

Evolution of sheath and leading edge structures of interplanetary coronal mass ejections in the inner heliosphere based on Helios and Parker Solar Probe observations

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Received Dec xx, 2021; accepted xx

ABSTRACT

Context. We investigate the evolution of the sheath and leading edge structure of interplanetary coronal mass ejections (ICMEs) as function of distance in the inner heliosphere. Results are related both to the magnetic ejecta and to the ambient solar wind.

Aims. The ICME sheath structure presumably consists of compressed plasma due to the turbulent solar wind material propagating ahead of the ICME front. From a sample of 40 well-observed Helios 1/2 events, we derive the average density separately for the sheath and leading edge structure of a CME as well as for the magnetic ejecta (ME). The results are placed into comparison with the upstream solar wind in order to investigate at which distance the sheath is formed in interplanetary space.

Methods. For the statistical investigation, we use plasma and magnetic field measurements from Helios 1/2 data from 1974–1981 on the basis of the ICME list compiled by Bothmer & Schwenn (1998). Helios data cover the distance range from 0.3–1 au. For comparison, we add a sample of four ICMEs observed with Parker Solar Probe 2019–2021 over the distance range 0.32–0.62 au.

Results. We derive for the distance of about 13 Rs that the CME sheath becomes denser than the ambient solar wind density. At about 38 Rs the sheath structure density starts to dominate over the density within the ME. The ME density falls below the ambient solar wind density at about 230 Rs. Besides the well-known expansion of the ME, the sheath size shows a weak positive correlation with distance, while the leading edge does not expand over distance. We find a moderate anti-correlation between sheath density and local solar wind plasma speed upstream of the ICME shock. An empirical relation is derived connecting the ambient solar wind speed with sheath and leading edge density.

Conclusions. The average starting distance for actual sheath formation is found to be located at a distance of about 13 Rs. The ME expansion behavior changes strongly at about 38 Rs, leading to a density dominance of the sheath structure. The leading edge can be understood as a structure isolated from the ambient solar wind flow by the sheath and by the magnetic ejecta. The results allow for better interpretation of ICME evolution and possibly mass increase due to sheath enlargement. The empirical results between sheath and leading edge density and ambient solar wind speed can be used for more detailed modeling of ICME evolution in the inner heliosphere.

Key words. solar coronal mass ejections – solar wind – heliosphere – observations – solar terrestrial relations

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1. Introduction

Coronal mass ejections (CMEs) are strongly magnetized plasma volumes that are sporadically ejected from the solar corona and propagate through interplanetary space. They typically consist of several structures. The CME structures can often be easily distinguished from in-situ plasma and magnetic field measurements, but less well in image data showing the CME brightness. The main reasons are plane-of-sky projection effects, solely density information from white-light image data, resolution and brightness limitations (see e.g., Vourlidas et al. 2013; Kwon & Vourlidas 2017). Using in-situ measurements, Kilpua et al. (2013) divide an interplanetary CME (ICME) into shock-sheath, leading edge/front, and magnetic ejecta followed by a trailing rear region. The interaction processes between the evolution of the (I)CME with the ambient environment, either the solar corona or the solar wind in interplanetary (IP) space, are still not well understood. The early strong lateral expansion behavior

of fast CMEs may be interpreted as combined bow/piston, driving shock waves in the corona (e.g., Temmer et al. 2009; Pat-sourakos & Vourlidas 2009). In IP space the ICME expansion seems to cover a wide range of strong to weak expansion rates, depending on the pressure balance and interaction processes, in a self-similar or non-self-similar manner (e.g., Vrřnak et al. 2019; Gopalswamy et al. 2020; Luhmann et al. 2020). As the solar wind is unable to fully flow around that growing structure, there is a tendency of plasma pile up at the ICME apex (Siscoe & Odstreil 2008).

The magnetic ejecta part together with a long-lasting negative B_z component is supposed to be the main driver of strong space weather effects and therefore most often the focus in ICME studies. The generation process and development of the sheath component, however, is less well investigated. But just this structure is highly relevant with respect to ICME mass variations (mass accretion, see e.g., DeForest et al. 2013; Temmer et al. 2021), hence, propagation behavior in IP space (Vrřnak et al.

