~~The Origins of a Near-Ecliptic Merged Interaction Region as a Magnetic-Cloud like~~ Longitudinally Spaced Observations of a Magnetic Cloud-Like Structure Embedded in a Co-rotating Interaction Region

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Abstract.

Interaction mechanisms in the solar wind affect the evolution of magnetic structures, thereby mediating the properties acquired during their formation processes at the Sun as they propagate outward. Using remote-sensing and in-situ observations across multiple spacecraft ~~with complimentary methods of analysis,~~ we investigate a Magnetic ~~Cloud Like-structure~~ Cloud-Like structure (MCL) ~~observed~~ detected in-situ on 3-4 July 2007 near the ecliptic at different longitudes with OMNI, STEREO-A and -B ~~(all within 15° longitude of Earth).~~. The MCL is entrained in a Corotating Interaction Region (CIR) originating in the Northern heliospheric sector, ~~to create~~ creating a Merged Interaction Region (MIR). ~~This event allows the comparison of MIR observations at different longitudes showing differences in size, formation of sheath, presence of forward and reverse waves and small-scale structuring, demonstrating the progression of the interaction between the CIR and MCL from West to East. In order to explore its origins further, we compare the MIR with the (Interplanetary) Coronal Mass Ejection (ICME/CME) studied in Maunder et al. (2022) in the mid-latitudes at *Ulysses* containing a Magnetic Cloud (MC) and present a comprehensive discussion of the challenges posed by observing and relating transients not in alignment, across different latitudes and longitudes, and in different solar wind environments. As the CME propagates almost directly towards *Ulysses*, we find through fitting and modelling that its flanks could also potentially skim the near-ecliptic spacecraft. Length-scale analysis appears to be consistent with this configuration. However, local expansion velocities~~ **The changes in the MIR across the three spacecraft, separated by 17° in longitude, show the differences in the radial progression of the interaction between the CIR and MCL from West to East due to increased radial distances.** Local **negative** expansion **speeds** of the MCL ~~/MC indicate compression near the ecliptic and expansion at *Ulysses* and the magnetic flux rope orientations and helicities at the different latitudes oppose each other. The CIR likely causes more compression and re-aligns the transient axis orientation near the ecliptic while a High Speed Stream (HSS) from the Southern sector propagates directly into the back of the ICME/MC near the mid-latitude. Opposing signs of helicity could provide indications of flux added in the first stages of CME evolution or magnetic reconnection with the Heliospheric Current Sheet (HCS). These observations and analyses demonstrate the continued challenge of modelling and fitting the propagation of transients embedded in complex solar wind environments.~~

We note some of the caveats and limitations in the methods and highlight the use of multi-spacecraft analysis to disentangle the origin and formation of ICME substructures from the solar wind and other transients. indicate compression **increasing further downstream. Differences in size, the formation of the sheath, the presence of forward and reverse waves, and the small-scale structuring demonstrate the progression of the interaction. This multi-spacecraft approach highlights the intricate nature of solar wind structures and their interactions at 1 AU.**

1 Introduction

The heliosphere is formed by the continuous outflow of the solar wind (Parker, 1958), in which we observe both small and large scale large-scale transients. Coronal Mass Ejections (CMEs) and their heliospheric counterparts (Interplanetary CMEs, ICMEs), are large-scale transients known to drive interplanetary shocks (Gosling et al., 1975). ICMEs with Magnetic Clouds (MCs) are a subset of ICMEs with distinct magnetic field characteristics: an enhanced magnetic field and smooth, large-scale rotation of the magnetic field vectors (Burlaga, 1984, 2001). Marubashi (1986) and Bothmer and Schwenn (1998) suggest that a twisted magnetic flux tube can approximate the global magnetic structure of a MC, and fitting models to the magnetic field time series may provide an estimate of its large-scale topology (Lepping et al., 1990; Bothmer and Schwenn, 1998). A MC is usually identified when a spacecraft passes near its cloud axis. Magnetic Cloud Like structures Cloud-Like structures (MCLs) are magnetic structures identified using the same definition as a MC, except that a traditional flux-rope model cannot be fitted (Lepping et al., 2005; Foullon et al., 2007). Wu et al. (2006) found that the occurrence rate of MCLs and joint sets (MCs plus MCLs) are related to both the solar activity and the CME occurrence rate. This correlation is not observed with MCs alone. It is possible that all ICMEs contain flux-ropes but that some are not recognised as MCs only because the spacecraft trajectories skim the flanks (Marubashi, 1997; Kilpua et al., 2012, 2017).

Identifying ICMEs from in-situ data is a challenging and somewhat ambiguous task; there are around two dozen recognised signatures (Zurbuchen and Richardson, 2006), each with its own limitations (Richardson, 2014), and longitudinal separations of a few degrees between spacecraft can still result in significantly different observations and event properties (Davies et al., 2020). Single spacecraft in-situ observations enable limited analysis as they are only able to measure a single track through the ICME as it passes over the spacecraft, leading to discrepancies or incomplete knowledge of the instantaneous structure and composition of ICMEs (Russell and Mulligan, 2002; Howard, 2011; DiBraccio et al., 2015). According to Kilpua et al. (2012), 'ICME-like' transients are defined as lasting more than three hours but not meeting the maximum magnetic field criteria of $(B_{max}) > 7$ nT and duration of more than 10 hours to be classed as an ICME. **ICME-like transients, which are smaller than full ICMEs, fit within the continuous size distribution of magnetic flux-ropes, ranging from small (0.004 AU) to intermediate (0.6 AU)-sized structures (Feng et al., 2007).** The identification becomes even more challenging in the case of flux-ropes in complex solar wind environments (e.g. Rouillard et al., 2009b; Winslow et al., 2021). In such cases, multi-spacecraft observations become key to disentangling features to give a more accurate estimation of flux-rope properties and structure of ICMEs at different points, permitting the development of a more accurate implied 3D structure (e.g. Foullon et al., 2007; Möstl et al., 2009; Palmerio et al., 2019).

Stream Interaction Regions (SIRs), sometimes referred to as Corotating Interaction Regions (CIRs), are regions in which the ambient plasma is compressed ~~(Pizzo and Gosling, 1994; Richardson, 2018)~~ (?Pizzo and Gosling, 1994; Richardson, 2018) as a result of fast wind **or High-Speed Stream (HSS)** emerging behind slow wind from adjacent longitudinal sources interacting

60 as they are brought into radial alignment by solar rotation. They are common high-density structures observed in situ during solar minimum (Gazis, 1996). Since coronal holes, the source of the fast wind at the Sun, tend to be long-lived, CIRs are the subset of SIRs observed at regular intervals of approximately the solar rotation period **(for instance by a single observatory in-situ)**. Conventionally SIRs and CIRs are associated with the streamer belt and its embedded Heliospheric Current Sheet (HCS), which can extend north and south of the solar equator to heliographic latitudes of about $\pm 30\,°$. ~~For~~

65 ~~clarity, we refer to a CIR when observed near the equatorial region and to a SIR more broadly to include an interaction region resulting from a high latitude High Speed Stream (HSS) . Merged Interaction Regions (MIRs) are complex structures arising from flux-rope interactions including, but not limited to , interactions with a HSS, SIR (Rouillard et al., 2009b, 2010b) or the HCS.~~ **The interaction of CIRs with transients, such as CMEs, is not uncommon (e.g. Kay et al., 2023). Complex structures arising from flux-rope interactions, including interactions with HSS, CIR/SIR, or HCS, are a type of Merged**

70 **Interaction Regions (MIRs, e.g. ?). While much is known about MIR formation beyond 1 AU, recent studies have increasingly focused on MIRs within or at 1 AU, primarily examining large structures with radial extents of 2 to 4 AU (e.g. Burlaga et al., 2003; Rouillard et al., 2010b; Rodkin et al., 2018), their impacts on geomagnetic and ionospheric activity (e.g. Farrugia et al., 2011), as well as solar wind propagation (e.g. Shugay et al., 2018).**

We focus on small-scale ICMEs or ICME-like transients, likely associated with small-scale transients at the Sun. In a

75 study by Rouillard et al. (2008), Heliospheric Imager (HI) images from the Solar Terrestrial Relations Observatory (STEREO) were used to attribute CIR-associated waves to continual release of small-scale transients in the slow solar wind, which are subsequently compressed in CIRs. **The formation of plasmoids, or magnetic 'blob' islands, in the solar wind is a complex process influenced by several mechanisms. The seemingly quiescent slow wind consists, at least in part, of transient events from magnetic reconnection generated either at the cusps of streamers or between the coronal hole boundaries**

80 **and the cusps of streamers (e.g. Wang et al., 2000). Crooker and Intriligator (1996) first reported the observation of a flux-rope transient "in the HCS", showing an ICME forming a highly distended flux-rope "occlusion." Less obvious transient signatures are generally detected as multiple field reversals and smaller coiled features, which give a layered structure appearance to the HCS (e.g. Crooker et al., 2004; Foullon et al., 2009). A multi-spacecraft study of the HCS for a 2008 event looked at the slow solar wind around the HCS as a boundary layer (Foullon et al., 2011). The study**

85 **allowed the observation of evolution from East to West in heliospheric longitudes, showing evidence of the continuous releases of plasmoids and a differential rotation-driven evolution leading to asymmetry by interchange. The transient release of density blobs and flux-ropes through sequential magnetic reconnection at the tip of the helmet streamer has been observed with STEREO remote sensing (Sanchez-Diaz et al., 2017) and with the Parker Solar Probe in-situ (Lavraud et al., 2020).**

90 In the present study we investigate complex structures **of the sector boundary** observed in-situ on 3-4 July 2007. Using remote-sensing and in-situ observations across multiple spacecraft near the ecliptic with ~~complimentary~~ complementary meth-

Table 1. Spacecraft positions on 4 July 2007.

