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On the validity of the Taylor Hypothesis in the inner heliosphere as observed by the Parker Solar Probe

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ABSTRACT

We study the validity of the Taylor "frozen-in" hypothesis in the inner heliosphere during the orbit of Parker Solar Probe. We examine the ratio of the Alfvén velocity to the apparent solar wind velocity, and the magnitude of the turbulent fluctuations of the velocity of the solar wind, as observed by the spacecraft in its own reference frame. The necessary conditions appear to be satisfied for most of the orbit, with both these ratios being far below unity. However, at heliocentric distances smaller than $\sim$ 50 solar radii, these ratios are observed to rise above 0.1, and can consistently exceed 0.3, leading to the conclusion that the Taylor hypothesis may begin to break down in these inner regions. At larger distances, both ratios remain generally low. However, we observe some periods where the plasma conditions change significantly, either due to a lower plasma density or much stronger turbulent fluctuations, leading to much higher values, suggesting that the Taylor hypothesis may break down in such transient regions. An alternative formulation of the frozen-in hypothesis, which could be valid for outward-propagating dominant fluctuations, is also examined. Its conditions, namely that the Elsässer variable corresponding to inward propagating fluctuations is much smaller than both the perpendicular spacecraft velocity, and the outward propagating fluctuation, were found to be satisfied near perihelion for encounters 1 and 2 and for parts of the encounters 4 and 5. We conclude that although the basic conditions for the validity of the Taylor hypothesis may cease to be satisfied in the inner heliosphere at distances below $\sim$ 50 solar radii, alternative frozen-in hypotheses may be successfully employed.

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1. INTRODUCTION

In situ measurements have been instrumental in understanding the dynamics and evolution of the solar wind. Most spacecraft observations are single-point measurements of a time-series obtained at the location of the spacecraft.

These measurements capture both the temporal evolution of the plasma and the spatial variation as the spacecraft moves with respect to the surrounding medium. Often, we can assume the velocity at which the probe travels through the plasma is much faster than the characteristic velocities at which the plasma evolves. Therefore, the medium does not change significantly during the measurement and can be assumed to be "frozen in" as the probe sweeps through it. If that approximately holds, we can convert the temporal increments of the measured signal into spatial increments. This is the standard Taylor hypothesis (Taylor 1938; Jokipii 1973).

The necessary condition for this assumption is that the speed of the spacecraft relative to the plasma is much larger than characteristic speed of the dynamic evolution of the plasma. This approximation has been widely used in studies of solar wind turbulence at 1AU (Matthaeus & Goldstein 1982, 1986; Bruno & Carbone 2013; Verscharen et al. 2019). Inside 1AU, however, issues related to the Taylor hypothesis in the inner heliosphere have been raised, first by studies of the Helios observations (Goldstein et al. 1986).

The Parker Solar Probe (Fox et al. 2016) spacecraft was launched in 2018, aimed at the study of the outer corona. Its orbit brings the spacecraft in the inner heliosphere, at very small distances from the Sun. In this region, the typical assumptions for the Taylor hypothesis are not expected to necessarily hold. This is due to the local plasma conditions in the inner heliosphere region, namely a stronger magnetic field, higher density, and eventually a sub-Alfvénic solar wind. Moreover, the orbital characteristics of Parker Solar Probe's trajectory mean the spacecraft velocity is significant compared to the local plasma velocity.

Here we examine the conditions necessary for the Taylor hypothesis to be applicable, focusing on the Alfvén velocity and the turbulent velocity fluctuations. We find that although the conditions are generally satisfied for most of the orbit, this is not the case for measurements made within $\sim 50\ R_\odot$ from the Sun. At larger heliocentric distances, we observe transient periods where those conditions are violated due to the variability of the local plasma conditions, such as regions of lower density or larger turbulent fluctuations. We also examine a modified version of the frozen-in hypothesis, considering solely transverse fluctuations propagating outward from the Sun as formulated by Klein et al. (2015). We found those alternative conditions to be satisfied at the smaller distances from the Sun, near the closest approach for the first two encounters, and large parts of encounters 4 and 5, suggesting such an approach can viable in order to employ the Taylor hypothesis at small heliocentric distances.