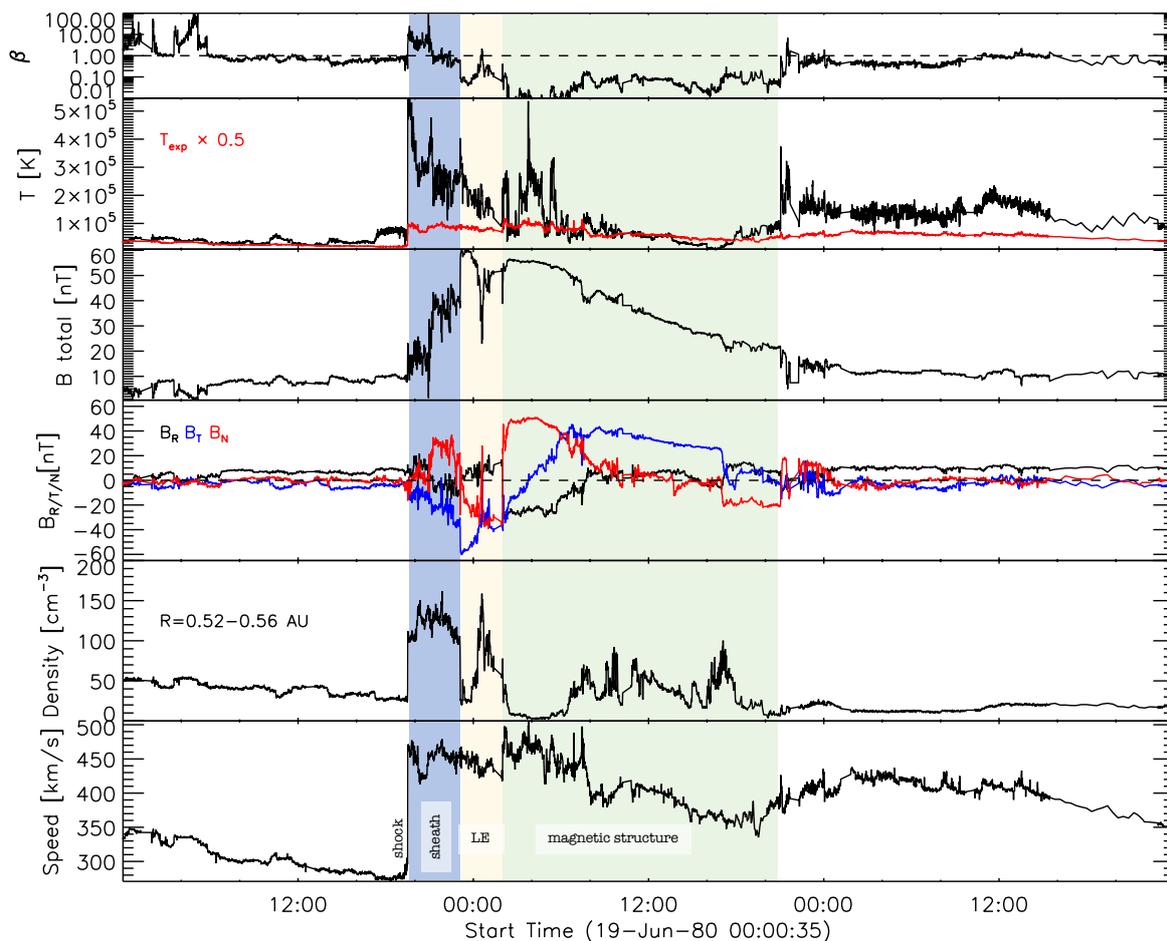


Fig. 1: This overview plot shows the plasma and magnetic field data from a well-observed ICME example in June 1980 (DOY171–173; see also Burlaga et al. 1982). From top to bottom we present the parameters plasma-beta, proton temperature (in red we give the expected solar wind temperature $\times 0.5$, as described in Richardson & Cane 1995), total magnetic field strength, vector components of the magnetic field, proton density and proton bulk speed. The four different identified structures are marked, with the shock arrival indicating the start of the sheath region (blue shaded area) that is followed by the LE (yellow shaded area) and the ME (green shaded area). The ICME was measured with Helios 1 at 0.53 au (see also Bothmer & Schwenn 1998). It should be noted that the green labeled interval matches well with a bi-directional flow of suprathermal electrons covering the period June 20, 02–21 UT (see Figure 6 in Bothmer 1999).

2010), and upstream magnetic field line draping that affects its potential geoeffective impact (e.g., Gosling & McComas 1987; McComas et al. 1988, 1989; Zurbuchen & Richardson 2006; Lugaz et al. 2016).

Observational studies showed that the CME mass increase close to the Sun (up to 20Rs) as derived from remote sensing image data, is most probably related to outflows from the Sun (Bein et al. 2013; Howard & Vourlidas 2018). These outflows form well in temporal coordination with coronal dimming regions at the footpoints of a CME, and could be directly related to the early CME mass evolution (Temmer et al. 2017; Dissauer et al. 2019). Hence, the sheath region most probably builds up later on, in IP space. This is consistent with ICME in-situ composition measurements showing that the sheath region consists of ambient solar wind material, while the CME is made from coronal material (see e.g., Kilpua et al. 2017). DeForest et al. (2013) found from a case study combining EUV, white-light and in-situ data, that the sheath consists of compressed and coronal material. A similar conclusion is given in a more recent case study by Lugaz et al. (2020) investigating an ICME from Mercury to Earth. Salman et al. (2021) used STEREO data to investigate the

sheath close to 1 au and concluded that the magnetic driver part causes most of the variations in the sheath. A study by Temmer et al. (2021) derived at 1 au a strong linear anti-correlation between the sheath density and the solar wind speed measured 24 hours before the shock-sheath arrival. This raises the question, how strongly local solar wind conditions shape the sheath, at which distance and under which conditions the sheath starts to become a significant region of a CME.

In the current study we address the question about the “starting” distance of sheath formation and how local solar wind conditions relate to the sheath. In addition we aim to give more detail about the physical characteristics of the different ICME structures over various distances in IP space. For this purpose we investigate a Helios set of 40 well-observed ICMEs over the distance range 0.3–0.9 au. For comparison, we study the structure densities for a set of four observed ICME events between 0.32–0.63 au by the recently launched Parker Solar Probe (PSP) mission.

In Section 2 we describe the data and methods and the results in Sections 3 and 4. Discussion and conclusion of the outcomes are presented in Section 5.

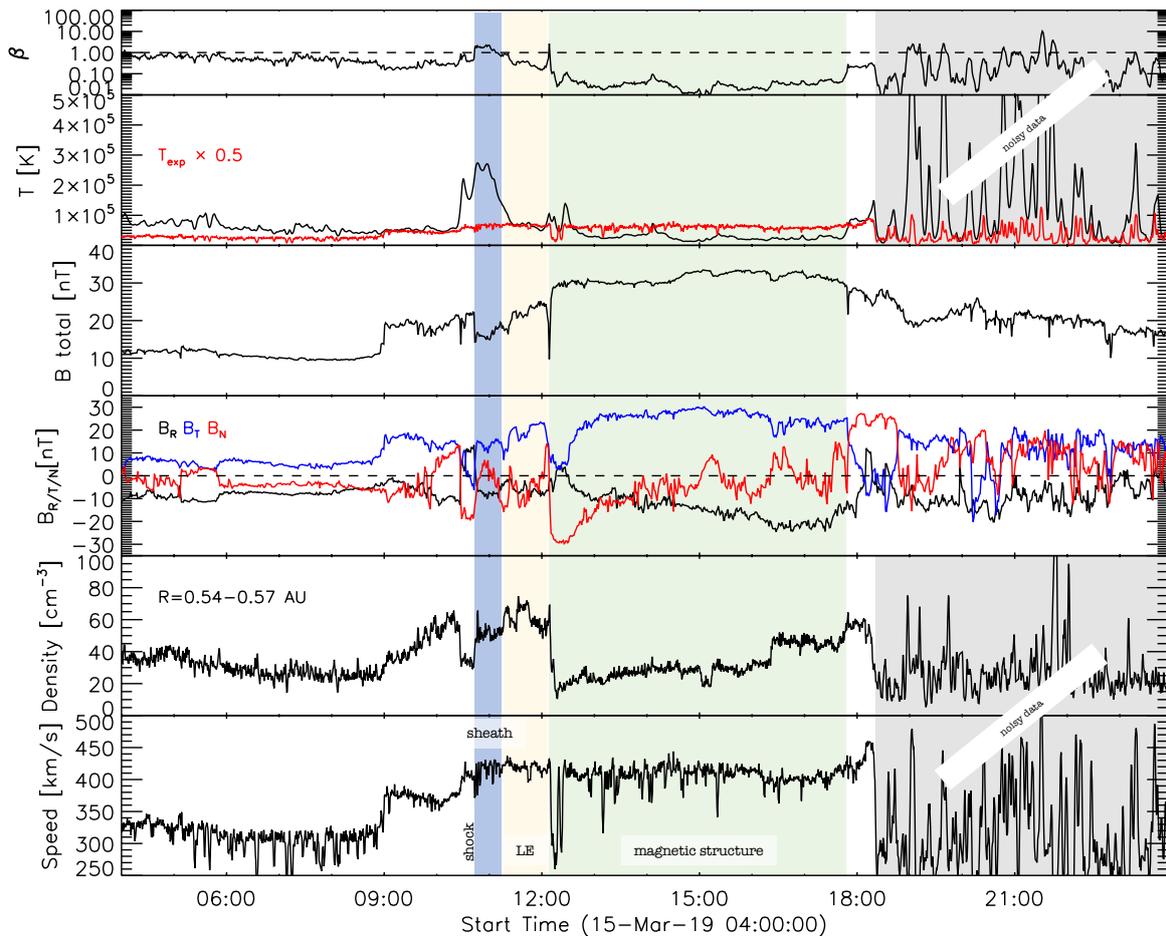


Fig. 2: This overview plot shows the plasma and magnetic field data from an ICME observed with PSP in March 2019 (DOY 74). Panel parameters and identified sub-structures are the same as shown in Figure 1. The plasma data cover a lot of noise, which is marked with gray shaded areas. We note that before the shock another magnetic structure is observed possibly related with some small scale eruption propagating ahead of the ICME.

