME could have been estimated at 02:00 UT on 22 October, thus providing an accurate (within 2.5 hr) estimation of the ICME arrival with the prediction issued one day and a half in advance.

Besides improving the estimated arrival time at Earth, a coronagraph at L5 in addition to a monitor at L1 could also help in determining the 3-D structure, direction, and speed of an Earth-directed CME to a greater accuracy, as shown in Mierla et al. (2010). This is important in order to determine if a CME will arrive at the Earth at all. Furthermore, one of the key benefits of coronagraphic L5 observations is that while, from just an L1 perspective, there would be an ambiguity over whether or not the event was backsided, with even the most basic of L5 observations that could be known immediately. Nevertheless, for the case shown here, it was clear that the CME was front-sided from L1 observations already (see Figure 3, left panel) In our case, the bulk of the CME was seen to move toward the south from the perspective of L1, which corresponds well to the position of the on-disk source region in the Southern Hemisphere as detected in EUV images. The CME was observed as a partial halo from L1, thus suggesting that it will arrive at the Earth (see ENLIL run 01 in Table 2).

From the perspective of L5, the CME is clearly seen to propagate to the west of the Sun. Although it would not be possible to determine the heliospheric longitude of the CME propagation from the L5 coronagraph data alone, EUV imaging from the same perspective demonstrates that the CME is directed to the Earth as far as the longitude is concerned. However, the L5 data alone suggest that the resulting ICME would miss the Earth passing to the south of the ecliptic plane (see Run 02 in Table 2).

Somewhat surprisingly, combining coronagraphic data from L1 and L5 vantage points does not provide an unambiguous evidence of the CME propagation direction toward the Earth. Half of the ENLIL runs based on L1 and L5 data (Runs 03, 05, and 07) predict that the CME would miss the Earth, and the other half (Runs 04, 06, and 08) predict only a glancing blow. The GCS reconstruction of the CME configuration and propagation based on L1 and L5 data suggests the CME passage to the west of the Earth. This reconstruction does not look fully reliable due to a very low CME brightness detected by LASCO.
Significant parts of the CME could be missed by LASCO due to unfavorable viewing geometry (head-on observation).

It is clear then that any two viewpoints are not always sufficient to constrain the 3-D geometry of the CME. If from one of the viewpoints the CME is seen as a weak halo (as in Figure 2, left panel), then this observation is of limited use to determine the full 3-D angular width of the CME. A second viewpoint that observes the CME well (with the bulk of the material close to the plane of the sky) is needed. This seems to be corroborated by the COR-2 observations from STEREO A located at the L4 point. Together with the COR-2 B data from L5, COR-2 A data show the CME structure clearly, propagating close to the plane of the sky from both vantage points. This allows a more reliable reconstruction of the 3-D structure of the CME, suggesting a CME propagation direction toward the Earth. We would like to point out that it is of no particular importance that for our CME the second viewpoint useful to determine the 3-D configuration was provided by an observatory located at L4 (namely, STEREO A). An observatory situated, for example, in quadrature with the Earth (30° further to the west from L4) would provide a similarly useful input.

These considerations demonstrate a different utility of space weather observatories located at L1 and L5. In our event, the L1 observations were not fully reliable to determine the 3-D structure of the CME in combination with an L5 monitor. However, L1 observations alone provided a good indication that the CME is directed at the Earth. The information from L5 observations alone (or in combination with L1 data) was not sufficient to determine this. However, once it is determined that the CME would arrive at the Earth, the coronagraph and HI observations from L5 provided a drastic improvement in our ability to predict the arrival time of the CME at the Earth in comparison with L1 observations.

5. Summary and Conclusions

We have analyzed the coronal and heliospheric propagation of a CME observed when the STEREO B spacecraft was located at the L5 Lagrangian point of the Sun-Earth system. To our knowledge, this is the only case where an Earth-directed halo CME (as seen from the Earth’s perspective, and triggering a space weather alert) was also observed by a spacecraft located around the L5 point. The real-time space weather forecasts corresponding to this event were briefly described. They were done using SOHO data (EIT and LASCO). We demonstrated how these forecasts could have been improved by the use of the STEREO B data. In particular, the use of the HI data can provide a much better accuracy when predicting the arrival time to the Earth, even without the use of propagation models like DBM and ENLIL, but based only on observations. The linear relation between the time and the distance of the CME leading edge during its propagation in the HI-2 field of view allows us to make an estimate of the ICME arrival time 1.5 days before the actual arrival (for a case of a slow CME described in this paper). Furthermore, the location of the L5 point at the angle of 60° from the Earth reduces the difference between the results given by different methods to estimate the true radial distance of heliospheric structures from elongation angles measured by HI. In the case of Earth-directed CMEs, this is important for operational forecasting.

The partial halo CME was very weak in the L1 data, but its morphology suggested that the resulting ICME would arrive at the Earth. Using the L5 data alone could lead to a prediction that the CME would miss the Earth, passing to its south. Somewhat surprisingly, combining the L1 and the L5 data does not significantly improve the estimate of the possibility of the CME arrival, with half of the ENLIL runs predicting that the ICME would miss the Earth and the other half predicting a glancing blow. Only a combination of the coronagraphic data from two vantage points observing the CME close to the plane of the sky (L5 and, coincidentally, L4 in our case) allowed us to to derive the 3-D configuration of the CME and determine unambiguously that it is directed toward the Earth. This event demonstrates that L1 observations may be of better use to determine if a CME would arrive at the Earth at all, but L5 observations are superior in constraining the CME arrival time.

We also point out that the STEREO/SECCHI science data used in this study are normally available within 3 days from the time of observation. Therefore, these data could not be used in real time for the analysis described in this paper. It is possible to use the space weather beacon data from STEREO in real time, but the many data gaps and poor quality of the beacon HI data could have hampered their use in this case. The analysis reported in this paper could only be done after the science data were available, which would have been too late for real-time space weather forecasting. A future dedicated space weather mission at
the L5 point should take this caveat into account and improve the latency of the data that has the quality suitable for use in the operational context.

Data Availability Statement

STEREO EUVI, COR, and HI data can be accessed via the data link on the STEREO homepage (https://stereossc.nascom.nasa.gov/data.shtml). SOHO EIT, and LASCO data can be accessed via the SOHO Science Archive at ESAC (https://sohowww.nascom.nasa.gov/data/archive/index_ssa.html). The SOHO/LASCO CME catalog (https://cdaw.gsfc.nasa.gov/CME_list/) is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. Wind data can be accessed via the Wind webpage data portal (https://wind.nasa.gov/data.php). The SEEDS CME catalogs (https://spaceweather.gmu.edu/seeds/) are generated and maintained by George Mason University with the support of the NASA Living With a Star Program and NASA Applied Information Systems Research Program. This paper uses data from the Heliospheric Shock Database (http://ipshocksfi), generated and maintained at the University of Helsinki. Simulation results have been provided by the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center through their public Runs on Request system (https://ccmc.gsfc.nasa.gov). The CCMC is a multiagency partnership between NASA, AFMC, AFSOR, AFRL, AFWA, NOAA, NSF, and ONR. The ENLIL Cone CME Model was developed by D. Odstrcil at the University of Colorado at Boulder. All the simulation results discussed in this paper can be accessed online via the view results link on the NASA/CCMC website (https://ccmc.gsfc.nasa.gov/ungrouped/SH/Helio_main.php), under the name Camilla Scolini and the keyword L5_2020_runXX, where the XX label runs between 01 and 10.

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