2. DATA SELECTION AND METHOD

We use data from the first five orbits of Parker Solar Probe. Encounter 3 is not analyzed due to the lack of SPC data. Here, we express heliocentric distances in units of solar radii $R_\odot$. For each encounter we consider a window of approximately one month around each perihelion. These intervals begin at a heliocentric distance of around 130 $R_\odot$, up to the closest approach at 35.6 $R_\odot$ for encounters 1 and 2 and 27.9 $R_\odot$ for encounters 4 and 5. The magnetic field was measured by the fluxgate magnetometer of the FIELDS instrument suite (Bale et al. 2016). For the plasma density and velocity we used the fits of the proton moments measured by the faraday cup of the SPC instrument (Case et al. 2020), which is part of SWEAP (Kasper et al. 2016). An overview of the evolution of the plasma parameters during the first encounter is shown in Figure 1, where Panel A shows the magnetic field and Panels B and C show the proton density and velocity, respectively.

For the present study, we are interested in measurements of the solar wind velocity as measured in the spacecraft frame. Therefore, we use the quantity $\vec{V}_{SW(PSP)} = \vec{V}_{SW} - \vec{V}_{SC}$, where $\vec{V}_{SW}$ is the true solar wind velocity in an inertial reference frame, $\vec{V}_{SC}$ is the velocity of the Parker Solar Probe spacecraft, and consequently $\vec{V}_{SW(PSP)}$ is the apparent velocity observed by the spacecraft in the spacecraft's own co-moving reference frame.

The other quantity of interest is the magnitude of turbulent fluctuations of the velocity. We define that as

$$\delta v/v = \frac{\sqrt{\langle(|\vec{v} - <\vec{v}>_{T_c}|)^2\rangle_{T_c}}}{\langle|\vec{v}|\rangle_{T_c}} \tag{1}$$

where $\langle\ldots\rangle_{T_c}$ denotes time-averaging over a timescale T_c, $\vec{v}_0 = \langle\vec{v}\rangle_{T_c}$ is the average of $\vec{v}$, over the same timescale T_c. The velocity used here is $\vec{v} = \vec{V}_{SW(PSP)}$, the solar wind velocity as measured in the spacecraft reference frame.