2. Data and Methods

We investigate in-situ plasma and magnetic field measurements from two missions covering a wide distance range in the inner heliosphere. Our main focus lies on the Helios 1/2 spacecraft with a perihelion around 0.3 au (Rosenbauer et al. 1977). From Helios 1/2 using hourly averaged plasma and magnetic field data, we identify for 40 well-observed events covering the time range 1975–1981 the ICME structures sheath, leading edge (LE) and magnetic ejecta (ME). The identification of these ICMEs is based on the list given in Bothmer & Schwenn (1998). An example of the ICME event in June 1980 from Helios 1 at 0.53 au (DOY 171–173; see also Burlaga et al. 1982; Bothmer & Schwenn 1998) is shown in Figure 1.

For comparison, we cross-check the results with in-situ measurements from the currently operating PSP mission using data from the SWEAP and FIELDS investigations (Bale et al. 2016; Kasper et al. 2016). PSP will encounter the Sun in the near future as close as up to 0.046 au (Fox et al. 2016). Using the regularly updated list of ICMEs measured by PSP as compiled by Bothmer and Chifu (see http://cgauss-bsp.astro.physik.uni-goettingen.de/pro_work.php), we investigate a set of four ICME events observed in 2019–2021 over the distances 0.32–0.63 au. Compared to Helios mission time, the solar activity is weaker, hence, we currently miss events with strong

shock and sheath regions. From daily plots of 1 minute resolution plasma and magnetic field data we identify the different ICME structures and derive the average density for each of it. An example of the ICME event in March 2019 from PSP at 0.55 au is shown in Figure 2. Table 1 gives PSP event dates, distances and references for each event.

We first investigate the plasma and magnetic field data to identify the different sub-structures of the ICME (see Figures 1 and 2). After the shock, we identify the sheath structure by its high density, temperature, plasma-beta larger than one, and strongly fluctuating magnetic field. The LE is identified by a moderate plasma-beta, increased magnetic field and density, and discontinuities before and after, marking the end of the sheath and start of the ME, respectively. The ME structure itself reveals very low plasma-beta, low temperature together with a smooth and rotating magnetic field vector and decreasing speed profile. Producing such plots from Helios 1/2 plasma and magnetic field measurements and using the criteria described above, we manually identify the start and end time of the (shock)-sheath region, the leading edge (LE) and the magnetic ejecta (ME) part. For each identified structure, we extracted the density, bulk speed, total magnetic field strength, temperature and duration. In addition, we investigate for speed and density the up- and down-stream conditions and calculate the average of these parameters over 3 hours before and after the shock front arrival. Further pa-

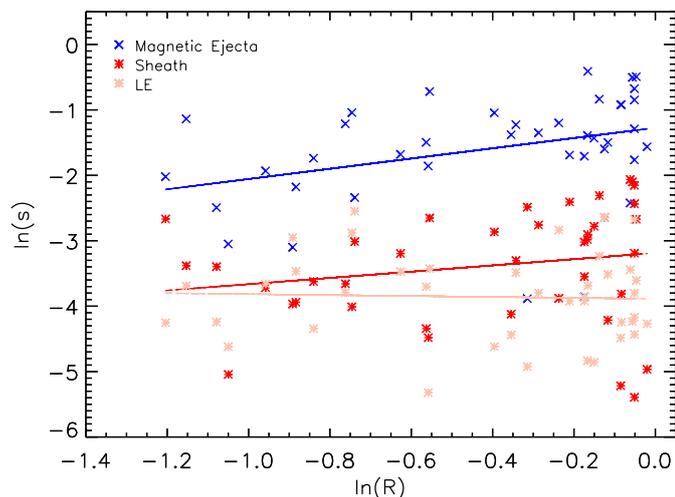


Fig. 3: Double logarithmic plot showing the radial sizes, s , of the different ICME structures (see legend) versus solar distance, R . The linear regression lines for each structure are obtained with: $s_{\text{ME}}(R) = 0.27 \times R^{0.78}$; $s_{\text{sheath}}(R) = 0.04 \times R^{0.48}$; $s_{\text{LE}}(R) = 0.02 \times R^{-0.07}$.

parameters are derived and statistically related to each other by calculating the Spearman correlation coefficient on a 90% confidence level. We give a correlation matrix of the results in the Appendix.

3. Results

Main focus is the large statistical sample from Helios 1/2 data. For inspecting the conditions in the up- and downstream regions, we first derive the Alfvén Mach number and density compression ratio for each event. The Alfvén Mach M_A is calculated as $M_A = u/(B/\sqrt{\rho\mu_0})$ where u is the upstream solar wind speed, B is the average magnetic field strength of the sheath region, ρ is the sheath mass density (assuming 4% helium and 96% protons) and μ_0 is the permeability of vacuum. From that we derive for M_A an average value and standard deviation of 5.54 ± 2.37 . For the density jump, given as ratio over down- and upstream region ρ_d/ρ_u , we derive 2.97 ± 1.59 , and we find a value of 3.05 ± 1.62 when applying the average density over the entire sheath duration instead of the 3 hours averaged density after the shock arrival. While the Alfvén Mach number shows a weak dependency over distance, the derived values for the density jump are randomly distributed over distance. The correlation matrix in the Appendix reveals, that the Alfvén Mach number is, as expected, positively correlated to the magnetic field strength and fluctuations in the magnetic field of the ICME structures sheath and LE. The density fluctuation in the LE is moderately and in the ME weakly correlated to the Mach number, however, there is no significant correlation found to the density parameter of the sheath structure.

Figure 3 shows the radial size of each structure as function of distance. The radial size is simply determined by multiplying the duration of the structure with its average speed. A linear fit is provided for the data points from each structure in order to study its variation in size over distance with R in au. We derive for the ME a linear trend with $s_{\text{ME}}(R) = 0.27 \times R^{0.78}$, for the sheath structure $s_{\text{sheath}}(R) = 0.04 \times R^{0.48}$ and for the LE $s_{\text{LE}}(R) = 0.02 \times R^{-0.07}$. Not surprising, the ME shows the typical expansion behavior in the inner heliosphere which causes a strong increase in ra-

Dis. [au]	Date	Reference
0.32	20/Jan/2020	Joyce et al. (2020)
0.48	12/Sep/2020	Bothmer & Chifu list
0.55	15/Mar/2019	Bothmer & Chifu list
0.63	11/Feb/2021	Bothmer & Chifu list

Table 1: PSP ICME event dates and distances (Dis.) together with some reference.

dial size with distance. We find the sheath structure enlarging with distance from the Sun, while the LE structure is actually not showing a clear increase in size. Calculating the Spearman correlation coefficient on a 90% confidence level, the ME shows a moderate correlation with distance with $cc=0.44$, the sheath a weak one with $cc=0.26$, and no significant relation is found for the LE (see Appendix). This finding could be interpreted that the LE is rather a distinct feature from the ambient solar wind flow and shows low evolutionary aspects. We find no obvious relation between Mach number and sheath or LE duration.