Spacecraft	Latitude (°) [HEE]	Longitude (°) [HEE]	Radial Distance (AU)
STEREO-A	0.12	~~9.39~~ 10.12	0.96
OMNI (Earth)	0.00	0.00	1
STEREO-B	-0.26	~~-6.39~~ -6.46	1.08
~~Ulysses -32.85 49.06 1.48~~			

ods of analysis, we demonstrate the presence of a MCL embedded in a CIR, resulting in a MIR. ~~We address (1) the presence of a CIR and how this combines with the MCL and is observed as a MIR , (2)the arrival times of the entrained MCL, which are consistent with an ICME entrained in a CIR , (3)the difference in the MIR observed~~ We present: the in-situ observations of
95 ICME or ICME-like transients at STEREO-A, STEREO-B, and OMNI showing evidence for a MIR (Sect. 2); further analysis of the transients focusing on how they interact with the CIR to form the MIR (Sect. 3); a multi-spacecraft combined view of dynamics and evolution, using modelling and predictions derived from remote sensing observations and a comparative analysis of MIR observations at different longitudes ~~with a small separation angle.~~ (Sect. 4); followed by a summary of our findings (Summary).

100   A contemporaneous solar event was presented in Maunder et al. (2022), where the multi-spacecraft study of a mid-latitude CME revealed by a unique orbital configuration permitted the analysis of remote-sensing observations from the twin STEREO -A and -B spacecraft and of its subsequent in situ counterpart outside the ecliptic plane, at *Ulysses*. Here our study focuses on near-ecliptic in-situ observations.

2   Near-ecliptic observations

105 **2.1   Spacecraft Data and Configuration**

We include data sets from the STEREO (STEREO-A and STEREO-B, Kaiser et al., 2008) Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) HI-1 and HI-2 cameras, with respective elongation ranges of $4-24°$ and $18-88°$ in the ecliptic plane (Eyles et al., 2009), the ~~Plasma and Suprathermal Ion Composition Magnetometer (IMPACT Luhmann et al., 2008)~~ **In situ Measurements of Particles And CME Transients** (IMPACT Luhmann et al., 2008) **Magnetometer**, the IMPACT
110 Solar ~~Wind Plasma Electron~~ **Wind Electron** Analyzer (SWEA Luhmann et al., 2008), and the Plasma and Suprathermal Ion Composition (PLASTIC) investigation (Galvin et al., 2008). We also use in-situ observations from the OMNI virtual observatory, which combines multiple near-Earth (L1) data sets, including the Advanced Composition Explorer (ACE) (Stone et al., 1998) and Wind (Lepping et al., 1995); see King and Papitashvili (2005).

    The spacecraft positions on 4 July 2007 are given in Table 1 in Heliographic Earth Ecliptic coordinate system (HEE) coor-
115 dinates, and are shown in Fig. 1 as seen from above the North pole (panel (a)) and ~~from 90° longitude~~ **in a 3d view** to the East of the Sun-Earth line (panel (b)). On a heliospheric scale, we can consider OMNI's position as Earth (rather than the adjusted

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Figure 1. Spacecraft positions on 04 July 2007 ~~,~~ obtained with the Solar MAgnetic Connection Haus (Solar-MACH) tool (Gieseler et al., 2023): (a) view from above the solar north pole including Earth's orbit **(1 AU)**, ~~(green dashed line).~~ (b) ~~:~~ **3d** view ~~from 90° longitude~~ to the East of the Sun-Earth line ~~.~~ **showing the spacecraft above the equatorial plane (grey shaded). Magnetic connections in interplanetary space are obtained by the classic Parker Heliospheric Magnetic Field for solar wind speeds of 600** km s^{-1}.

Earth bowshock nose location). ~~This event~~ **The event under study** was observed very early into the STEREO mission, where both spacecraft are close to Earth; STEREO-A and STEREO-B have a longitudinal separation of ~~9.4° and 5.8°~~ 10.12° and −6.46° [HEE] from Earth respectively. Given their HEE latitudes, we will refer to the STEREO-A, OMNI, and STEREO-B in-situ observations as 'near-ecliptic'.

~~Here our study focuses on the near-ecliptic in-situ observations, and we compare them with the contemporaneous solar event presented in Maunder et al. (2022) to investigate whether these events could be related. In Maunder et al. (2022), the multi-spacecraft study of a mid-latitude CME revealed by a unique orbital configuration permitted the analysis of remote-sensing observations from the twin STEREO -A and -B spacecraft and of its subsequent in situ counterpart outside the ecliptic plane, at *Ulysses*. A triangulation method was applied to the STEREO/SECCHI COR2 coronagraph images of the CME, and a single-spacecraft geometrical fitting method to the time-elongation profile of the CME's apex from STEREO/SECCHI HI-B data. The ICME is observed on 04 July 2007 by *Ulysses* near 1.5 AU and 33° latitude and 49° longitude HEE. This includes a preceding forward shock, followed by a sheath region, a MC, followed by a compression region driving a second forward-shock, due to a succeeding HSS interacting with the ICME. In particular, the MC had a duration of 24h, a West-North-East configuration, a length scale of ≈0.2 AU, and mean expansion speed of 14.2 $^{-1}$ inferred through a Minimum Variance Analysis (MVA) and a length-scale analysis at *Ulysses*. The relatively small size of this ICME is likely to be a result of its interaction with the succeeding HSS which in itself drives the second forward shock into the back of the MC.~~

~~We present: the in-situ observations of ICME or ICME-like transients at STEREO-A, STEREO-B, and OMNI showing evidence for a MIR (Sect. 2); further analysis of the transients and a comparison of the observations against that of the event observed at *Ulysses* presented in Maunder et al. (2022) (Sect. **??**); followed by a summary of our findings (Summary).~~

3 ~~Near-ecliptic observations~~

2.1 ICME and ICME-like transients

Figures 2, 3, and 4 show the structures observed at OMNI, STEREO-A, and STEREO-B respectively. Further observations from ACE are shown in Fig. 5 to complement those at OMNI (as the ACE data are not shown in the same time frame, similar observations to those in Fig. 2 are shown for context). The MCL boundaries are indicated by magenta vertical lines and specific MCL properties are given in Table 2. A CIR is also observed across all spacecraft and Table 2 gives the arrival time of each

Figure 2. The MIR observed on 3 - 4 July 2007 by OMNI. (a) Magnitude and (b-d) normalised components of the magnetic field vector **(GSE)**; (e) proton speed; (f) proton temperature (black), expected temperature calculated from the observed solar wind speed (blue); half the expected proton temperature, (purple); (g) proton density; (h) total pressure (black), magnetic pressure (purple) and proton pressure (navy); (i) proton plasma beta with a threshold of 1 (blue). Magenta vertical lines labelled 'MCL' and '~~FW2~~CIR' represent the leading and trailing edges of the MCL, respectively; the black vertical line labelled 'RW' ~~represent~~ represents the reverse pressure wave behind the compression region.

Figure 3. The MIR observed on 3 July 2007 at STEREO-A. Captions for panels and labels are as those in Fig. 2 with **the magnetic field vector shown in the RTN system and** the addition of (j) the electron pitch angles at 272 eV~~and 'FW1'~~, the black vertical line labelled 'FW1' representing the pressure wave in front of the sheath ~~,~~**and the label 'FW2' coinciding with the magenta vertical line 'CIR' to represent the pressure wave created by the fast wind propagating into the back of the MCL.**

part of the transient and CIR combined, which we refer to as the MIR. The combined ICME-CIR structure will be discussed as an MIR in Sect. 3.

145   Panels (a)-(d) ~~show~~ of Fig. 2-5 show the magnitude and normalised components of the magnetic field vector. For the twin STEREO observations, ~~they~~ the components are presented in the Heliographic Radial Tangential Normal (RTN) system of reference (Burlaga, 1984) and normalised. In this coordinate system, R points from the Sun to the spacecraft, T is the Sun's rotation vector crossed into R (thus towards west for a spacecraft near the ecliptic) and N completes the right-handed system. The magnetic field components of the OMNI **and ACE** observations are given in the Geocentric Solar Ecliptic (GSE) system

150   of reference. In the OMNI **and ACE** data, the correspondence between GSE and RTN is then $B_X \equiv -B_R$, $B_Y \equiv -B_T$, $B_Z \equiv B_N$ for the magnetic field components and so we refer to the transformed components for ease of comparison. The MCL is identified by an enhanced magnetic field followed by a clear rotation in the B_T and B_N vectors in STEREO-A and -B and in the $-B_Z$ vector in OMNI ~~. The flux rope~~ **and ACE. The flux-rope** leading edge (labelled 'MCL') ~~is first observed~~ **arrives first** at STEREO-B at 04:00 UT on 3 July, then at OMNI at 11:00 UT and ~~at~~ STEREO-A at 16:16 UT the same day

155   (time t_{MCL}). The MCL, identified between time t_{MCL} and the trailing edge at time ~~t_{FW2}~~t_{CIR}, has a mean magnetic field intensity (averaged over the time range between t_{MCL} and ~~t_{FW2}~~t_{CIR}) $\langle B \rangle = 7, 9, 7$ nT in STEREO-A, OMNI, and STEREO-B respectively. The structures at STEREO-A and STEREO-B meet the ICME criteria proposed by Kilpua et al. (2012); only the MCL structure at OMNI lasts less than 10 hours and can therefore be classified as an ICME-like structure.