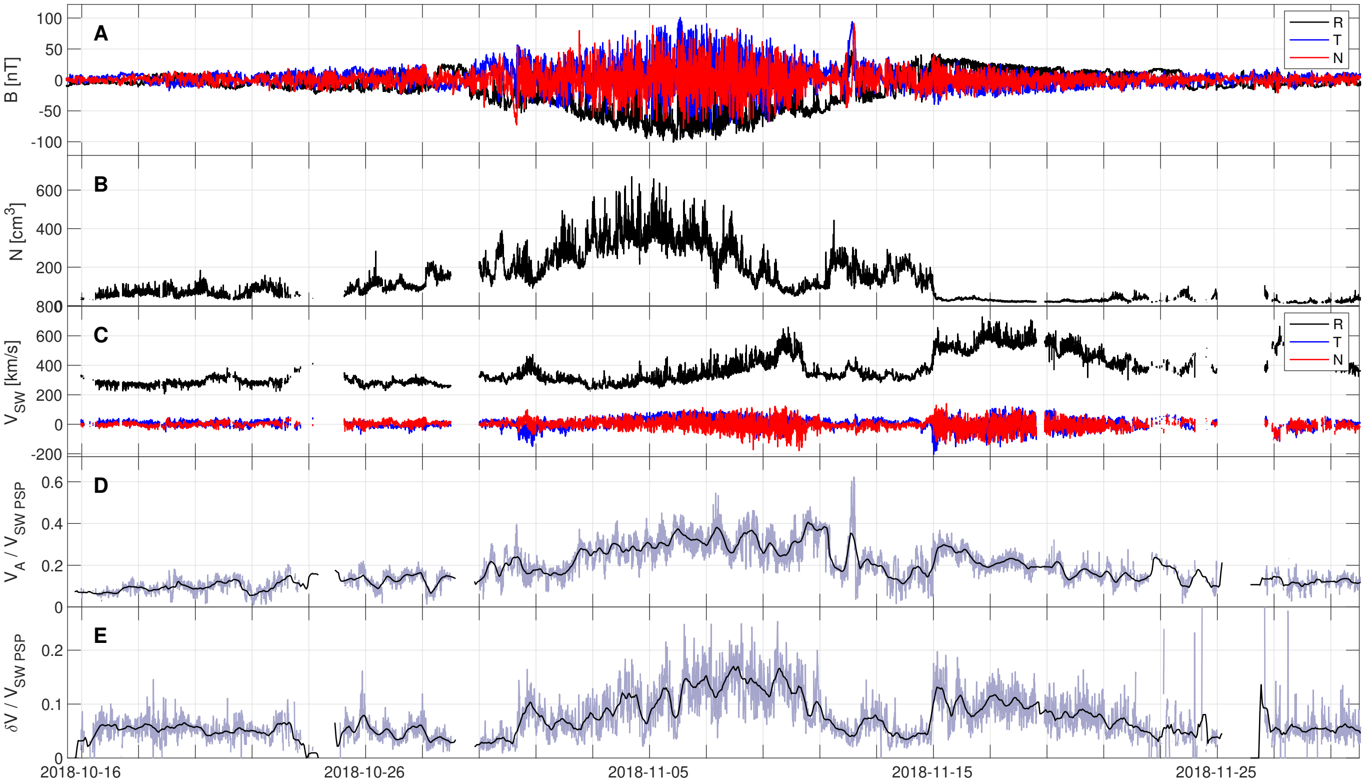

Figure 1. Overview of magnetic field and plasma measurements during the first encounter. Panel A shows the magnetic field. Panels B and C show the proton density and velocity in RTN coordinates. Panels D and E show respectively the ratio of the Alfvén velocity V_A to the apparent solar wind velocity m $V_{SW(PSP)}$, and magnitude of the turbulent velocity fluctuations $\delta v/v$, both calculated in the spacecraft frame. The solid black line is an 8-hour average, and the grey line a 2 minute average.

The size of the averaging interval T_c chosen corresponds to the correlation scale of the turbulence. The correlation time can be defined as the time when the autocorrelation function of the signal drops below $1/e$ (Isaacs et al. 2015; Krishna Jagarlamudi et al. 2019), or alternatively from the time-scale corresponding to low end of the inertial scale, when the spectrum breaks from f^{-1} to the steeper values observed in the inertial range (Matthaeus & Goldstein 1986). For the observations presented here, both approaches lead to comparable estimates as shown by Parashar et al. (2020); Chhiber et al. (2020); Bandyopadhyay et al. (2020); Chen et al. (2020). For the present study, we use a value of $T_c = 1200$ s, following the estimated values reported by these studies.

Finally we also estimate the Elsässer variables (Elsasser 1950), $\vec{z}^{\pm} = \vec{v}' \pm \vec{b}'$, were $\vec{v}' = \vec{v} - <\vec{v}>_{TC}$ and $\vec{b}' = \vec{b} - <\vec{b}>_{TC}$ are the velocity and magnetic field respectively. Here, the $\vec{v} = \vec{V}_{SW}$, and the velocity used is the solar wind velocity measured in the inertial reference frame. From that we obtained $Z^{\pm} = \sqrt{<z^{\pm 2}>}$, and estimated the ratio Z^{+}/Z^{-}. As in the previous case, $\langle \ldots \rangle_{T_c}$ denotes a time average over a time interval T_c.

3. RESULTS

We calculated a few different quantities to examine to what extent the Taylor hypothesis is applicable in the regions where the Parker Solar Probe travelled during its first two encounters. The results are compared with the predictions made by Usmanov et al. (2018) and Chhiber et al. (2019).

Firstly, we examine the magnitide of the Alfvén velocity V_A compared to the apparent velocity of the solar wind plasma as observed in the spacecraft reference frame $V_{SW(PSP)}$. In order for the plasma to be considered "frozen in", we require that $V_A \ll V_{SW(PSP)}$, and therefore the ratio $V_A/V_{SW(PSP)}$ to be much smaller than unity. A second condition examined here is related to the evolution of turbulent fluctuations, and can be expressed as$\delta v/v \ll 1$, where $\delta v/v$ is the magnitude of the turbulent velocity fluctuations observed in the spacecraft frame as defined in Equation 1. As noted in the previous section, we estimated $\delta v/v$ over a time-scale corresponding to the correlation length, and therefore this calculation applies to the inertial range of the turbulent cascade.