Figure 4 shows the density evolution of each structure and the ambient solar wind in a double logarithmic plot covering the distance range 0.05–1.1 au. The linear regression line for each structure is obtained with the values of $N_{\text{p,SW}}(R) = 7.0 \times R^{-2.1}$ for the upstream solar wind, $N_{\text{p,ME}}(R) = 7.1 \times R^{-2.4}$ for the ME, $N_{\text{p,sheath}}(R) = 22.3 \times R^{-1.7}$ for the sheath, and $N_{\text{p,LE}}(R) = 26.6 \times R^{-1.5}$ for the LE. Extrapolating the linear fits for ME and sheath density, we obtain three intersection points. The first close to the Sun at about 0.06 au (=13 Rs) between sheath density and the upstream solar wind density, the second between sheath and ME density at about 0.18 au (=38 Rs), and the third between ME density and upstream solar wind density at about 1.07 au (=230 Rs). From that we may conclude, that at about 13 Rs the sheath might become denser than the ambient solar wind, which could be interpreted as average starting distance for actual sheath formation. On the other hand, at about 38 Rs, the sheath density clearly overcomes the ME density. At this distance the ME expansion may start to dominate the propagation phase, that leads i) to a strong decrease in density within the ME and ii) due to the relative enlargement over distance becomes an efficient piston-type driver causing plasma pile-up (Hundhausen 1972). At distances beyond 1.07 au, the ME becomes lower in density than the ambient solar wind.

Complementary to Helios 1/2 data, we derived the average of ICME sheath and ME density measurements for a set of four PSP events observed at distances between 0.32–0.63 au. The results support our findings from Helios data showing a similar trend between sheath and ME density as function of distance (cf., Figure 4). Larger statistics from PSP (I)CME measurements closer to the Sun would be needed to derive more conclusive supporting evidence about sheath build up processes.

For distances below 30 Rs CME density results are available from indirect measurements analyzing coronagraph image data. Using multi-viewpoint SoHO and STEREO remote sensing white-light image data, the 3D CME mass and volume can be derived to calculate the ME density from (Temmer et al. 2021). To compare with the extrapolated profiles from Helios in-situ measurements, we show in Figure 4 the results from the recent study by Temmer et al. (2021), covering a sample of 29 CMEs observed during 2008–2014. The median ME density is derived from remote-sensing image data over the distance range 0.07–0.14 au (15–30 Rs; i.e., SOHO/LASCO C3 coronagraph field of view). The results reveal an ME density that is substantially higher than the extrapolated ME density profile from Helios in-

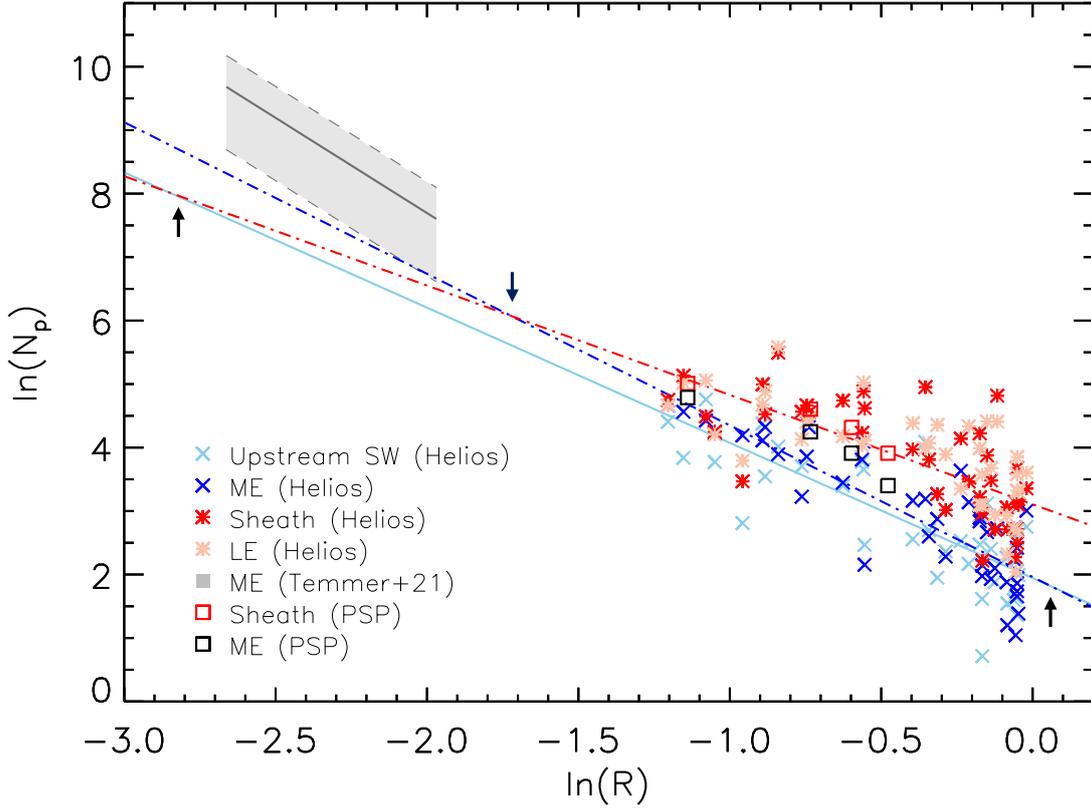


Fig. 4: Double logarithmic plot showing the average proton density, N_p , of the different ICME structures and upstream solar wind (SW) versus solar distance, R , in au. The linear regression lines for each structure are obtained with: $N_{p,SW}(R) = 7.0 \times R^{-2.1}$; $N_{p,ME}(R) = 7.1 \times R^{-2.4}$; $N_{p,sheath}(R) = 22.3 \times R^{-1.7}$; $N_{p,LE}(R) = 26.6 \times R^{-1.5}$. Extrapolating the Helios based fits for ME and sheath density, three intersections are derived (black arrows). Between sheath density and upstream solar wind density at about 0.06 au (=13 Rs) – which can be interpreted as average starting distance for sheath formation – between sheath density and ME density at about 0.18 au (=38 Rs) and between ME density and the upstream solar wind density at about 1.07 au (=230 Rs). Complementary we show PSP sheath and ME density measurements for a set of four events supporting the general trend derived from Helios. In addition, we provide results for the mean calculated ME density (solid gray line with upper and lower limit, i.e., standard deviation, marked as light gray dashed lines) over 15–30 Rs based on indirect ME density measurements derived by Temmer et al. (2021).

situ data. However, the lower ME density estimate (median minus standard deviation) is quite comparable. The discrepancies might be due to line-of-sight integration effects causing large uncertainties in the indirect method, namely 3D mass and volume derivation, as well as the different data set, i.e., solar cycle effects. We note that the steep drop in ME density during the early CME evolution might be a real effect that could be related to a different expansion behavior of CMEs close to the Sun. It is found that a strong lateral expansion dominates in the early CME evolution phase (Patsourakos & Vourlidis 2009; Veronig et al. 2018), that could lead to a faster decay in ME density when close to the Sun.

Table 2 summarizes for each structure over two distance bins, average values of density, plasma-beta, temperature, total magnetic field, speed and duration. For statistical reasons we divide the distance coverage 0.3–1 au into two roughly similar distance bins with $r_1 < 0.7$ au and $r_2 > 0.7$ au, having sample sizes of 16 and 24 events, respectively. The density of the ME drops faster over distance than in the sheath and LE. The plasma-beta of the sheath stays on average larger than 1, while the LE shows a clear increase over distance and the values for the ME are found to be similar. The sheath reveals slightly larger temperatures than the LE, and the speed of the LE is enhanced compared to the sheath. The magnetic field drop over distance is in

the same range for all structures. The duration of the structures clearly increase with distance except for the LE. The average values for the ME are in accordance with the results given in Bothmer & Schwenn (1998).