      In panel (e) of Fig. 2-4, the MCL is characterised by a consistent and relatively slow proton speed (e.g. Lepping et al.,

160   1990) with a mean solar wind speed (and standard deviation) of 337 ($\pm$ 6.8), 362 ($\pm$ 14.1), 411 ($\pm$ 32.9) $\mathrm{km\,s^{-1}}$ at STEREO-A, OMNI, and STEREO-B respectively (again averaged over the time range between t_{MCL} and ~~t_{FW2}~~t_{CIR}). The proton temperature, in panel (f) is below the expected ~~proton temperature for STEREO-A and OMNI, indicative of a MC, but matches approximately the expected solar~~ **solar** wind temperature T_{ex} (over plotted in blue, Richardson and Cane, 1995; Lopez, 1987) ~~across all three near-ecliptic spacecraft~~**for STEREO-A and OMNI, indicative of a MC, but matches approximately T_{ex} for**

165   **STEREO-B**. Panel (g) shows a drop in proton density. Panel (h) shows the total pressure (black), magnetic pressure (purple)

Figure 4. The MIR observed on 3 - 4 July 2007 by STEREO-B. Captions for panels and labels are as those in Fig. 3.

Figure 5. The MIR observed on 3 - 4 July 2007 by ACE. Captions for panels (a)-(~~f~~e) are as in Fig. 2~~,~~; **(f) magnetic pressure (purple) as in panel (h) of Fig. 2**; caption for panel (g) as in panel (j) ~~in~~ of Fig. 3.

and proton pressure (navy); here we observe a drop in proton pressure, consistent with the passage of a MC (Gosling, 1994; Gosling et al., 1994).

The proton-beta, β_p in panel (i), is consistently less than 1 across the MCL (0.01-0.38, 0.04-0.27, 0.03-0.67 in STEREO-A, OMNI, STEREO-B respectively) and we see a distinct drop in comparison with the surrounding plasma. This is a convincing
170 signature ~~at~~ for all three spacecraft. For STEREO-A and -B we present the suprathermal electron pitch angle distribution, in panel (j). The ACE electron pitch angle data is shown in panel (g) of Fig. 5 (OMNI does not include pitch angle data). This is predominately anti-sunward in STEREO-A and ACE with some spreading in STEREO-B.

At STEREO-A, we observe a preceding forward pressure wave (FW1) at 07:40 UT on 3 July, characterised by ~~a~~ pressure and speed increases. This wave, 8:36 hours before and a result of plasma ~~build up~~ build-up at the leading edge of the MCL, is
175 not evident in the other near-ecliptic spacecraft observations. Instead, if a pressure wave is present at OMNI and STEREO-B, it coincides with the start of the MCL (this time is shown ~~between~~ in brackets in Table 2). Similarly, the trailing edge of the MCL at STEREO-A **(labelled 'CIR' - see below)** coincides with a second forward wave (FW2); this is less evident at the other spacecraft. At all near-ecliptic spacecraft, a CIR achieving speeds above 600 $\mathrm{km\,s^{-1}}$ runs into the back of the MCL. At STEREO-A, this interaction drives the forward wave (FW2) at the front of the ~~compression region, the latter being the CIR.~~
180 **CIR (compression region)**. At all spacecraft, a reverse wave (RW) propagates back into the fast wind behind the CIR, marking the rear of the CIR.

Thus FW1 and FW2 are reasonably clear at STEREO-A but not obviously present in STEREO-B and OMNI data. The front sheath (FS, between 'FW1' and 'MCL') and the MCL at STEREO-A form an ICME. The ICME at STEREO-B and the ICME-like transient at OMNI contain only the MCL. The MCL is followed by two distinct boundaries, 'CIR/FW2~~and~~
185 ~~RW~~' and 'RW': at STEREO-A, they are the forward and reverse waves from a CIR, while at STEREO-B and OMNI, ~~FW2~~ 'CIR' only marks a boundary between the MCL and CIR and ~~RW~~ 'RW' marks the location of a reverse wave. Comparing the speed profile at STEREO-B with those at the other spacecraft, it is possible that the wave driven by the CIR compression ('FW2') has propagated through the front of the MCL. In other words, the MCL is more entrained at STEREO-B than at the other spacecraft. The reverse wave RW is detected at 08:00 UT, 08:10 UT and 22:00 UT 04 July, in STEREO-B, OMNI and
190 STEREO-A, respectively 17:50, 13:10, 15:00 hours later than the ~~FW2~~ 'CIR' boundary.

~~The MIR observed on 3 - 4 July 2007 by ACE. Captions for panels (a)-(f) are as in Fig. 2, panel (g) as in panel (j) in Fig. 3.~~

Table 2. MIR and MCL (STEREO/OMNI) ~~/ MC (*Ulysses*)~~ Properties: the arrival time of the wave front t_{FW1}, flux-rope leading edge t_{MCL}~~or t_{MC}~~, ~~second forward wave t_{FW2}~~**CIR leading edge** t_{CIR}, trailing reverse waves t_{RW}, the ~~mean~~ **average** velocity ~~,~~ $\langle V \rangle$ **within the MCL**, ~~velocity V_{MCL} or V_{MC}, leading edge velocity,~~ maximum total magnetic field strength B_{max} ~~,~~**and** average magnetic field $\langle B \rangle$ **within the MCL. Brackets for t_{FW1} giving t_{MCL} values at OMNI and STEREO-B indicate that, if present, the pressure wave 'FW1' coincides with the leading edge of the MCL**.

Spacecraft	t_{FW1}	~~$t_{MC(L)}$~~t_{MCL}	~~t_{FW2}~~t_{CIR}	t_{RW}	~~V_{MC}~~
STEREO-A	03 Jul 07:40	03 Jul 16:16	04 Jul 07:00	04 Jul 22:00	350
OMNI	(03 Jul 11:00)	03 Jul 11:00	03 Jul 19:00	04 Jul 08:10	346
STEREO-B	(03 Jul 04:00)	03 Jul 04:00	03 Jul 14:10	04 Jul 08:00	360

~~*Ulysses* 04 July 08:00 04 July 13:00 05 July 13 05 July 20:50 396 13.3 11.5~~

Table 3. Magnetic sector and electron pitch angle characteristics for each part of the transient and flux-rope orientations for the ~~MC(L)~~ **MCL** at each spacecraft.

	Magnetic Sector and Electron Pitch Angle Characteristics		
	Before	~~MCL/MC~~ **MCL**	After
STEREO-A	Away, 0°	Towards, 180°	Towards 1
ACE (OMNI)	Away, 0°	Towards, 180°	Towards, 1
STEREO-B	Away, 0°	Towards, 180°	Towards, 1
	with brief reversals, $0 - 180°$	(with spreading)	(with sprea

~~*Ulysses* Away, 0° (Counter-Streaming) (Counter-Streaming) West-North-East (WNE)~~

2.2 Magnetic orientation

In Figs. 3-4, between the leading and trailing edges of the MCL, we distinguish a clear coherent rotation of the magnetic field vector with a low level of magnetic field-magnitude fluctuations, and low values of proton plasma beta. Although a MVA analysis did not reveal reliable axis orientations, these are clear signatures of ~~MCL~~ MCLs and support the flux-rope interpretation. We adopt the method proposed by Bothmer and Schwenn (1998) and Mulligan et al. (1998) to deduce the magnetic configuration of the MCLs, and the sign of helicity, **the helicity being** a measure that describes how the magnetic field lines are wound around each other (applied in the same manner as Dasso et al., 2006; Foullon et al., 2007; Kilpua et al., 2017). The method assumes that a MC (or MCL as in this case) possesses a specific magnetic configuration, of which the sense of the rotation indicates the sign of its helicity. We also use the suprathermal electron pitch angle characteristics from STEREO-A, -B, and ACE (see Fig. 3, 4 and 5) to assist in the interpretation of the magnetic topology of the field lines local to the spacecraft. The flux-rope orientation and characteristics are listed in Table 3.

At STEREO-A, the local orientation of the MCL normalised magnetic field vector, as shown in panels (c,d) of Fig. 3, turns from North ($B_N > 0$), to West ($B_T > 0$), to South ($B_N < 0$) on the cloud's axis. This flux-rope cloud can be interpreted as a North-West-South (NWS) cloud with left-handed (negative) helicity. In panel (c) the (normalised) B_R component of the magnetic field is mostly negative during and after the MCL. In panel (j) we find the streaming of electrons at a pitch angle of $180\,^\circ$ during the MCL and CIR, and behind those structures, which confirms that STEREO-A is in the towards sector, North of the HCS, at this point. The lack of counter-streaming in the MCL suggests that the magnetic field lines are open, thus only one end of the magnetic field lines which form the flux-rope are rooted at the Sun. A magnetic field reversal with electrons reversing in pitch angle from 0 to $180\,^\circ$ appears close to the start of the MCL. Thus, the reversal is likely to be a crossing of the HCS (see Crooker et al., 1993). This can indicate that the MCL is acting as an occlusion in the current sheet.

At OMNI, the normalised magnetic field, shown in panels (c,d) of Fig. 2 turns from North ($B_Z > 0$) to West (-$B_Y > 0$) to South ($B_Z < 0$) in the MCL, again indicating a NWS cloud with left-handed (negative) helicity. The ACE electron pitch angle data ~~in panel (g) of Fig. 5 shows~~ **and magnetic field vector data in panels (g) and (b-d) of Fig. 5, respectively, show** a similar result to STEREO-A, with outward magnetic field and streaming at $0\,^\circ$ before the MIR event (Away sector) and inward field and streaming at $180\,^\circ$ during and after the event (Toward sector), indicating that ACE had crossed the HCS close to the start of the MCL and is likely north of the HCS when the MCL is observed.

