Radial Scaling of Alfvénic Behavior of the Solar Wind

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Abstract

This project aims to determine whether or not evidence of Alfvén wave behavior within the radially-oriented solar wind scales with distance from the Sun. To do this, our research utilizes data collected from the FIELDS and SWEAP instruments aboard the Parker Solar Probe. We first establish a mathematical relationship between the radial magnetic field magnitude (collected by the FIELDS instrument) and the radial proton velocity vector (measured by instruments housed by SWEAP). This relationship, also referred to as the "normalized cross-helicity", follows derivations for Alfvén speed and Alfvénicity (which also require proton density data from SWEAP) as previously established by Bruno & Carbone 2013 and Stansby et al. 2019. Once a mean Alfvénic content is determined, this process is then repeated across multiple Parker Solar Probe encounter dates. We then aim to compile these mean values alongside their respective radial distances into a single plot.

Introduction

Alfvén Waves are a mode of wave propagation within an electrically conductive region of charged particles that are governed by the electromagnetic forces. Alfvén waves are often characterized by the low frequency oscillation involving ions and magnetic field within plasma. Alfvén waves propagate along magnetic field lines due to the motion of ions and the inertia from the ion mass density, along with the magnetic field that deviates from the system. The motion of these ions and magnetic fields are transverse in the direction of propagation. Thus, the Alfvén wave is created through a constant use of restoring force, which allows the wave to propagate in the direction of solar magnetic field line. The Alfvén speed is then the speed of said waves and is extrapolated from proton density and magnetic field magnitude.

There are many Alfvénic fluctuations in the solar wind, especially in high-speed streams. From the observations statistics of Mariner 5, larger-amplitude Alfvén waves are responsible for about 30% of solar wind fluctuation. This is important because it is believed that Alfvén waves can be contributing to some energy transmission and dissipation occurring in phenomena that is not fully understood such as solar coronal heating, solar wind acceleration, and geomagnetic disturbances. These Alfvén waves can be characterized with the strong correlation between functions in the Magnetic field and the plasma velocity from the many in situ measuring the solar wind Liu et al. (2020). Most Alfvén waves that are measured in the interplanetary medium are likely generated from remnants of wave that were developed near the sun Belcher and Davis Jr. (1971).

The solar wind speed has been shown as a well-defined bimodal structure during solar minima. While between 0.1 AU and 1.0AU the evolution of the solar wind is more pronounced at solar minima than at solar maximum. The solar wind speed at 1.0 AU is between 400 and 500 $\frac{km}{s}$, while fast and slow wind experience little acceleration and deceleration. Implying that there is more bimodal solar wind at 0.1AU than at 1.0AU McGregor, Hughes, Arge, Odstrcil, and Schwadron (2011). The solar wind speed has the most drastic change within 0.3AU of the sun, although the change is not limited to this region as there are still changes beyond 0.3AU. This can aid in the understanding that slow wind shows low proton temperature, higher density, and many other properties of the solar wind Lopez and Freeman (1986).

Alfvénic waves that lie within the solar wind are an essential property of fast streams. These properties can fluctuate drastically depending on the velocity of the solar wind, slower intervals often have a lower level of Alfvénicity, with many other variables to consider. This is not always the case as some slower solar winds has a possibility of being highly Alfvénic. Even beyond this Alfvénic fluctuations can vary depending on the phase of the solar cycle. Although, it has been found that Alfvénic Fluctuations are most frequent during the decline from solar maximum to solar minima Tanskanen et al. (2017). Alfvénic fluctuation is an important aspect of understanding the solar wind and can be understood more thoroughly by understanding the Alfvénic correlation coefficient. The Alfvénic correlation can be even contributed to switchbacks in the expanding solar wind. Through developing analytic models that make several predictions it has been predicted that switchbacks should occur in areas where the solar wind plasma undergoes greater expansion Mallet, Squire, Chandran, Bowen, and Bale (2021).

The degree in which Alfvén correlation fluctuates radial has many dependencies such as the proton density, velocity of the solar wind, and the radial distance from the sun. The Alfvénic correlation tends to have a considerable time dependency which has been observed to range. Using the knowledge of how the Alfvén correlation fluctuates radially it was determined that the greatest Alfvénic correlation occurs with 1 AU of the solar surface. Figuring out Aflvénic regions and non-Alfvénic regions was determined though calculating the normalized cross-helicity which is defined and evaluated in Bruno and Carbone (2013) and Perrone et al. (2020).

$$\sigma_c = 2\frac{\langle \mathbf{v} \cdot \mathbf{b} \rangle}{\langle |\mathbf{v}|^2 + |\mathbf{b}|^2 \rangle} \tag{1}$$