Figure 5 gives a cartoon illustrating the four different ICME structures and their average parameter values. According to the statistical results given in Table 2, we show with two different colors the change of the parameter values over the two distance bins ($r_1 < 0.7$ au and $r_2 > 0.7$ au). This has implication for the comparison with remote sensing image data (see also Vourlidis et al. 2013).

4. Relating sheath+LE density to the ambient solar wind

The recent study by Temmer et al. (2021) showed another interesting result that is worth to investigate with the large statistical ICME sample from Helios data. At 1 au a strong linear anti-correlation between the solar wind upstream speed (averaged over 24 hours before the arrival of the disturbance) and the measured sheath+LE density was derived ($cc = -0.73$). In comparison, the upstream solar wind density showed a less strong relation to the sheath density which is most likely due to stronger

Parameter	Sheath	LE	ME
N_p [cm ⁻³]	108 ⁽²⁴³⁾ ₍₃₂₎ 36 ⁽¹⁴¹⁾ ₍₉₎	105 ⁽²⁶⁵⁾ ₍₄₄₎ 39 ⁽⁸²⁾ ₍₈₎	58 ⁽¹⁰⁵⁾ ₍₉₎ 12 ⁽³⁸⁾ ₍₃₎
β	1.1 ^(4.6) _(0.1) 1.4 ^(11.0) _(0.2)	0.8 ^(1.8) _(0.1) 1.6 ^(8.0) _(0.1)	0.1 ^(0.3) _(0.02) 0.1 ^(0.7) _(0.04)
T_p [$\times 10^4$ K]	39 ⁽¹⁶¹⁾ ₍₆₎ 26 ⁽¹²⁰⁾ ₍₃₎	35 ⁽¹²⁶⁾ ₍₈₎ 19 ⁽⁸⁸⁾ ₍₃₎	12 ⁽³³⁾ ₍₄₎ 11 ⁽⁷⁰⁾ ₍₃₎
B [nT]	48 ⁽¹¹⁷⁾ ₍₁₆₎ 17 ⁽⁴⁷⁾ ₍₇₎	50 ⁽¹²⁴⁾ ₍₁₅₎ 16 ⁽⁴³⁾ ₍₅₎	57 ⁽¹³⁸⁾ ₍₂₈₎ 19 ⁽⁴³⁾ ₍₇₎
v [km s ⁻¹]	510 ⁽¹¹⁰⁰⁾ ₍₃₁₀₎ 500 ⁽⁹³⁰⁾ ₍₃₅₀₎	540 ⁽¹⁰⁴⁰⁾ ₍₃₀₀₎ 510 ⁽⁹⁸⁰⁾ ₍₃₆₀₎	480 ⁽⁷²⁰⁾ ₍₃₅₀₎ 480 ⁽⁷³⁰⁾ ₍₃₄₀₎
t_{dur} [h]	2.7 ^(6.6) _(0.7) 4.7 ^(13.0) _(0.5)	2.5 ^(10.5) _(0.5) 2.1 ^(13.0) _(0.6)	17.7 ^(35.5) _(4.3) 26.5 ^(56.8) _(1.6)

Table 2: Mean values together with their minimum and maximum range (\min^{\max}) are given for two distance ranges $r_1|r_2$ with $r_1 < 0.7$ au and $r_2 > 0.7$ au. Parameters for the different structures given are, proton particle density (N_p), plasma-beta (β), temperature (T_p), total magnetic field strength (B), proton bulk speed (v), and duration (t_{dur}). See also Figure 5, roughly depicting the average values given here.

fluctuations of the density compared to the speed component of the solar wind (Gosling et al. 1990, 1991). From that we may suggest that the ambient solar wind speed has some strong influence on the sheath build-up. Helios data could be used to empirically define relations between sheath density and solar wind speed as function of distance, which could be applied as additional input for ICME propagation models.

As a first step we simply multiply the upstream solar wind speed u (defined as three hours average before the arrival of the disturbance) with the average proton density N_p of the disturbance. Results for sheath+LE and ME structure are given in Figure 6. We find that the ME part can be fitted best with a 4th order polynomial fit, given by

$$uN_p = 3.25 \cdot 10^5 r^4 - 1.07 \cdot 10^6 r^3 + 1.32 \cdot 10^6 r^2 - 7.44 \cdot 10^5 r + 1.70 \cdot 10^5,$$

with the distance r in au. At distances $r > 0.35$ au, the ME part becomes comparable to the solar wind speed-density profile derived from the Leblanc solar wind density model (Leblanc et al. 1998) multiplied by the average upstream solar wind speed of ~ 375 km s⁻¹ as derived from our data sample (see dashed line in Fig. 6). On the other hand, the sheath+LE part is best fit with a linear function given by

$$uN_p = -5.70 \cdot 10^4 r + 6.32 \cdot 10^4.$$

In a first approach, we can use these simple relations to estimate the density of sheath+LE and ME structure as function of distance and solar wind speed.

In a second approach, we separate the data into different distance bins and check the relation between solar wind speed and density of the identified ICME structures for each bin separately. As already defined in Sect. 3 we use $r_1 < 0.7$ au covering 16 events and $r_2 > 0.7$ au with 24 events. We derive for sheath+LE a mean density of $N_p(r_1) = 106.2$ cm⁻³ and $N_p(r_2) = 37.8$ cm⁻³ and for the ME $N_p(r_1) = 57.6$ cm⁻³ and $N_p(r_2) = 12.4$ cm⁻³. As comparison we also use four bins, being aware of the lower statistics, with $r_{1,2,3,4} = [0.3-0.47, 0.47-0.75, 0.79-0.92, 0.92-0.98]$ au covering [9,11,11,9] events, from which we derive mean densities of $N_p(r_{1,2,3,4}) = [119.3, 78.4, 42.6, 22.4]$ cm⁻³ for sheath+LE and $N_p(r_{1,2,3,4}) = [70.1, 32.4, 14.8, 7.6]$ cm⁻³ for the ME.

Figure 7 (left panel) shows N_p of sheath+LE structure in relation to u for the entire data set and color-coded for the two distance bins $r_1 < 0.7$ au (red) and $r_2 > 0.7$ au (blue). Not surprising, we derive a wide range of mean densities of 10–250 cm⁻³ that relate to a smaller range of upstream solar wind speed with 250–650 km s⁻¹. When inspecting the distance bins, the density ranges become smaller and we may apply a simple linear fit to

relate u and N_p in each bin which can be expressed by

$$N_p(u) = ku + c,$$

with k the gradient and c a constant. For comparison, we plot as gray line the density-speed relation from the 1 au results as derived in Temmer et al. (2021). The parameters for the linear fits are shown in the legend of the left panel of Fig. 7. When separating into 4 bins (not shown), the trend is the same, however, the scatter gets larger.