Similarly, at STEREO-B, in panels (c,d) of Fig. 4, we observe the normalised magnetic field turn from North ($B_N > 0$) to West ($B_T > 0$) to South ($B_N < 0$) indicating a NWS cloud, a bipolar flux-rope with a low-inclination and left-handed (negative) helicity. The (normalised) B_R, component of the magnetic field (panel (b)) is mostly negative during and after the MCL, again indicating that the magnetic field within the MCL is predominantly orientated towards the Sun. We observe electrons streaming unidirectionally at a pitch angle of $180\,^\circ$ along field lines (panel (j)), albeit with some spreading, indicating a location predominantly in the towards sector of the Sun, north of the sector boundary. While again the HCS crossing appears to coincide with the start of the MCL, ahead of the MCL there are magnetic field sign changes associated with brief pitch angle reversals, indicating more structure in the field and electron data than at the other spacecraft. A main field reversal, seen first in B_R turning negative, is observed around 18:30UT on 2 July, about 9.5 hours ahead of the MCL, with electrons streaming at $180\,^\circ$. From 21:00 UT, the magnetic field turns back and forth while the electrons are counter-streaming. From 3 July, another main reversal is observed with B_R turning back to positive and with electrons streaming at $0\,^\circ$. Those field reversals suggest multiple folds in the magnetic field.

2.3 ~~**MIRs**~~

3 Analysis of Combined MCL-CIR Structures: MIRs

In this section~~we address~~, we address **in more detail** the presence of ~~a~~ the CIR, observed at all three near-ecliptic spacecraft and **focus on** how this combines with the transient presented earlier to become an MIR. ~~(e.g. Burlaga et al., 2003; Rouillard et al., 2009b; Farrug~~ ~~. We provide evidence that the MIR is the result of the fast wind interacting with the slow wind in which the flux rope is~~ ~~embedded leading to the flux rope being entrained in the resulting CIR. In particular we comment on how the arrival times at~~

3.1 Interaction Regions

In the near-ecliptic spacecraft observations, it is clear that, in addition to the presence of a MCL, the in-situ observations resemble a CIR (Pizzo and Gosling, 1994). Despite the lack of CIR forward waves at STEREO-B and OMNI, we are able to match distinct magnetic field rotations and pressure waves across the observations. There is one missing property, however. CIRs traditionally show high plasma beta (Borovsky and Denton, 2006). Here we observe a low plasma beta, which is a distinct signature of ICMEs and MC(L)s.

One piece of evidence to indicate the presence and influence of a CIR is given by the arrival timings. This evidence is provided by the observation that the MCL arrives at STEREO-B first, then Earth and STEREO-A, even though STEREO-B is the furthest of the near Earth near-Earth spacecraft from the Sun. We expect, and in this case observed, timings consistent with a CIR in the solar wind for a MCL that is greatly influenced by its surrounding solar wind. In cases where CMEs are compressed by HSSs, we can reasonably expect that the magnetic field lines joining the leading edge of the CME to the Sun are forced to co-rotate due to the high pressures induced by the compressive effects of the HSS.

These complex interactions offer a probable explanation as to why the event is relatively short, with little compression ahead of the MCL (an ICME front sheath region can only be found at STEREO-A), and why it is also difficult to disentangle the structure in the in-situ data without comparison across different spacecraft. The transients are not reported by any in-situ ICME catalogues relating to the near-ecliptic spacecraft as it is unlikely to have been spotted by usual automated methods and the event duration may be too short to meet catalogue criteria. Kilpua et al. (2012) found that ICME-like transients (in contrast to ICMEs) occur closer to CIRs.

The interaction of CIRs with transients including CMEs is not uncommon. In particular, Rouillard et al. (2008) used HI images to attribute CIR-associated waves to continual release of small-scale transients in the slow solar wind, which are subsequently compressed in CIRs

3.2 Length Scale and Expansion Speed

Analysis of the **MIR signatures** near the ecliptic shows that they have two to three distinct regions: (1) a front sheath FS (at STEREO-A only), (2) a **MCL**, and (3) a subsequent compression region created by the interaction between the **MCL** and a HSS. In order to compare these, we calculate the length scale of each region for each set of observations by taking the mean velocity of the region multiplied by the duration of the region, with the standard deviation included for reference. Durations

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Table 4. Length scales given with standard deviation for the FS, **MCL, and CIR**, their total and the expansion velocity V_{exp} at each of the near-ecliptic spacecraft.

Spacecraft	FS		MCL		CIR		Total		V_{exp}
	$(10^6$ km$)$	$(\approx$ AU$)$	$(10^6$ km$)$	$(\approx$ AU$)$	$(10^6$ km$)$	$(\approx$ AU$)$	$(10^6$ km$)$	$(\approx$ AU$)$	$($km s$^{-1})$
STEREO-A	10.8 ± 0.8	0.07	17.9 ± 0.36	0.12	26.8 ± 4.0	0.18	55.5 ± 12.3	0.37	-7
OMNI		0	10.3 ± 0.41	0.07	23.8 ± 3.2	0.16	34.3 ± 6.7	0.23	-22.25
STEREO-B		0	15.1 ± 1.20	0.10	36.1 ± 2.4	0.24	51.2 ± 0.8	0.34	-76.5

can be obtained from Table 2 and the estimated length scales for each of the regions at each spacecraft are presented in Table 4.

The MCL **extents** are relatively short across all observations, ranging between 0.07-0.12 AU; the compression is due to the CIR. This is much smaller than the 0.2-0.3 AU MC average at 1 AU (Lepping et al., 1990; Owens et al., 2005).

Additionally, for the MIR or ICME-CIR as a whole, we estimate the length scale of the disturbance to be 0.23-0.37 AU. There is significantly more disturbance and a larger front sheath (FS) region at STEREO-A (there is no front sheath at OMNI and STEREO-B).

Finally, the mean expansion speeds, V_{exp}, calculated as half of the difference between the speed of the leading and trailing edge of the MCL, is negative for all spacecraft, indicative of compression (see Table 4). **The measure of compression is increasing from West to East ($V_{exp} = [-7, -22.3, -76.5]$ km s^{-1}).** Such compression is common in transients entrained in CIRs.

4 Multi-Spacecraft Analysis of Dynamics and Evolution

4.1 Modeling and Predictions from Remote Sensing Observations

To investigate connections to the Sun, Figure 6 displays various Carrington maps at the time of the event (Rotation 2058). Panels (c-e) show maps derived from the photospheric magnetic field (panel (a)) using a potential field source surface (PFSS) model with a spherical source surface at 2.5 R$_\odot$. For ease of comparison, panel (b) presents a map of coronal emission, identifying bright active regions and dark coronal holes. The subsequent maps represent simulated coronal holes (panel (c)), the global magnetic field configuration of the corona (panel (d)), as well as the associated radial flow at 5 R$_\odot$ (panel (e)). These maps are from the "MHDweb" project of the Predictive Science Modeling Support for SECCHI and IMPACT (PREDSCI) [1] (Maps (a) and (d) use photospheric field from the Global Oscillations Network Group (GONG); maps (c) and (e) use photospheric field from Mount Wilson Observatory).

During this period near solar minimum, the toward sector (sunward interplanetary magnetic field) is connected to the northern solar magnetic hemisphere, while the away sector (anti-sunward interplanetary magnetic field) is connected

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[1] http://www.predsci.com

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Figure 6. Carrington (synoptic) maps for Rotation 2058 showing (a) the photospheric magnetic field from GONG, (b) 195Å EUV emission from SoHO/EIT (Hess Webber et al., 2014) (c) coronal hole polarities (blue negative, red positive) with Earth mapped back to the Sun (solar wind ballistic mapping in green using OMNI), (d) the PFSS model-derived global magnetic field configuration, and (e) radial flow at 5 $R_\odot$ together with the projected neutral line on the source surface from PREDSCI/MHDweb. The dashed vertical line indicates the approximate Carrington longitude and time corresponding to the source of the 600 $\mathrm{km\,s^{-1}}$ HSS in the corona.

to the southern hemisphere. Assuming that it travelled to 1 AU with the HSS speed of about 600 $\mathrm{km\,s^{-1}}$, the relevant coronal hole plasma parcel for the in-situ observations will be seen at the Sun 2.9 days earlier on July 1, 2007 (dashed vertical line in Fig. 6). On this date, an active region is centred on the disk (panel (a)), located across the field inversion
295 **neutral line, thus at the base of the helmet streamer belt (panels (d,e)). Coronal holes with inward and outward IMF polarity are on either side of the heliospheric current sheet. Solar wind ballistic mapping using OMNI shows that the HSS is associated with an equatorial coronal hole from the northern sector (panel (c)).**

Since the possible source region of the MCL and HSS is centred on the disk and the STEREO spacecraft separation is relatively small, we cannot have a side view of their evolution in any coronagraphs operating at the time. However,
300 **we can still learn about the likely behaviour of disturbances (blobs entrained in a CIR) from the contemporaneous observations of adjacent heliospheric longitudes.** As seen in Fig. 7, the time–elongation maps, or *J-maps*, from STEREO/SECCHI-HI-A extending ~~form the~~ **from** 19 June to ~~the~~ 5 July 2007 show a nest of converging tracks, which can be interpreted as a pattern of CIR-entrained blobs. We believe the ~~MCL structure is associated with~~ **likely behaviour of the** MCL structure **resembles that of** one of those disturbances. One cannot be more specific, but for reference, we can take one of the CIR distur-
305 bances, $HSIR\_STA\_20070623\_100341$, reported in the HELCATS STEREO SIR/CIR Catalogue (Plotnikov et al., 2016)[2]. The nest of tracks overplotted in Fig. 7 corresponds to a set of blobs all travelling with the same speed as the HELCATS CIR **disturbance**, which is found to have a speed of $302\pm21\ \mathrm{km\,s^{-1}}$ (see Rouillard et al., 2010a, for more details on the uncertainty value). The timings are derived relative to that CIR with the knowledge that one of the blobs therein was fitted to be travelling at $64\pm6°$ angular separation from the Sun-spacecraft line. The CIR is predicted to arrive at STEREO-B at 15:15 UT on 3
310 July and at STEREO-A at 03:13 UT on 4 July 2007. This is similar to the observed earlier arrival time for STEREO-B and separation of ∼12 hours.