This paper utilized previous research and equations to catalog the Alfvén behavior in the solar wind as it scales radially over the length of the year 2021. We use the equation (1) Which allows for the calculation of the Alfvén correlation coefficient. The Alvféncity of a wave correlates with magnetic field alignment. Through tracking the correlation coefficient every day for the entirety of 2021, we give some insight into how Alfvénic correlation alters over radial distance from the sun. This may allow others to access this data for future research. Aflvénic correlation can aid in research surrounding the understanding of the heating and acceleration of the solar wind. This may also help with the understanding of magnetic switchbacks, solar coronal heating, and possibly the origins of the solar wind. As these are topics that currently are still widely debatable. Many other studies use different methods for finding the correlation coefficient. Most use the ion temperature as well in this calculation but for our current research it was decided that ion temperate would not be needed as there is no current intention to search for correlation with the temperature of the solar wind.

To obtain these calculations, the Parker Solar Probe (PSP) mission is used to collect data from the Electromagnetic Fields Investigation (FIELDS) instrument and The Solar Wind Electrons Alphas and Protons (SWEAP) instruments. This is valuable as PSP got within 0.035AU from the solar surface in 2021. Which is closer than earlier work done on the solar wind. Which may show to be valuable in furthering our understanding of the solar wind.

Each instrument aboard the Parker Solar Probe is unique in design and has many implications that will be discussed further in later sections.

Methodology

We extracted data from the FIELDS instrument data set and SWEAP instrument data set. From FIELDS we were able to use the magnetic field data and extract the radial, tangential and normal (RTN) components. Allowing for use to use each individual component to calculate the magnitude of the B-field along with the time. A very similar process was used for extracting data from SWEAP.The main difference lies within the different instrumentation that is used with SWEAP as it is vital for the instruments collecting data to change as the orientation of the space craft approaches the sun. When PSP is within $30R_{\odot}$ we used the Solar Probe Analyzer Ion instrument(SPI) and when the space craft is beyond $30R_{\odot}$ we use data Solar Probe Cup instrument(SPC). The distance of the space craft in reference to the sun for each individual day in 2021 was found using Orbital data and this was crossed checked using PSP Position Calculator. Using these tools we were able to extract the correct data from the correct instruments.

In addition, there are many of the SWEAP files did not contain the normal vector which is vital for determining the velocity, density, and the position of the solar wind. Without the normal vector it was critical to filter each individual data file to find if all needed vectors were available. Furthermore, the sampling cadence of for the FIELDS and SWEAP instruments were different. The FIELDS magnetometer sampled at a much higher rate than the SWEAP instrument. To make these data sets comparable we used a linear interpolated to interpolate the FIELDS data down to the SWEAP data, so that each would have the same sample rate. The linear interpolation was decided based on understanding of code and the way that data was analyzed later in the process. After sorting though the many data collection issues it was now possible to graph the B-Field and velocity of the solar wind measured by PSP as shown in Figure 1. The beging portion of this experiment was repeated through the several valid days in 2021. The main prediction was to find a pattern of Alfvénicity over large time scales.

The main equation used to discover the Aflvénic correlation was equation 1. When solving for the correlation coefficient between the B-field and radial velocity, other components are used to normalize both values. When looking at the first equation given in the introduction we see that the ion velocity vector is using the dot product with the magnetic field vector. This only work if the vectors are normalized to correctly. The normalizing coefficient labeled as the Alfvén Speed in Equation 2. Alfvén Speed is the speed at which an Alfvén wave propagates. The Alfvén speed equation is applied to the interpolated B-Field and converts the units to velocity units: $\frac{km}{s}$. This changes the vector so that it is more viable for the normalized cross-helicity from Equation 1.

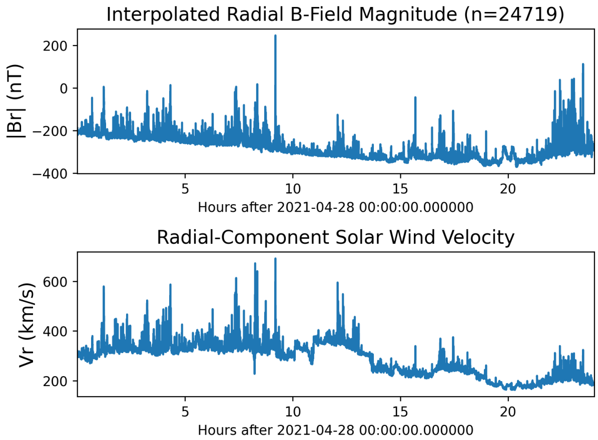

Figure 1: The interpolated radial B-field magnitude above its corresponding solar wind velocity component, collected on 2021-04-28.

$$v_a = \frac{B}{\sqrt{\mu_0 n_i m_i}} \tag{2}$$

Calculating the Alfvén Speed includes one other new variable, the proton density: n_i. The proton density is pulled from the SWEAP instrument on PSP. Since velocity and proton density are collected from the same instrument, it was necessary to reduce the data to the same days as the collected velocity data. The other two variables are physical constants. The mass of a proton, m_i, and the vacuum permeability constant, μ_0.