In a next step, we inspect the dependence of c and k over distance. Figure 7 (right panels) shows the derived constants and gradients from the fit for each distance bin as function of distance (r). In the top right panel values for c are given derived from separating the sample into two and four bins, respectively. In addition, we show the constant from the linear relation from Temmer et al. (2021) for 1 au. As comparison, we also plot the Leblanc solar wind density, normalized for $N_p = 9$ cm⁻³ at 1 au (dotted line). The lower right panel shows k values obtained from the linear fits using two bins, four bins, and results by Temmer et al. (2021), respectively.

As can be seen, depending on the number of bins the constants c and k change slightly, but seem to follow a linear trend over distance, r (given in au). We therefore may relate the parameters simply by

$$c(r) = p_1(r)r + p_0$$

and

$$k(r) = q_1(r)r + q_0,$$

deriving $p_{0,1} = [234.9, -196.8]$ and $q_{0,1} = [-0.21, 0.15]$ for the constant and gradient, respectively, from the linear fit using two bins. For four bins we derive $p_{0,1} = [279.3, -255.1]$ and $q_{0,1} = [-0.30, 0.27]$. From that we express an empirical relation to calculate the ICME sheath+LE density as function of distance and solar wind speed ahead of the ICME that can be given by

$$N_p(u, r) = k(r)u + c(r).$$

Figure 8 shows the resulting sheath+LE densities as derived from the empirical relations described above in comparison to the measured sheath+LE densities over distance. The “simple linear fit” refers to the first approach using a linear fit to the sheath+LE density multiplied by the upstream solar wind speed. The “c=lin, k=lin” refers to the second approach when separating the upstream speed and density into two distance bins from which the linear fit parameters are calculated as function of distance. Applying these empirical methods we obtain a strong correlation with the measured sheath+LE densities with correlation

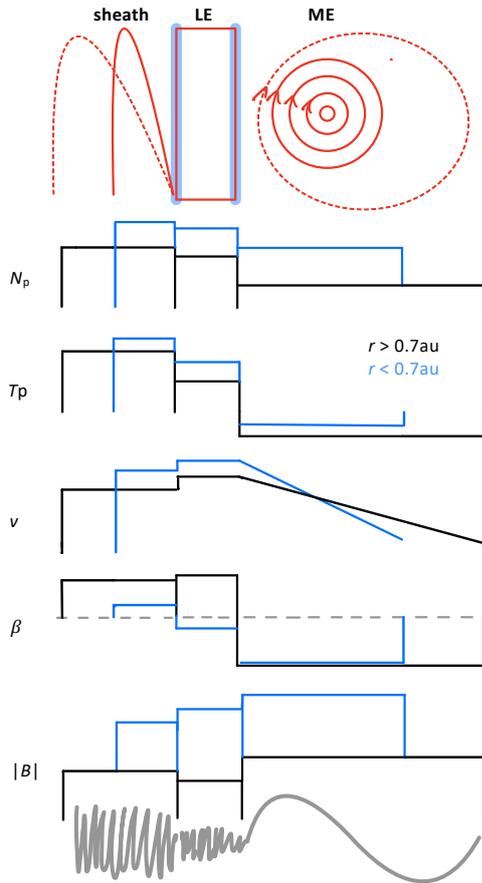


Fig. 5: Cartoon illustrating the four different ICME structures and their relative parameter values. Top panel: discontinuities are marked as blue shaded areas before and after the LE, the expansion/evolution of the sheath and ME is marked with dotted red lines. Lower panels: particle density (N_p), temperature (T_p), speed (v), plasma-beta (β) and total magnetic field strength (B) with magnetic field variations from very fluctuating to smoothly rotating depicted below. For statistical reasons we derived the values for two different distance ranges and sketch the change in the average values accordingly ($r < 0.7$ au in blue and $r > 0.7$ au in black). For the actual average values and minimum/maximum ranges see Table 2.

coefficients of $cc=0.73$ for the simple linear fit and $cc=0.75$ when separating the data into distance bins.

5. Discussion and Conclusion

Using a sample of 40 ICME events measured in-situ from Helios data, we were able to identify four distinct features, shock, sheath, LE and ME. The average density values of the structures, sheath, LE, and ME are in focus to be investigated as function over distance, together with other parameters such as speed, temperature, magnetic field, magnetic field variations, and structure size.

We find that the density of the sheath decreases as linear function with $R^{-1.7}$ and that of the LE with $R^{-1.5}$. We also derive the results for ME density decrease as linear function with $R^{-2.4}$ and for the solar wind measured upstream of the disturbance with $R^{-2.1}$ confirming previous findings (e.g., Schwenn & Marsch 1990; Leitner et al. 2007; Gulisano et al. 2010; Venzmer

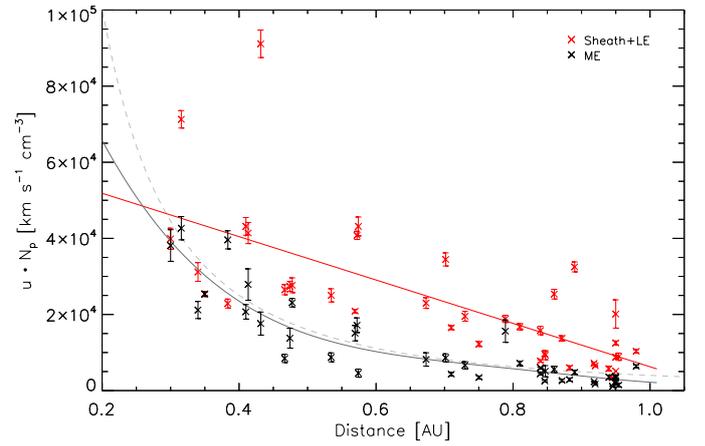


Fig. 6: Upstream speed, u , multiplied by the average density, N_p , of the sheath+LE as well as the magnetic structure. The solid lines give the linear and fourth order polynomial fit, respectively. As comparison, the dashed line gives the empirical Leblanc solar wind density formula (Leblanc et al. 1998) for a 1 au density of 9 cm^{-3} , multiplied by the average upstream solar wind speed as derived for our data sample ($\sim 375 \text{ km s}^{-1}$).

& Bothmer 2018). From the extrapolations of the linear fits we obtain on the one hand, that the ME becomes lower in density than the ambient solar wind at a distance of 1.07 au. In comparison, the study by Wang et al. (2005) found that the ME density becomes lower than the ambient solar wind at about 1.17 au. On the other hand, we find interesting results with respect to the density relation between sheath and ME as well as sheath and ambient solar wind for distances closer to the Sun. At about 0.06 au ($=13 \text{ Rs}$) the sheath density becomes higher than the ambient solar wind density, which could be interpreted as the distance where the sheath starts to be formed. This is also about the distance that CMEs have fully developed their structure as observed in white-light data (e.g., Vourlidas et al. 2000; Pluta et al. 2019). At about 0.18 au ($=38 \text{ Rs}$) the ME density clearly starts to fall below the sheath density which could be related to the stronger expansion of the ME in comparison to the sheath and/or a change in the expansion behavior of the ME. Interestingly, Sachdeva et al. (2017) found that on average at the distance of about 40 Rs the drag force starts to dominate over the Lorentz force initially driving the CME. PSP results from the smaller sample of four events basically support the results derived with Helios data. The recent ground-breaking PSP measurements revealed that the sub-Alfvénic point is located at roughly 18 Rs (see Kasper et al. 2021). Hence, CME in-situ measurements from the SWEAP and FIELDS investigations aboard PSP for distances below 20 Rs are of great interest (Bale et al. 2016; Kasper et al. 2016).