Figure 7. STEREO/SECCHI/HI-A *J-maps* for the period from 19 June to 5 July 2007 constructed in the ecliptic at a PA of $280°$: (Left) without and (Right) with tracks superimposed. The tracks ~~corresponds~~ correspond to a set of blobs all travelling with the same speed as the blob that corresponds to HELCATS CIR $HSIR\_STA\_20070623\_100341$, which travels at $64°$ angular separation from the Sun-spacecraft line. The trajectories are derived from $180°$ to $0°$ separation angles from the Sun-spacecraft line, in steps of 10 degrees. Each blob is tracked over a somewhat arbitrary time of 10 days.

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[2]https://www.helcats-fp7.eu/catalogues/wp5_cat.html

Figure 8. Sketch of the MIRs observed at different longitudes near the ecliptic, at STEREO-B, Earth and STEREO-A. The view is from the solar north pole. The MIR is shown as the result of the MCL interacting with both the CIR and the HCS. The MCL flux-rope with the main axis (black arrow) pointing Westward is embedded between the toward Northern sector (blue) and away Southern sector (red) field lines. The MIR variations across the spacecraft demonstrate the progression of the interaction between the CIR and MCL from West to East.

Another ~~signature evidencing the MIR are the sector boundaries detected~~ **characteristic signature of the MIR, related to the MCL nature, is the identification of** the sector boundaries in the magnetic field and the near-ecliptic electron pitch angle data (Figures 3-5). The data ~~show~~ shows that the magnetic field is anti-sunward before and sunward during and after the MCL and CIR, which is consistent with the crossing of the HCS near the start of the MCL. Sector boundaries are often found just upstream of CIRs or having just been swept up by the forward waves of CIRs since they are embedded in the slow wind into which the fast wind is running ~~into~~ to create the CIR (Pizzo and Gosling, 1994). The proximity of the sector boundary crossing to the start of the MCL is also consistent with a flux-rope, originating from the streamer belt below the sector boundary as a result of reconnection, locally replacing the HCS, while expanding outwards (Crooker and Intriligator, 1996; Crooker et al., 1998, 2004; Foullon et al., 2011). It is thus likely that this MIR is the result of the MCL interacting with both the CIR and the HCS near the ecliptic.

~~This type of MIR is not uncommon, and the prevalence of small flux-ropes caught within the leading edge of CIRs observed in situ is discussed by Rouillard et al. (2009b), who confirm that HI observes CIRs in difference images via small-scale transients caught up in the compression region. In fact, Rouillard et al. (2009b) report on a small-scale transient entrained by a CIR that has parallels with our event. Their event is observed later on 20 July 2007. Resemblances between the two events include similar flux-rope profiles observed at STEREO-A with a clear reversal of the polarity of magnetic field lines and a change of suprathermal electron pitch angle from 0° to 180° at the start of the MC(L). For the event presented by Rouillard et al. (2009b), there is no corresponding MC or MCL at the other spacecraft during the same CIR passage, while in our case, we observe clear MCLs at STEREO-B and OMNI, which are smaller and more turbulent than at STEREO-A.~~

4.2 Comparative Observations Across Spacecraft

The in-situ measurements are consistent with one or more structures developing between spacecraft, suggesting that MCL signatures may not correspond to the same structure. About two to six streamer blobs per day are recorded during solar minimum and maximum conditions, respectively (e.g. Rouillard et al., 2010a, at solar minimum). In this period of solar minimum, there could be two blobs released with a 12-hour offset between them, from the base of the same streamer. The 12-hour difference observed between the arrival of the MCLs at STEREO-B and STEREO-A could potentially support a scenario where for instance STEREO-B or OMNI (Earth) and STEREO-A encounter different blobs from the same streamer. The transient observed at STEREO-A is then the younger and most likely equivalent perturbation to the one observed at STEREO-B in a family of blobs.

However it is also more likely that we are presented with the same blob. Fig. 7 shows a few significant families of tracks (each family being associated with the passage of a single CIR). Tracks that propagate beyond 60° of elongation indicate transients entrained by a HSS. Taking the family of tracks highlighted as an example, it is not clear that one can observe a set of density perturbations with a 12-hour interval beyond 60° of elongation, but this could be due to instrument sensitivity.

Moreover, STEREO-A, OMNI (Earth) and STEREO-B are separated by 0.11 AU radially and less than 16.6° in longitude (less than 0.32 AU in the East-West direction). The magnetic orientation analysis (Sec. 2.2) indicates that, for each spacecraft observation, the MCL's cloud axis is in the ecliptic plane and its major size extends in the longitudinal direction, while its cross-section is compressed along the HCS. According to the findings of Liu et al. (2006), the cross-section aspect ratio of MCs is estimated to be no smaller than 6:1. Applied to our case, MCL transverse extents for all three observations are estimated to range between 0.42-0.72 AU at the minimum, which is larger than the East-West spacecraft separation.

Thus our event allows the comparison of MIR observations at different ~~longitudes.~~ **radial distances due to the small longitudinal separation relative to the scale size of the MCL. This comparision effectively maps the interactions of structures across a radial distance of 0.11 AU. The in-situ measurements are not to be interpreted as observing the exact same structure crossing all three spacecraft at different longitudes for the same radial distance, but they are consistent with different cross-sections of the same structure or of potentially two equivalent structures evolving from the same family, crossing all three spacecraft. This allows us to infer the evolution of such structure radially.** In Fig. 8, the MIR is shown as the result of the MCL interacting with both the CIR and the HCS. ~~From~~ **Moving** from West to East (right to left)~~the different observations provide in turn~~, observations **from different locations** provide snapshots of the ~~extent of the~~ interaction between the CIR and MCL~~, progressing as we move~~. As we move **downstream** from STEREO-A to OMNI (Earth) to STEREO-B, **we can see the extent of this interaction**. ~~In~~

At the earlier stage of interaction, **specifically** at STEREO-A, a forward wave and front sheath are produced ahead of the MCL and a reverse wave is found at the back of the CIR as a result of the interaction with the HSS.

In the next stages, at Earth and STEREO-B, the MCLs are smaller and more turbulent, and the main sector boundary crossing appears to coincide with the start of the MCL (~~no~~ **without a** sheath). ~~Finally~~

Finally, in the later stage at STEREO-B, the MCL appears to be fully entrained in the CIR~~(noting~~. **Notably,** the higher speed of the MCL at STEREO-B compared to the other spacecraft ~~); ahead~~ **is observed. Ahead** of the MCL, small-scale structures in the field and electron data are indicative of multiple magnetic folds, ~~that may result~~ **possibly resulting** from greater interactions with the HCS (e.g. produced by interchange reconnection with the HCS). ~~Hence~~

Therefore, the MIR variations ~~across longitudes demonstrates the radial evolution of the MIR. Due to corotation, the HSS is more caught up with the MCL at STEREO-B and progressivley less so at OMNI and STEREO-A.~~ **between spacecraft demonstrate the radial evolution of the MIR, with the HSS increasingly catching up with the MCL from STEREO-A to Earth and STEREO-B.**

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5 ~~Comparison with *Ulysses*~~

~~The origins of the MIR near the HCS as a MCL embedded in a CIR can be the result of reconnection near the sector boundary. During June-July 2007, (I)CME events were relatively rare and isolated as they occurred during a period of solar minimum. Given this and the various ways in which (I)CMEs can change during propagation, we ask the question: is it feasible that the MC observed at *Ulysses* and the MCL near the ecliptic are actually part of the same ejecta or at least have a common origin? In other words, are we observing different substructures of the original CME or associated with the same event?~~

4.1 ~~Self-similar expansion fitting~~

~~HI-1B images of the CME taken at 06:50 UT on 28 June 2007. (Left) Level 2 background-subtracted image provided as part of the standard calibration performed by the PI team (STFC/RAL Space), with additional smoothing applied in order to remove some of the background starfield. (Right) running difference image between consecutive Level 2 images. The position angles at 245° and 280°, over-plotted in both images, represent the two position angles at which the CME disturbances at Ulysses and near-ecliptic were tracked.~~