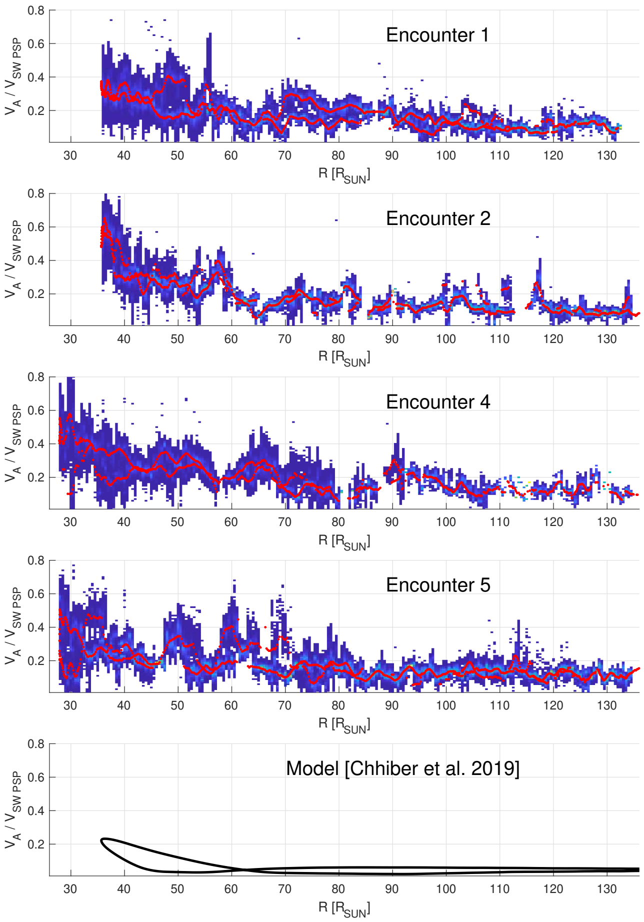

Figure 2. Evolution of the ratio of the Alfvén velocity V_A to the apparent solar wind velocity m $V_{SW(PSP)}$ as a function of the distance from the Sun. Each panel shows encounters 1,2 4 and 5. The solid red line is an 8-hour average while the colored shade is a histogram with the spread at each heliocentric distance. The bottom panel shows the numerical predictions by Chhiber et al. (2019).

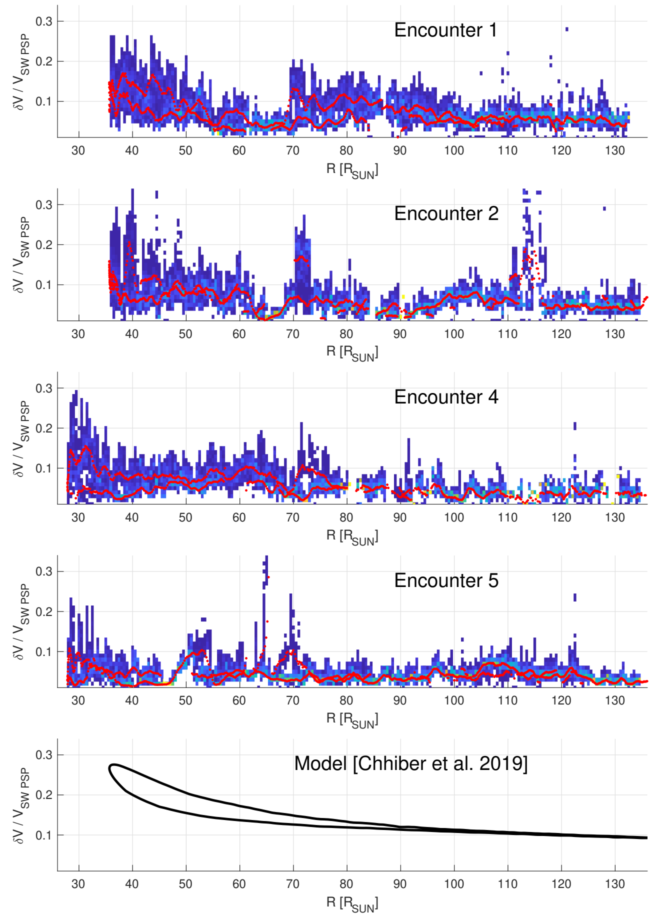

Figure 3. Evolution of the ratio of the turbulent velocity fluctuations $\delta v/v$ as a function of the distance from the Sun. Each panel shows encounters 1,2 4 and 5. The solid red line is an 8-hour average while the colored shade is a histogram with the spread at each heliocentric distance. The bottom panel shows the numerical predictions by Chhiber et al. (2019).