The size of sheath and ME structure clearly increases with distance, while the LE size is not showing strong variations. The LE structure seems to be wedged in between sheath and ME. For the sheath size we find the highest correlation with the ambient solar wind density ($cc = -0.52$) and the plasma-beta of the ME ($cc = -0.51$). A weak correlation between the sheath size and driver speed (LE, ME) exists, as well as a weak anti-correlation to the sheath density itself. In total, the statistics in the Appendix also shows, that the ME magnetic field relates very strongly to the LE and sheath density. With that we support the results by Salman et al. (2021) who concluded that ME properties shape the sheath properties and that slower CMEs, spending longer time in the solar wind, do not drive larger sheaths. These results are

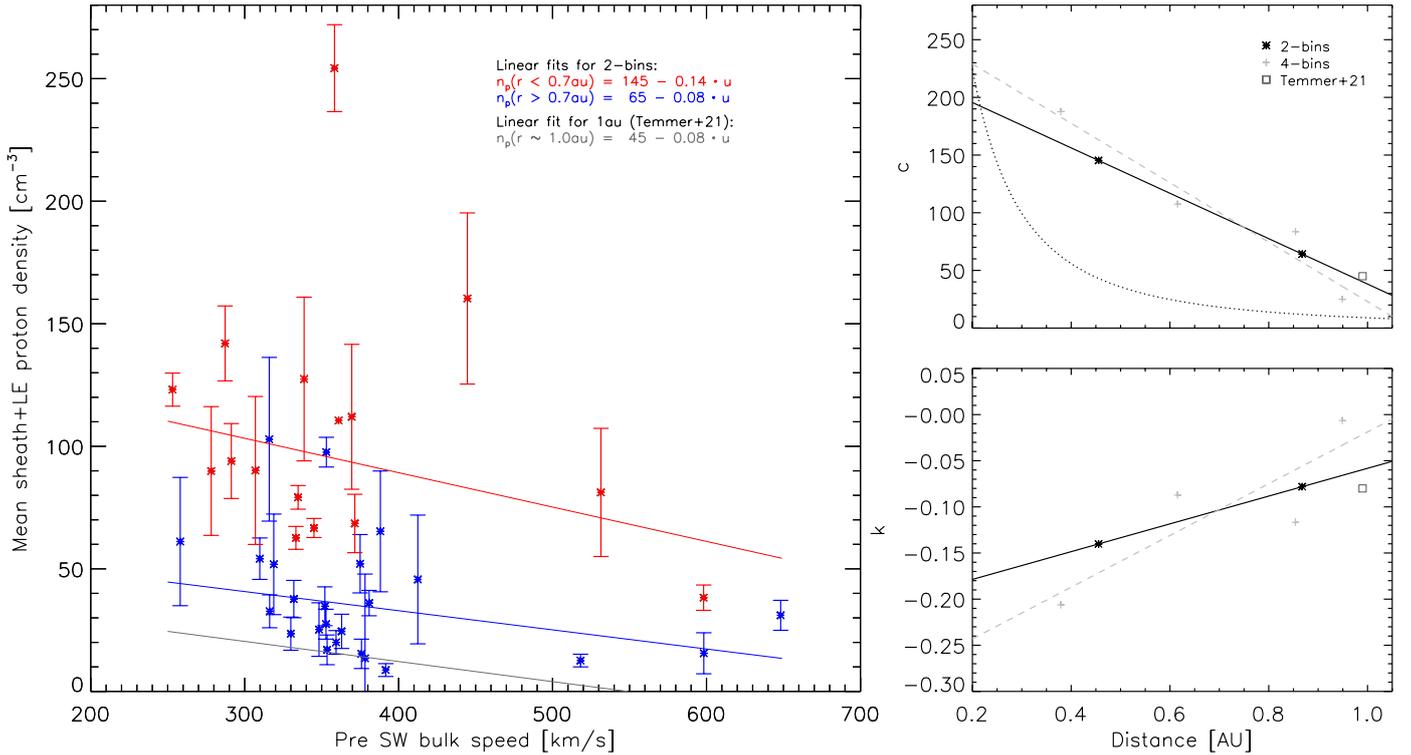


Fig. 7: Left: Average density, n_p , and upstream solar wind speed, u , for two distance bins (red: $r_1 < 0.7 \text{ au}$ covering 16 events; blue: $r_2 > 0.70 \text{ au}$ covering 24 events). Right: Constants (top) and slope (bottom) for the fits from the 2-bin distribution, as given on the left, as well as for a 4-bin distribution ($r_{1,2,3,4} = [0.3-0.47, 0.47-0.75, 0.79-0.92, 0.92-0.98]$). In addition we give the results from Temmer et al. (2021) who derived for a sample of 29 events a linear relation between the upstream solar wind speed and sheath density for 1 au. We show for each sample a linear fit and give the resulting regression formula in the legend.

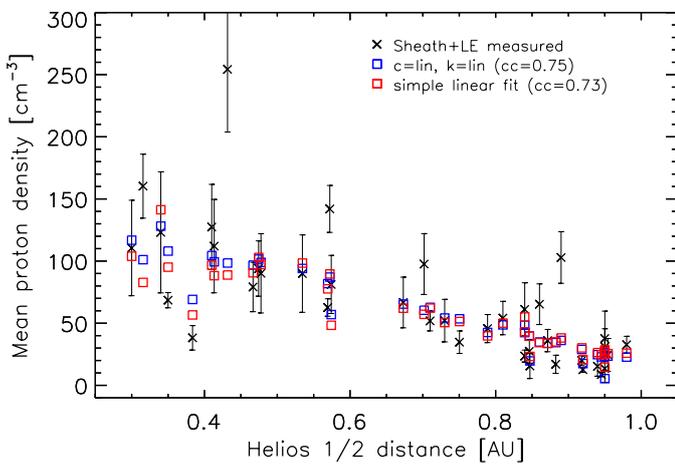


Fig. 8: Measured average sheath and LE density including error bars, together with the results from the empirical relation between upstream solar wind speed and average density between shock and start of the magnetic structure (i.e., covering sheath and LE). Correlation coefficients between calculated and measured sheath+LE density are given as obtained from different empirical models. See legend for more details on the parameters.

important for better understanding the CME mass evolution due to sheath enlargement.

The study by Temmer et al. (2021) found for a set of 29 ICME data at L1, a strong anti-correlation ($cc = -0.73$) between sheath+LE density and the ambient solar wind speed measured 24 hours ahead of the disturbance. In contrast, the current study covers a distance range from 0.3 au to 1 au. For that we find the sheath density to be moderately anti-correlated with the local solar wind plasma speed upstream of the ICME shock ($cc = -0.41$). Repeating the analysis of the upstream solar wind speed-sheath density relation for two different distance bins (r_1, r_2), we find for the events measured at distances larger than 0.7 au an increase in the Spearman correlation coefficient with $cc = -0.58$ (80% confidence level). For events closer to the Sun the relation is less clear and the scatter increases. Assuming there is a local dependency between the sheath density and the ambient solar wind speed, these results allow to define some empirical relations. Those enable to model the density of sheath and LE structure over distance simply by knowing the upstream solar wind speed at that distance. This supports the more reliable model output of the background solar wind speed component and the results presented here could be implemented in numerical models in order to add the pile-up or compression of material ahead of the propagating ICME. In a similar way Kay et al. (2020) relates the downstream density and magnetic field strength to the upstream properties from which an empirical model is derived to predict the sheath structure at 1 au.