~~Here we re-visit the remote-sensing observations presented in Maunder et al. (2022), in which a CME observed in situ as an ICME at *Ulysses* was clearly visible in STEREO/SECCHI/HI-B images. In Maunder et al. (2022), we then applied a self-similar expansion fitting (SSEF) (Davies et al., 2012) to the data points obtained by tracking the CME front in *J-maps* constructed at a fixed position angle (PA) of 245°, close to the CME apex in the STEREO-B HI field of view (see Fig. **??**). To estimate the CME's speed and 3D propagation direction, the SSEF works by assuming that the CME front possesses a circular cross-section that expands with a constant half-width (see Davies et al., 2012; Barnes et al., 2020). Maunder et al. (2022) adopted a half width of 90°, equating to the so-called Harmonic Mean geometry (e.g. Lugaz, 2010). This resulted in an apex propagation direction of -28.8° latitude, 55.1° longitude HEE, consistent with its subsequent detection at *Ulysses*.~~

~~Predicted timings and speeds of in-situ impacts of the CME leading edge determined from SSEF using HI, July 2007. PA of fit (degrees) Impact Time (UT) Speed ($^{-1}$) STEREO-A 280 05:42 03 July 2007 306 OMNI/ACE 280 05:48 04 July 2007 270 STEREO-B 280 12:44 05 July 2007 242 *Ulysses* 245 12:13 05 July 2007 328~~

~~Using the same STEREO/SECCHI/HI-B images, an additional *J-map* was constructed to track the CME front at a PA of 280°, which corresponds almost exactly with the Ecliptic at this time (see Fig. **??**), giving values of 2.0° latitude and 41.3° longitude HEE. Table **??** presents the speed and , derived therefrom, the predicted impact times of the CME front, calculated at the positions of *Ulysses*, both STEREOs and OMNI/ACE, using the results of both fits. The SSEF method provides CME launch time, propagation direction and speed, which are used to determine impact times at the different spacecraft locations, where we also account for the curvature of the CME front using the method described in Möstl and Davies (2013). The SSEF-derived longitude near the ecliptic implies that the CME is directed 41.3° longitude West from OMNI/ACE, thus 31.9° from STEREO-A and 47.7° from STEREO-B, indicating that these positions would only be likely impacted by the ICME Eastern flank rather than the nose.~~

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405   Assuming that the proposed scenario that the CME flank does impact STEREO/ACE is correct, the results, showing that the SSEF speed of the CME apex is larger at the high-latitude of *Ulysses*, are in agreement with the CME apex being faster than its flank. The SSEF method however does not account for complicated morphology and behaviour, particularly CME interactions with background structures and we note that, contrary to the predicted impact times from SSEF, the event arrives at STEREO-B first (then Earth and STEREO-A). As explored in Sect. 3, this is expected as, whilst STEREO-B is the furthest of the near Earth

410 spacecraft from the Sun, the CME is entrained in the CIR near the ecliptic and combines as an MIR. We also note the similarity between the inferred SSEF speeds near ecliptic and the HELCATS CIR speed of 302 ± 21 $^{-1}$. Thus, the observed timings and inferred SSEF speeds near ecliptic are more consistent with a CIR in the solar wind than the flank of a CME that is not largely influenced by its surrounding solar wind.

4.1 ~~Length scale analysis~~

415 ~~The ICME-SIR combination at~~ *Ulysses* ~~may be seen as a MIR, but to distinguish it from the MIR structure near ecliptic, we choose to refer to it as the ICME-SIR. Analysis of the ICME-SIR at~~ *Ulysses* ~~and MIRs near the ecliptic show that they have two to three distinct regions: (1) a front sheath FS (at~~ *Ulysses* ~~and STEREO-A only), (2) a MC(L), and (3) a subsequent compression region created by interaction between the MC(L) and a HSS. In order to compare these, we calculate the length scale of each region for each set of observations by taking the mean velocity of the region multiplied by the duration of the~~

420 ~~region, with the standard deviation included for reference. Durations can be obtained from Table 2 and the estimated length scales for each of the regions at each spacecraft are presented in Table 4.~~

    ~~Length scales given with standard deviation for the FS, MC(L), and SIR, their total and the expansion velocity~~ V_{exp} ~~at each of the near-ecliptic spacecraft and at~~ *Ulysses*. ~~Spacecraft~~ V_{exp}(≈) (≈) (≈) (≈) ($^{-1}$) ~~STEREO-A 10.8 ± 0.8 0.07 17.9 ± 0.36 0.12 26.8 ± 4.0 0.18 55.5 ± 12.3 0.37 -7 OMNI 0 10.3 ± 0.41 0.07 23.8 ± 3.2 0.16 34.3 ± 6.7 0.23 -22.25 STEREO-B 0~~

425 ~~15.1 ± 1.20 0.10 36.1 ± 2.4 0.24 51.2 ± 0.8 0.34 -76.5~~ *Ulysses* ~~6.8 ± 0.3 0.05 32.6 ± 1.0 0.2 12.2 ± 1.5 0.08 51.7 ± 4.3 0.34 14.2~~

    ~~The MCL durations are relatively short across all observations at 1 near the ecliptic, ranging between 0.07-0.12 ; there the compression is due to the CIR. This is much smaller than the 0.2-0.3 MC average at 1 (Lepping et al., 1990; Owens et al., 2005) . At~~ *Ulysses* ~~the duration of the MC is 24 hours, the MC has a mean speed of 378~~ $^{-1}$ ~~, and an expansion speed of 14.2~~ $^{-1}$ ~~. We~~

430 ~~obtain an estimated length scale of 32.6 ± 1.0 × 10^6 (≈0.2) at~~ *Ulysses*, ~~which is typical for slower ICMEs (Lepping et al., 1990) . This length scale is somewhat short at the radial distance of 1.48 but expected, since the HSS is propagating directly into the back of the MC, which prevents its trailing edge from decelerating and thus the cloud from expanding (Maunder et al., 2022).~~

    ~~Additionally, for the MIR or ICME-SIR as a whole, we estimate the length scale of the disturbance to be 0.23-0.37 near the ecliptic and ≈0.34 at~~ *Ulysses*. ~~The interaction regions (CIR and SIR) are approximately twice as large near the ecliptic than~~

435 ~~at~~ *Ulysses*, ~~indicating different HSS sources originating from the northern sector and the southern sector, respectively. There is significantly more disturbance and a larger front sheath (FS)region at STEREO-A (there is no front sheath at OMNI and STEREO-B). If the two FS at~~ *Ulysses* ~~and STEREO-A were related, the observations would be consistent with the FS region being thinner towards the nose of the ICME, sampled by~~ *Ulysses*, ~~and thicker at the Eastern flank of the ICME, sampled by~~

STEREO-A, in accord with the expected thickness of the FS increasing from the nose of an ICME (see Kilpua et al., 2017, for a review of IC

440 .

Assuming no variations in the MC(L) size due to longitude and latitude, a comparison of MC(L) length scales as it travels the radial distance R of 7.8 $\times 10^7$ (0.52) between STEREO-A and *Ulysses* indicates that the ICME would have expanded by 14.7 $\times 10^5$ (82 % increase, see Table 4) over 20 hours 44 minutes, giving an expansion velocity of 20 $^{-1}$ as the ICME travels outwards. The non-dimensional expansion rate calculated by dividing the increase in radial extent by R is 0.19.

445 Richardson (2014) noted in his study of 11 ICMEs between 1 and *Ulysses* that most ICMEs increased in radial size with R (10^6), with size variations ranging between $R^{-0.27}$ and $R^{0.91}$. The present case corresponds to $R^{0.62}$, thus within the same range. However, while Richardson (2014) only considered ICMEs in relative ($\pm 30°$) radial alignment, we must exercise caution in comparisons here as we may be observing different (sub)structures and cannot quantify if this is an effect of the difference in separation angle (combining the large difference in longitude and latitude) rather than of radial expansion.

450 However, the mean expansion speeds, V_{exp}, calculated as half of the difference between the speed of the leading and trailing edge of the near-ecliptic MCL, is negative for all spacecraft, indicative of compression (see Table 4). Such compression is common of transients entrained in CIRs, which is also consistent with the arrival times and the evidence of a CIR-entrained MCL. This MIR is consistent with other findings from MIR studies of entrained flux-ropes. In contrast, at *Ulysses* we have clear signatures of local expansion (declining flow speed and expansion velocity of 14.2 $^{-1}$).

455 ## 4.1 ~~Enlil~~

In Maunder et al. (2022, see their Fig. 10) we presented simulations of the (I)CME propagation in the heliosphere using Enlil (available via the Community Coordinated Modelling Centre, model run id: `Megan_Maunder_062322_SH_2` [3]). This time-dependent 3D MHD model solves equations for plasma mass, momentum and energy density, and magnetic field, with a Flux-Corrected-Transport algorithm to model the ICME (Odstrčil, 2003). The choice of geometric input parameters (see properties in the linked control

460 file) was guided by the STEREO/SECCHI COR2 and HI analysis alongside the observed properties of the MC at *Ulysses*, and the simulation results show the ICME propagating towards *Ulysses*, and a corresponding disturbance seen at *Ulysses* of the same duration but one day earlier than observed.

A snapshot at 18:00UT on 2 July 2007 of the solar wind radial flow velocity in the heliosphere within 1.02 AU simulated with Enlil in **(a)** the ecliptic plane, **(b)** the meridional plane, **(c)** the radial plane. The simulated CME is shown as a *black*

465 *contour*. The HCS is shown as a *white line*, the IMF as a *black* and *white dashed line*, and spacecraft and planet positions are projected onto the planes. **(d)** Temporal profiles of the radial solar wind velocity, simulated in *blue* and measured in *red*.