The treatment presented here is focused on MHD scales. Therefore, we would not extend those results at the kinetic range, below the ion gyro-radius, where kinetic processes in the plasma become important. Near the perihelion, the kinetic range would correspond ~ 20 km, or ~ 50 ms. Studies by Duan et al. (2020) and Bowen et al. (2020) examine Parker Solar Probe observations of such kinetic scale fluctuations, and discuss the application of the Taylor hypothesis at those scales. Modified versions of the Taylor hypothesis at kinetic scales are discussed in Klein et al. (2014) and Howes et al. (2014).

For these conditions to be satisfied, we should expect these two quantities to have values much smaller than unity. In practice we take this to mean a value below 0.1 for a strong condition and below 0.3 for a weak condition. Above 0.3 we consider the validity of the Taylor hypothesis to be in question. These numbers follow the ones used in Usmanov et al. (2018) and Chhiber et al. (2019).

The time-series of the ratios $V_A/V_{SW(PSP)}$ and $\delta v/v$ during the first encounter are shown in Panels D and E of Figure 1, respectively. The data shown start when Parker Solar Probe is at around 120 $R_{\odot}$. At closest approach on November 6^{th} 2018, the spacecraft was at about 35 $R_{\odot}$. As expected these two metrics have values around 0.1 and below when Parker Solar Probe is far from the Sun at the edges of the interval shown in Figure 1. We can clearly observe the gradual rise to larger values as the spacecraft gets closer to the Sun, with a maximum at the perihelion followed by a drop off on the outbound leg of the orbit.

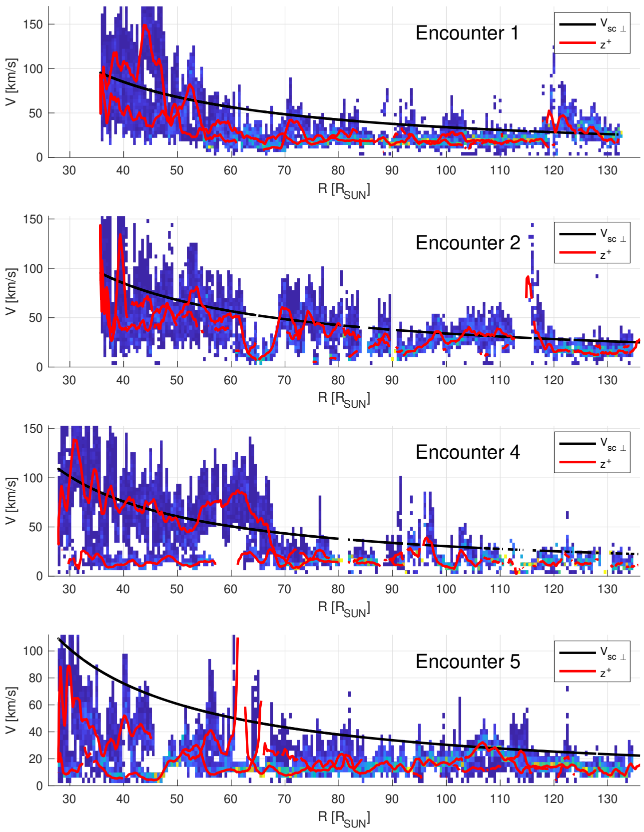

Figure 4. Comparison of the perpendicular spacecraft velocity $V_{SC\perp}$ (solid black line) and Elsässer variable z^+ as a function of radial distance from the Sun for each encounter. The red line shows an 8-hour average of z^+, while the colored shade is a histogram with the spread at each heliocentric distance.