We summarize our main findings:

- Four main ICME structures, shock, sheath, leading edge, and magnetic ejecta are identified using characteristic features in plasma and magnetic measurements
- The start of the sheath formation distance is found at about 0.06 au (=13 Rs) where the observed sheath density overcomes the ambient solar wind density.
- The sheath density predominance is found at about 0.18 au (=38 Rs) where the ME density clearly starts to fall below the sheath density.
- The ME density becomes lower than the ambient solar wind at a distance of about 1.07 au (=230 Rs).
- The sheath characteristics seem to be related to the upstream solar wind and ME properties.
- Assuming a local linear relation between sheath density and ambient solar wind speed, we give empirical relations that could support CME propagation models.
- The LE seems to be a structure rather isolated from the ambient solar wind flow wedged in between ME and sheath.

With PSP approaching the Sun as close as 10 Rs, we will certainly detect more CME events to obtain measurements that might re-affirm the presented results and give more detailed insight about the sheath build up processes. With increasing solar activity we expect also stronger events to get more conclusive results (see also Venzmer & Bothmer 2018). Moreover, the Wide-field Imager for PSP (WISPR Vourlidas et al. 2016) enables comparative studies with remote sensing white-light data with high spatial resolution.

Acknowledgements. VB acknowledges the support of the Coronagraphic German And US Solar Probe Survey (CGAUSS) project for WISPR by the German Aerospace Centre (DLR) under grant 50OL1901 as a national contribution to the NASA Parker Solar Probe mission. We thank Iulia Chifu for her support in PSP data provision. Parker Solar Probe was designed, built, and is now operated by the Johns Hopkins Applied Physics Laboratory as part of NASA's Living with a Star (LWS) program (contract NNN06AA01C). Support from the LWS management and technical team has played a critical role in the success of the Parker Solar Probe mission. For the access to the PSP FIELDS and SWEAP data we acknowledge the Parker Solar Probe Science Gateway at <https://spgway.jhuapl.edu>.

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Appendix A: Spearman correlation coefficient matrix for different solar wind parameters

Figure A.1 shows the statistical relation between various parameters extracted from Helios 1/2 plasma and magnetic field data. The Spearman correlation coefficients are calculated on a 90% significance level. Correlations with significance below are not given (i.e., left blank). The matrix covers for each structure sheath (sh), leading edge (LE) and magnetic ejecta (ME) their average parameters in density (den), magnetic field (mag), speed (v), and respective fluctuations (fl) from the standard deviation of these parameters. Furthermore we give the plasma-beta (pb), upstream solar wind speed measured 3 and 24 hours, respectively, ahead of the disturbance (u_u3h, u_u24h), as well as downstream solar wind density and speed, respectively, measured 3 hours after the disturbance (d_d3h, u_d3h). The calculated correlations additionally cover the size (s) of each structure, the Alfvén Mach number (Mach_A, see Section 3), and the distance at which the measurements were done.

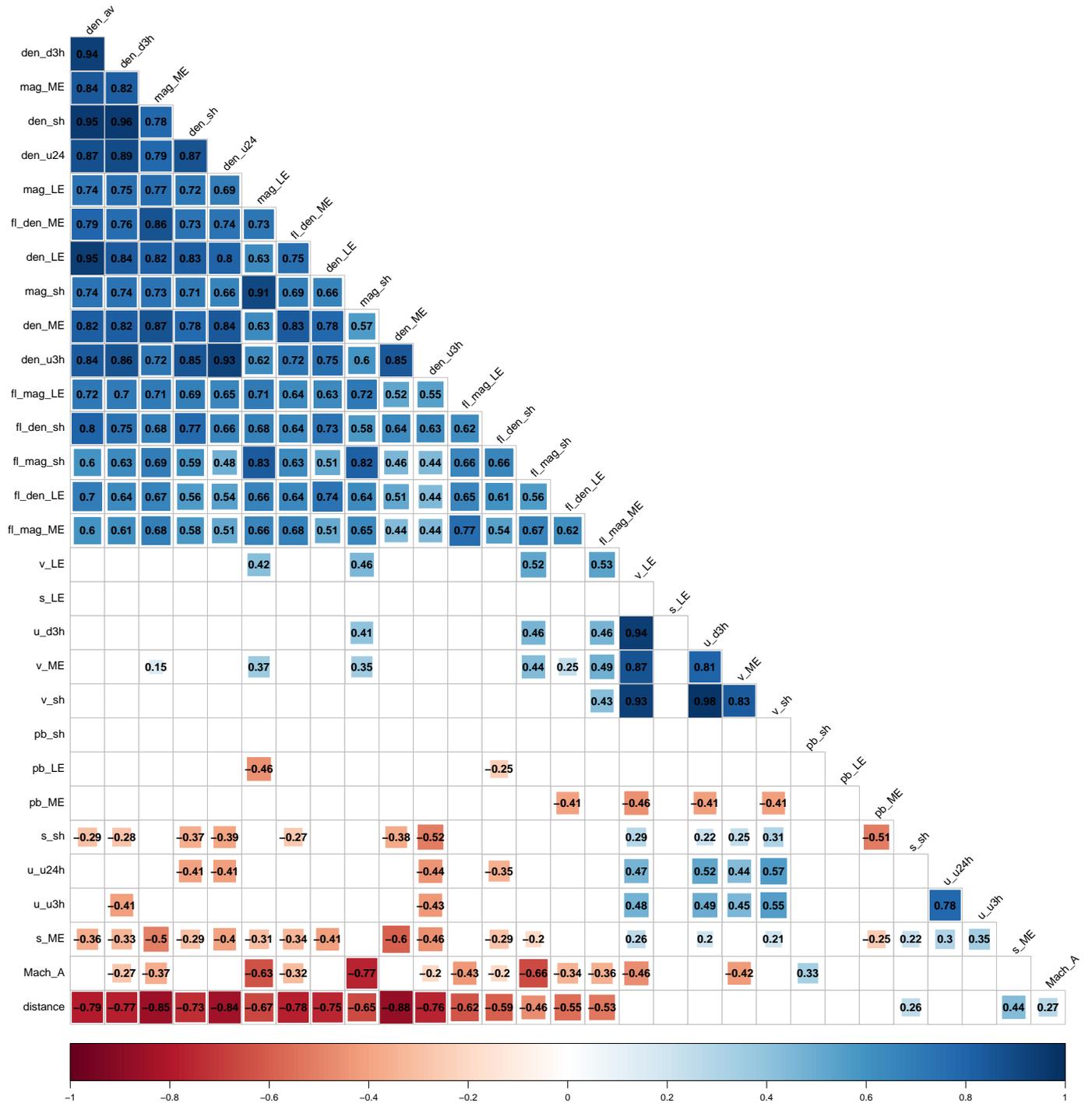


Fig. A.1: The Spearman correlation coefficients are calculated on a 90% significance level. Correlations with significance below are not given (i.e., left blank).