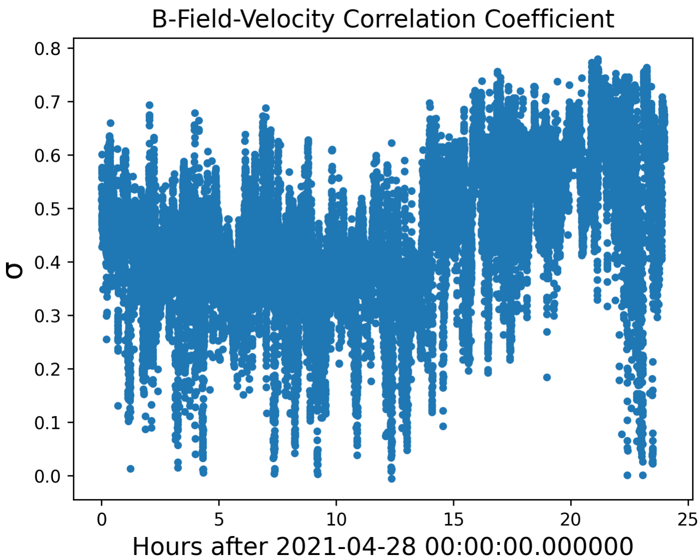

Figure 2: The resultant correlation between the velocity and B-Field of the solar wind in velocity units on 04-28-2021

A caveat to note with sigma is the switching from the SPI and SPC instruments. As Parker Solar Probe travels along its orbit, depending on the distance it will use one of the two instruments. At 30 $R_\odot$ is where this switching occurs. Our team decided to negate days in which this switching occurs since the very act corrupts the data we are trying to analyze. Latency in transfer of instruments interferes with the collection of data causing us to throw out the whole day. Down below shows the effects of the switching on the other components of the collecting data: Magnetic field, proton density, velocity, resultant sigma.

The leftmost graph shows the relationship between the distance over time. Where the graph deviates from its decreasing linearity is where the switch takes place