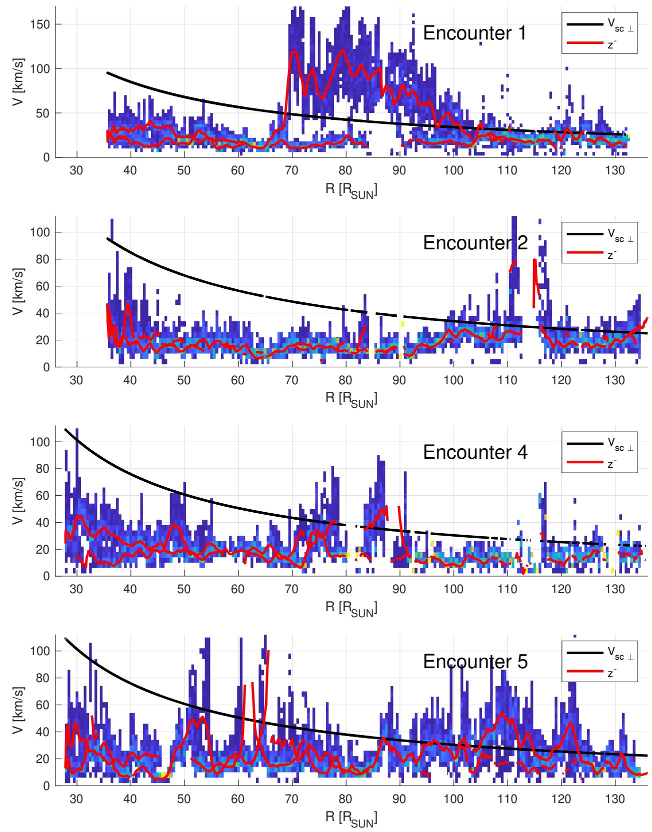

Figure 5. Comparison of the perpendicular spacecraft velocity $V_{SC\perp}$ (solid black line) and Elsässer variable z^- as a function of radial distance from the Sun for each encounter. The red line shows an 8-hour average of z^-, while the colored shade is a histogram with the spread at each heliocentric distance.

The dependence of the ratio $V_A/V_{SW(PSP)}$ on the radial distance from the Sun is shown in Figure 2, for each encounter. The contextual predictions from the numerical simulations presented in Chhiber et al. (2019) are shown in the bottom panel. Note, however, that model predictions were based on an untilted solar dipole as boundary condition, and did not employ solar magnetogram data corresponding to the time period of PSP's solar encounters. In the data, while the ratio remains relatively small for most of the orbit, it rises above 0.3 when the spacecraft is at distances lower than $\sim 50\ R_\odot$. The values at the closest approach are much higher during the second encounter reaching almost 1 at perihelion. This may be attributed to varying plasma conditions, such as the lower plasma density compared to the first encounter. Similar values are attained in encounters 4 and 5 although at smaller distances, following a similar trend to encounter 1.

The magnitude of the turbulent fluctuations $\delta v/v$ calculated in the spacecraft frame as described in Eq. 1, is shown as a function of the radial distance in Figure 3. We note that while the ratio becomes larger at $\sim 50\ R_\odot$, it remains relatively small throughout both encounters, staying below 0.3 even at the closest approaches during encounters 4 and 5. Contrary to the trend observed in the Alfvén velocity, the turbulent fluctuations are smaller than the estimate of the numerical predictions. Finally, one must note that there are intervals of significantly strong turbulent fluctuations, leading to much higher ratios.

Modified versions of the Taylor hypothesis for use in Parker Solar Probe observations close to the sun have been proposed (Matthaeus 1997). Here, we examine the one formulated by Klein et al. (2015), who note that, since the Elsasser mode $z^\pm$ is convected by the oppositely signed mode $z^\mp$, the relevant speed of turbulent evolution for, say, z^+, is determined by z^-. The frozen-in approximation may then be valid for the dominant outward-propagating modes near perihelion if a number of conditions are satisfied. Here we examine in detail whether two of those conditions are satisfied. The first condition is that the velocity of the spacecraft perpendicular to the radial direction is larger than the Elsässer variable corresponding to inward propagating fluctuations $z^- \ll V_{SC\perp}$. Note that this condition relies on the fact that the spacecraft velocity will have a small radial component at perihelion. The second condition is that the outward propagating fluctuations dominate and hence $z^- \ll z^+$. It should be noted that this analysis applies to inertial range fluctuatons.

Figures 4 and 5 show the radial evolution of the two modes Elsässer z^+ and z^- compared to $V_{SC\perp}$ for each encounter. Throughout the entire encounter, for both orbits, z^- remains on average much smaller than $V_{SC\perp}$. The ratio of z^+/z^- as a function of the heliocentric distance during each encounter is shown in Figure 6.

We observe that during encounters 1 and 2, z^+/z^- is larger than unity, while $z^- << V_{SC\perp}$, thus satisfying the required conditions. The same is true for parts of encounter 4 and 5. Both conditions appear to hold in this case, especially so when Parker Solar Probe is near its closest approach to the Sun, suggesting we can apply the Taylor hypothesis to study the spatial structure of z^+.