As shown in Fig. **??**, this simulation run also shows the ICME impacting STEREO-A and Earth. At STEREO-A the simulation shows, as seen in Fig. **??**, the ICME arriving over one day earlier than observed but approximately the same duration. Using Earth for comparison with OMNI, the simulation shows the ICME arriving around 12 hours earlier and approximately

470 the same duration. We model an event that is very narrow radially but has a relatively large latitudinal and longitudinal extent. Broadly, the model and observation agree on a slow ICME that is launched towards *Ulysses* with its Eastern-flank skimming

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STEREO -A, -B, and OMNI, supporting one possible interpretation that the observed structures could be related to the same CME or original eruption.

At both STEREO-A and Earth the temperature profiles of the simulated and observed (I)CMEs are consistent (see top right panel in Fig. **??**). However,the simulation does not show the rotation in the magnetic field vectors (bottom right panels in Fig. **??**). Additionally, as shown in Figs. **??** and **??**, the model does not account for the CIR and HCS. The difference between the red (observed at STEREO-A) and blue (simulated) velocity in panel (d) of Fig. **??** is up to 250 $^{-1}$. In this case, the CIR near the ecliptic (in the Northern Sector) succeeding the ICME is not accurately represented. We observe a small increase in solar wind radial flow velocity (green, ~ 500 $^{-1}$) in panels (a, b) of Fig. **??**, but not the observed 600 $^{-1}$ at STEREO-A. Thus the simulation does not account for solar wind speed changes and their interfaces (hence the observed pressure waves are not present in the simulations), nor does it account for sheath and interaction regions that form as a result of shock or waves from propagation and interaction with different ambient wind speeds.

The model inserts a cone CME into the simulated structured background solar wind, which is presumed to be both supersonic and super-alfvenic at the inner radial boundary. These assumptions and potentially small errors in the inner boundary conditions can lead to oversimplifications of the simulation which do not accurately reflect observations. A small latitudinal error in the position of the current sheet, at the inner boundary, can lead to large errors in modelling in situ profiles.

A plot of the simulated (*blue*) and measured (*red*) solar wind and magnetic field properties at STEREO-A (left top to bottom then right): density, N (cm^{-3}); total pressure, Pt (pPa); radial, Vr, tangential, Vt, and normal, Vn velocity ($^{-1}$); temperature, T (kK); magnetic filed strength magnitude, $|B|$ (nT); the radial, Br, tangential, Bt, and normal, Bn, magnetic filed vectors (nT). The *yellow* shade indicates the modelled CME.

4.1 Global magnetic structure

Based on the modelling and kinetic properties, we expect that *Ulysses* samples the nose of the ICME and the near-centre of the corresponding MC and that the near-ecliptic spacecraft could skim the flank of the ICME. As presented in Sect. 2,

5 Conclusions

Using remote-sensing and in-situ observations and across multiple near-ecliptic spacecraft, along with complementary analysis methods, we have investigated a MCL observed in-situ on 3-4 July 2007 near the near-ecliptic observations show clear signatures of a MCL which support the ecliptic. The MCL was found to be entrained in a CIR from the Northern toward sector which created a MIR. The MCL showed negative mean expansion speeds indicative of compression increasing from West to East (-7, -22.3, -76.5 km/s).

This type of **small-scale MC/CIR system** is not uncommon, and the prevalence of small flux-ropes caught within the leading edge of CIRs observed in situ is discussed by Rouillard et al. (2009b). They confirmed that HI observes CIRs in difference images via small-scale transients caught up in the compression region. In fact, Rouillard et al. (2009b) reported on a small-scale transient entrained by a CIR that has parallels with our event. Their event was observed later on 20 July 2007.

Resemblances between the two events include similar flux-rope ~~interpretation; only one end of~~ profiles observed at STEREO-A

505 with a clear reversal of the polarity of magnetic field lines ~~which form the MCL flux-rope appear to be rooted at the Sun. The lack of compression in the sheath at STEREO-A means that there is insufficient draping around the front of the MCL to create a planar structure and provide a conclusive result using a MVA. However, we deduce a North-West-South (NWS) axis configuration suggesting that the flux-rope has a left-handed (negative) helicity. In Table 3, we compare the flux rope properties with those at *Ulysses*. Examination of the~~ and a change of suprathermal electron pitch angle ~~characteristics at *Ulysses* show~~

510 ~~that, ahead of the ICME, we observe streaming predominantly away from the Sun with some evidence of counter-streaming from 0° to 180° at the start of the~~ **MCL**. For the event presented by Rouillard et al. (2009b), there is no corresponding MC or MCL at the other spacecraft during the ~~event, which is evidence of a closed magnetic topology in the ICME, consistent with the flux-rope interpretation (Maunder et al., 2022). The *Ulysses* analysis was done in the Heliographic RTN system of reference and indicates a West-North-East (WNE) axis configuration (given with approximate corresponding HEE directions as seen~~

515 ~~from *Ulysses*) suggesting a right-handed (positive) helicity. *Ulysses* has a much higher latitude (−32.5°), than the near-ecliptic spacecraft . The normalised components of the magnetic field are in a system of reference relative to each spacecraft rather than a global system.~~ same CIR passage**, except for a peak in the magnetic field ahead of the CIR, which may be related to a shock driven by the interaction.**

~~Even if the kinetics are in agreement, the magnetic properties appear to rule out that what is observed near Earth is~~

520 ~~a subsection of the ICME detected at *Ulysses*. Indeed, conservation of helicity asserts that the flux-rope helicity remains the same through the CME evolution (Ji et al., 1995; Rust, 1997; Li et al., 2011, 2014); Berger and Field (1984) showed that helicity decays in the corona on a diffusion time scale and thus helicity decay cannot be important in CME evolution. Eruptive events at the Sun associated with CMEs can be used as proxies of CME helicity (Marubashi, 1986; McAllister et al., 2001), as there are no precise observational methods available for estimating three-dimensional coronal magnetic fields, thereby the~~

525 ~~magnetic structure of CMEs (Pal, 2022). In this case, there is only some coronal dimming visible on the south west of the solar disk, pointing towards an origin in the south hemisphere, which would predict a left-handed (negative) helicity.~~

~~However, opposing axis orientations and signs of helicity deduced from the magnetic field structures do not necessarily contradict the notion that we are observing the same initial structure. Only around 80% of MCs are observed to have the same predicted helicity based on the hemispheric segregation rule (Rust and Kumar, 1994; Bothmer and Schwenn, 1994) and~~

530 ~~Good et al. (2015) note that it is possible to fit a force-free model flux-rope which has opposite helicity to that deduced by the empirical methods used here. Furthermore, there is a longitudinal separation of ∼ 40° between *Ulysses* and STEREO-A. In the study by Good et al. (2015) where a similar disparity in handedness was found with a 27° longitudinal separation (between observations at MESSENGER and~~

In our case, **the MCL/CIR system appears more complex and extended, qualifying as a small-scale MIR, based on**

535 **Burlaga et al. (2003)'s criteria for MIR terminology at 1 AU.** We observed clear MCLs at STEREO-B ~~, and those at Venus Express), the validity of the model fit at one flux rope (Venus Express) was questioned. In the study by Rodríguez-García et al. (2022) , a large longitudinal difference of 78° separates the ICME counterparts (in MESSENGER and both STEREO spacecraft in situ observations) of an CME observed in twin-STEREO spacecraft coronagraph images. A graduated cylindrical shell model~~

was applied to reconstruct the CME from the coronagraph images and the flux-rope structures detected in situ at all three spacecraft were found to belong to the same ICME, despite the helicity deduced at STEREO-A and MESSENGER opposing that at STEREO-B. Rodríguez-García et al. (2022) proposed that this might be due to the fact that STEREO-B intercepted one of the legs of the structure far from the flux-rope axis whereas STEREO-A and MESSENGER were crossing through the core of the magnetic flux-rope. They referred to studies that support the possibility of magnetic flux added in opposite directions during the first stages of the CME evolution (Cho et al., 2013; Vemareddy and Démoulin, 2017), so the centre and the legs of the flux rope can have opposite helicities.

Finally, the radial distance of 7.8×10^7 (0.52) between STEREO-A and *Ulysses* corresponds to a time difference of nearly 21 hours. Studies of ICMEs observed by radially aligned spacecraftare relatively rare and have been used to explore the structure of ICME flux-ropes in which the stability and low plasma beta of the flux-rope features are preserved in spite of macro-scale differences in the flux-rope structure (Good et al., 2019). Good et al. (2019) propose that orientation changes observed by radially aligned spacecraft may be due to flux-ropes aligning with the HCS and the flattening of the ICME front as it moves out from the Sun or due to the spacecraft sampling different regions of the flux-rope, with the different regions having different axis orientations . This suggests that global properties of ICMEs such as axis orientation can vary significantly across small angular distances.

Our study further illustrates how the ambient conditions can significantly affect the expansion and propagation of the CME, introducing additional irregularities to asymmetric eruptions. We note here that the near-ecliptic spacecraft are close to the sector boundary at this point. It is thus likely that the MIR is the result of the MCL interacting with both the CIR and the HCS near the ecliptic. The HSS observed in the towards sector near the ecliptic is distinct from the HSS that is observed at *Ulysses* in the away sector. The MC and MCL ejectas are influenced by two different types of HSS at different latitudes: a HSS which produces a CIR near the ecliptic associated to the northern hemisphere (Figs. 2, 3, and 4), and a HSS likely originating from a south coronal hole at *Ulysses*, producing a SIR in the mid-latitudes (Maunder et al., 2022, see their Fig. 7) . Thus the near-ecliptic MCL is likely to have aligned with the HCS and is entrained in a CIR from the northern sector, while the mid-latitude flux-rope/MC is interacting with a HSS from the southern sector.