One exception is during part of encounter 1 when z^- becomes very large, with values significantly larger than $V_{SC\perp}$, a change associated with a crossing of the heliospheric current sheet around November 14th 2018. During this period $z^+/z^- < 1$ and $z^+ < V_{SC\perp}$, which means the condition posited by Klein et al. (2014) may still hold although for the opposite mode. A similar situation occurs during parts of encounters 4 and 5 with heliospheric current sheet crossings occurring around January 31st 2020 and June 8th 2020. However, $z^+/z^- \sim 1$ during this part, thus not satisfying this condition.

One final aspect to consider is the impact of the spacecraft's radial velocity on the apparent velocity of the solar wind, and its change during the orbit. On Figure 7, the ratio $V_A/V_{SW(PSP)}$ is shown during the inbound and outbound legs. Comparing the two, we observe that this ratio has generally larger values during the inbound part of the orbit compared to the outbound part.

As expected, when the spacecraft is moving towards the Sun, on the inbound leg of the orbit, the apparent headwind will appear stronger. Accordingly, the opposite effect is observed on the outbound leg with the tailwind appearing weaker as the spacecraft moves away from the Sun. This effect becomes less significant, however, near perihelion, when the radial velocity of the spacecraft slows down to zero.

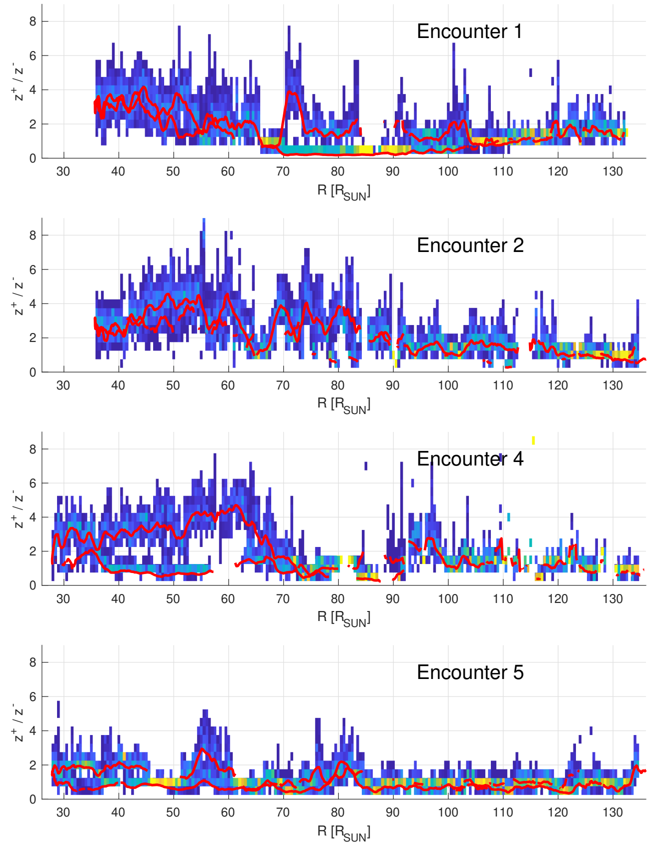

Figure 6. Evolution of the ratio of the Elsässer variables z^+/z^- as a function of the radial distance from the Sun for each encounter. The red line shows an 8-hour average, while the colored shade is a histogram with the spread at each heliocentric distance.

4. CONCLUSIONS

We present an evaluation of the validity of the Taylor hypothesis in the inner heliosphere using Parker Solar Probe observations during encounters 1,2,4 and 5.

We can conclude that the Taylor hypothesis appears to be valid for observations made at radial distances larger than $\sim 50\ R_\odot$ from the Sun. This gets much less certain as the spacecraft moves closer to the sun, although alternative formulations of the frozen-in condition may still hold.

Specifically, the values of the ratio of the Alfvén velocity to the apparent solar wind velocity $V_A/V_{SW(PSP)}$ and the turbulent velocity fluctuations $\delta v/v$, calculated in the co-moving spacecraft frame, remain relatively small for most of the orbit. However, when the spacecraft is at distances lower than $\sim 50\ R_\odot$, values above 0.3 are consistently observed, especially for $V_A/V_{SW(PSP)}$. Lower values are observed on the inbound leg of each orbit compared to the outbound leg, as expected given the effect of the spacecraft's radial velocity.

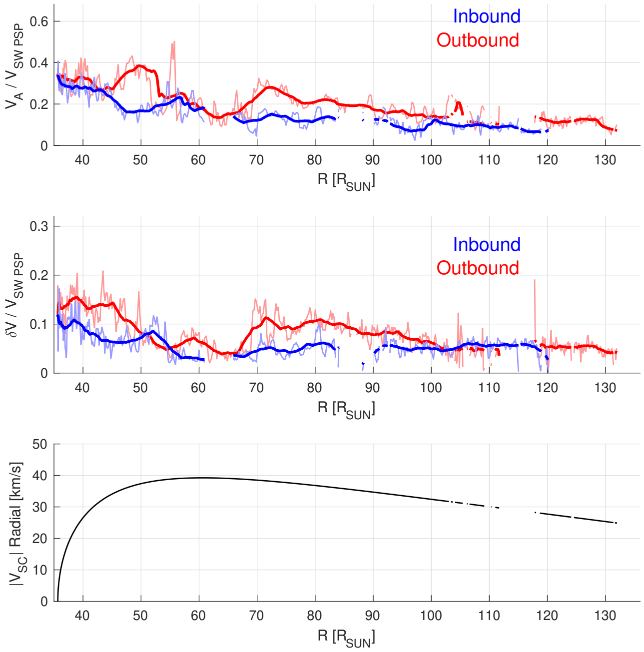

Figure 7. Comparison of inbound and outbould part of the first encounter. The top panel shows the ratio of the Alfvén velocity V_A to the apparent solar wind velocity m $V_{SW(PSP)}$. The middle panel shows the magnitude of turbulent velocity fluctuations $\delta v/v$. For each orbit the inbound leg is shown in blue and the outbound in red, with an 1-day average shown with a bold solid line and an 1-hour average in light shaded solid line. The bottom panel shows the radial velocity of the spacecraft.

The observed values for $\delta v/v$ are generally not far from the predictions of the numerical simulations carried out by Usmanov et al. (2018) and Chhiber et al. (2019). The Alfvén velocity ratio $V_A/V_{SW(PSP)}$ observed is higher than the model. The opposite is true for the turbulent fluctuations, although the discrepancy is less pronounced. Note, however, that the above model predictions are based on tilted solar dipoles as boundary conditions, and do not employ solar magnetogram data corresponding to the time period of PSP's solar encounters. A study comparing such magnetogram-based simulations with PSP data is currently underway.

One important feature that we observe is that local plasma conditions can vary to such an extent that the Taylor hypothesis can break down, even at larger heliocentric distances. This may be caused by transient periods of low density, leading to a much larger Alfvén velocity, compared to the apparent solar wind speed, or regions where strong turbulence leads to much larger fluctuations of the velocity.

An alternative to the Taylor hypothesis based on Klein et al. (2015) was examined, which may hold for dominant outward-propagating Elsässer fluctuations near perihelion. The conditions for this, namely that $z^- \ll V_{PSP\perp}$ and $z^- \ll z^+$, were found to be satisfied near perihelion for both orbits. Therefore, this modified version of the Taylor hypothesis may be employed for the dominant outward Elsässer mode, to the extent that their assumptions are taken into consideration.

It should be noted that this formulation relies on a nearly-radial magnetic field, which would exclude switchback structures where the magnetic field deviates from the radial direction, and future work will determine how these conditions vary in these regions. A recent discussion on Elsässer modes and cross-helicity evolution in switchbacks observed by Parker Solar Probe can be found in (McManus et al. 2020). Other alternative formulations could also be considered (Bourouaine & Perez 2019, 2020; Perez & Bourouaine 2020) and applied in such switchback regions Bourouaine et al. (2020).

In conclusion, the conditions for the application of the Taylor hypothesis appear to be satisfied for most of the observations in the inner heliosphere. However, the validity was less certain in regions with heliocentric distances less than $\sim 50\ R_\odot$. Alternative formulations of the frozen-in hypothesis can be employed, with some success, when a spacecraft is that close to the Sun. As Parker Solar Probe approaches closer to the Sun, studies relying on the Taylor hypothesis would have to carefully motivate its validity.

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