Additionally, both observations and models have shown that a flux-rope may kink and deform during propagation (Manchester et al., 2004 , a flux-rope can be eroded (Ruffenach et al., 2015), and that reconnection between a CME front and a HCS magnetic field in the interplanetary medium can significantly change the overall magnetic topology of ICME flux-ropes (Winslow et al., 2016). Nieves-Chinchilla et al. (2012) showed evidence for significant reorientation of the flux-rope axis and Rouillard et al. (2009a) observed the trailing part of an ICME which displayed highly distinct magnetic signatures at different spacecraft. Near the HCS, flux-ropes are also known to realign and locally replace the HCS (Crooker and Intriligator, 1996; Crooker et al., 1998; Foullon et al., 2009) . Therefore, it is possible that the flux-rope undergoes reconnection, erosion, or even significant reorientation which may offer some explanation for the different helicities and axis orientations observed. Chen et al. (2019) discovered a new foot-point drift phenomenon, which shows that the foot-points of erupting magnetic flux-ropes can drift to a new location during its eruption. This suggests that the CME embedded in the HCS can be connected to one of the different foot-points on either side of the sector boundary, which is used to indicate the helicity of the flux-rope (and its location with respect to the sector

boundary) OMNI, which were smaller and more turbulent than at STEREO-A. If the two events at *Ulysses* and near ecliptic are related, this offers more explanations as to why a different helicity is observed across large separations in heliospheric latitude, longitude, and radial distance, and given the considerable influence of the surrounding local solar wind conditions, including the proximity to the HCS near the ecliptic. The electron pitch angle characteristics, flux-rope orientations, and heliospheric orientations are consistent with this. At all spacecraft, the local orientations of the MCL magnetic field vector turned from North to West, to South on the cloud's axis, indicating a North-West-South (NWS) cloud with left-handed (negative) helicity.

5.1 Distortion

At launch, CMEs are often approximated as locally cylindrical objects with circular cross sections, yet they propagate almost radially away from the Sun into the bulk solar wind, which can severely flatten the initially circular cross section. From MVA analysis presented in Maunder et al. (2022), we obtained the orientation of the two shocks, that point northwards at *Ulysses*, consistent with a concave, inward curved geometry, also known as pancake geometry (e.g. Riley and Crooker, 2004; Savani et al., 2011) . The ICME is clearer at *Ulysses*, which is located closer to the direction of propagation, thus sampling nearer the centre of the flux-rope, and is significantly below the HCS, thus giving a less complex solar wind environment. In contrast, spacecraft near the ecliptic are sampling the flank of an ICME/MIR or ICME substructure and are observing the distortion of the structure as a result of interaction with the CIR/HCS. The argument that we would expect the structure to be less clear with increasing radial distance would only hold if the spacecraft were in radial alignment, close to the direction of propagation of the ICME; in this case we have a large (latitudinal) separation between spacecraft as well so we expect to be observing different parts of the ICME structure (discussed in Sect. **??**). Furthermore, we have demonstrated that the rear compression regions observed are caused by different solar wind environments: the pressure wave FW2 observed by STEREO-A is likely a result of MCL and Toward Sector HSS-CIR interaction whereas at *Ulysses* we observe a shock wave from MC and Away Sector HSS interaction.

We deduce that the ICMEs, related or unrelated, have not only 'pancaked' but have also been distorted by their interaction with the surrounding complex solar wind environment. Similar observations have been reported for the flattening and stretching of CMEs and associated ICMEs, indicating that ICMEs can deviate away from the ideal cylindrical structure with circular cross section (Savani et al., 2011) and for ICME interactions with solar wind streams, CIRs, and the HCS (e.g. Schmidt and Cargill, 2001; Odstrč . It is likely that this continues as the CME propagates through the heliosphere, demonstrating that the assumption that ICMEs undergo a spherical, self-similar radial expansion is only an approximation for, at least some, ICMEs. This has some relevance for the SSEF method that assumes a spherical, self-similar radial expansion but also does not account for complicated morphology and behaviour, particularly CME interactions with background structures. More sophisticated HI models that use HI time-elongation profiles to predict CME arrival can assume an elliptical front (ELEvoHI, Rollett et al., 2016).

In conclusion, using remote-sensing and in-situ observations and across multiple near-ecliptic spacecraft with complimentary methods of analysis, we have investigated a MCL observed in-situ on 3-4 July 2007 near the ecliptic and compared it with the (I)CME at *Ulysses* studied in Maunder et al. (2022). In Sect. 2, we presented in situ observations and provided evidence that what was detected near the ecliptic was a MCL and MIR. This event allowed **By comparing data from STEREO-A, OMNI/ACE, and STEREO-B with less than 16.6° separation angle in longitude (less than 0.32 AU in the East-West**

direction), the study mapped interactions of these structures across 0.11 AU in radial distance. This event allowed **for** the comparison of MIR observations at different longitudes showing differences in size, **(negative) expansion speed,** formation

610 of sheath, presence of forward and reverse waves and small-scale structuring, and providing a sequence of different interaction stages progressing ~~from West to East. In order to explore its origins, we conducted further analyses in Sect. **??**, through the application of a SSEF method to STEREO HI data and length scale analysis to in situ observations and compared the results to the observations at *Ulysses*; we also employed Enlil, a time dependent 3D MHD model, to assist in the interpretation of the (I)CME evolution and contributed to the discussion on whether or not this could be the same event or two related events.~~

615 ~~This problem is fundamentally asymmetric in nature. We have observations of a slow ICME that propagates almost directly towards *Ulysses* but through modelling (from SSEF analysis of HI data and Enlil simulation), we have shown it is possible that the flanks of this ICME or a related ICME substructure also skimmed the near-ecliptic spacecraft. The ICME/MC has a HSS (from the Southern away sector) propagating directly into the back of it and the Enlil simulation shows a narrow radial width but large longitudinal and latitudinal extent. Near the ecliptic we have an ICME/MCL entrained in a CIR (from the Northern~~

620 ~~toward sector), to create a MIR. Length-scale analysis appears to be consistent with this configuration and indicates that, if the ecliptic MCL is a flank cross of the ICME observed by *Ulysses*, it is smaller than the MC observed at *Ulysses*. Moreover the front sheath region is smaller at *Ulysses* than at the eastern flank of the ICME, where the sheath region is present at~~ **radially.** Thus, the study demonstrated the radial evolution of the MIR, with the HSS increasingly catching up with the MCL from STEREO-A ~~but is not evident near Earth (OMNI)~~ to Earth and STEREO-B. ~~However the modelling methods have caveats~~

625 ~~and limitations. It may be argued that the Enlil modelling results are dependent on the observational inputs, such as the initial CME width, and in the case of complicated morphology and behaviour, it may be helpful to employ a more sophisticated SSEF method (with an elliptical front). Nevertheless, due to other difficulties in establishing connections described below, the extent to which changing input parameters or models could yield similar or different results is unlikely to affect our conclusions.~~

~~Indeed, there are three main properties challenging the connection between the near-ecliptic MCL and the MC at *Ulysses*:~~

630 ~~local expansion velocities, magnetic flux rope axis orientations and helicities. From local expansion velocities of the MCL/MC, we observe compression near the ecliptic and expansion at *Ulysses*; from the magnetic structure of the MC and MCL, we observe different magnetic flux rope axis orientations and helicities. We have presented evidence that the near-ecliptic MCL has been 're-aligned' by its interaction with the surrounding solar wind environment (CIR) and demonstrated that the local solar wind environment can significantly affect the expansion and propagation of an ICME. Opposing signs of helicity could~~

635 ~~provide indications of flux added in the first stages of CME evolution or magnetic~~ The observed MCLs in the solar wind undergo interactions with the HSS, resulting first in shock waves and front sheath, then with increasing compressions from the HSS, leading to increased turbulence and magnetic folds (possibly from interchange reconnection with the HCS~~. We concluded that the differing properties do not necessarily contradict the notion that we are observing the same initial structure. These observations and analyses challenge the existing questions around (I)CME development, propagation and helicity conservation~~

640 ~~and poses questions for the further study of ICME-ICME connections and their interactions with complex solar wind.~~).

~~Regardless of the connection between *Ulysses* and near-ecliptic observations, we have presented a comprehensive analysis and discussion of this event as a challenge for observing ICMEs not in alignment, across different latitudes, and in multiple complex solar wind environments. The use of multi-spacecraft analysis~~

The findings emphasise the complex nature of solar wind structures and their interactions, particularly the formation and evolution of MIRs at 1 AU, contributing to our understanding of the formation processes starting at the Sun. They highlight the importance of using a comprehensive multi-spacecraft approach, which is essential for distinguishing between ~~remains key to disentangling~~ MCs/MCLs ~~from~~ and their solar wind environments ~~and to determine~~ , and **for identifying** connections between events observed in the heliosphere. ~~Useful~~ **For this specific event, we have observed a simultaneous event as presented in Maunder et al. (2022), where a multi-spacecraft study of a mid-latitude CME allowed for analysis of remote-sensing observations from the twin STEREO -A and -B spacecraft, as well as its subsequent in-situ counterpart outside the ecliptic plane, at Ulysses. Connecting these two events has posed challenges (Maunder, 2023).** Potential extensions, but beyond the scope of this study, could ~~be to consider~~ include considering energetic particle effects and interplanetary scintillation observations (e.g. Richardson, 2018, and references therein). ~~Nevertheless~~ However, the study ~~demonstrates that, in comparison~~ shows that, as compared to the identification of ICMEs and MIRs, the origin and formation of ICME-like transients and ICME substructures are less well understood.

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