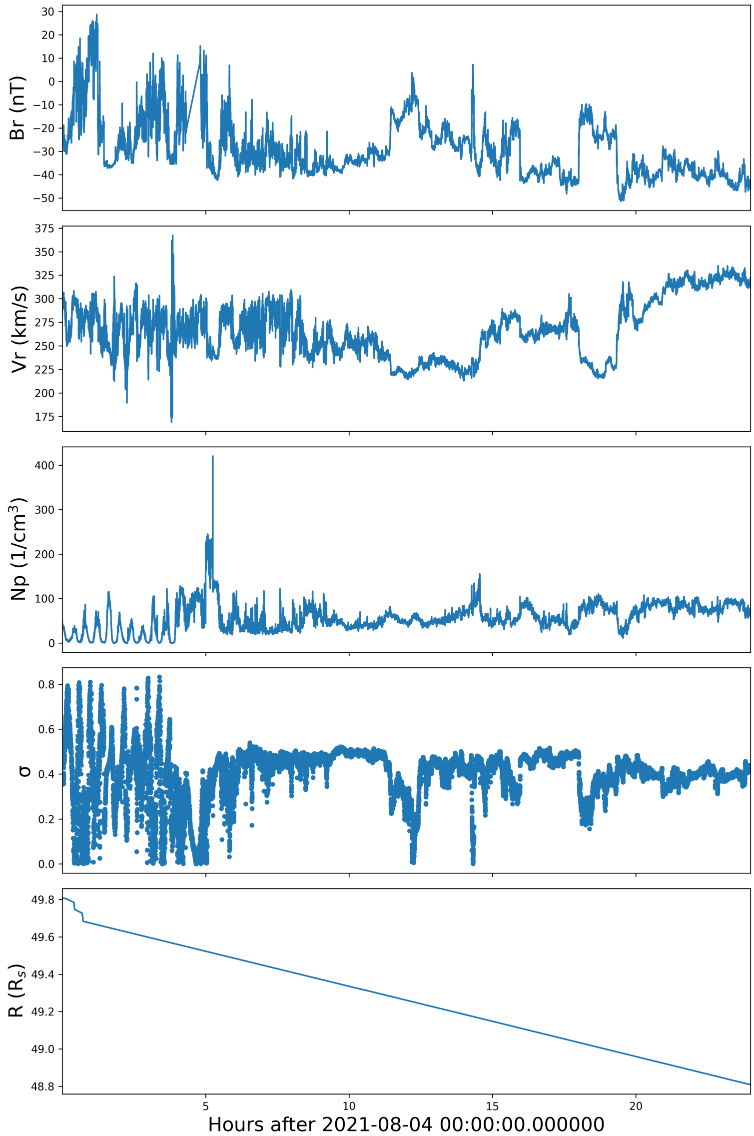

Figure 3: Switching of SPC and SCI instruments on August 4th 2021

With Alfvén Speed we are able to apply it the B- field data. To do this we take the unit vector of the B-field and then multiplying it by the Alfvén Speed. For **v**, we used the magnitude of the RTN components of velocity.

$$\mathbf{b} = v_A \frac{B}{|B|} \tag{3}$$

The resultant σ_c from Equation 1 will give us our correlation between the proton velocity of the solar wind and the B-field. For each day our team decided to take the mean value of σ_c. Figure 2 displays the Alfvénicity on 04-28-2021. Repeating this whole process over the course of the year, we are able to study the behavior of Alfvénicity throughout the orbit of PSP. Figure 4 shows the change in Alfvénicity as measured by proximity from the sun. The image displays the Alfvénicity for 158 days of the year 2021. As the value of σ_c approaches 1 we find a higher Alfvénicity and as we approach zero no Alfvénicity is present. The more aligned these two vectors are, the more Alfvénic the wind is.

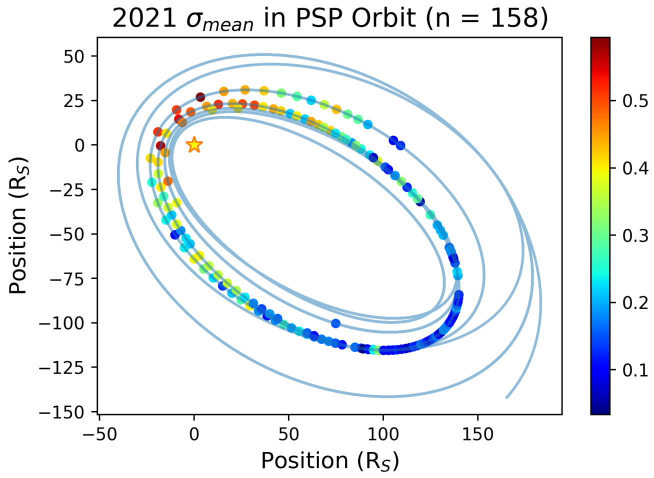

Figure 4: Shows the Alfvénicity of the solar wind in 2021 over the course of 158 days.

Observing Figure 4 we notice that Alfvénicity is most present on days where PSP reaches perihelion and least present at aphelion.

Results

As we observe at different distances and days we find that as we travel outward from the sun Alfvénicity decreases with respect to radial distance. This contradicts our hypothesis that Alfvénicity remains constant as we scale radially from the sun. Taking the σ_c value of each day and plotting it over radial distance we can again find this pattern of Alfvén drop off. This drop off can be described as linear with a curve fit. Figure 5 shows the behaviour of σ_c.

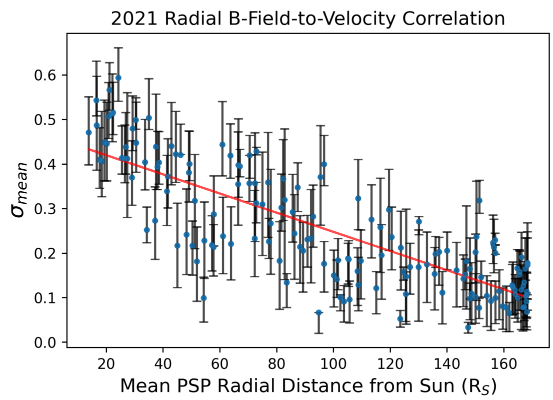

Figure 5: σ_c negative linearity over radial distance

Alvfénicity is a lightly studied subject in the field of astrophysics, specifically in solar dynamics and plasma physics. Prior research aided us in our research to learn more about the phenomenon. We first hypothesized the Alfvénicity over distance by suggesting it remained constant with respect to radial distance. With a lack of research comes a number of caveats. Invalid data, interpolation, sampling cadence, and the switching of on and off of the different SWEAP instruments. From all of this we were able to conjure a more solid result despite these caveats and contradict our previous conceptions. Alfvénicity scales with decreasing linearity as we observe radially outward from the sun.

Future Work

Further research into Alfvénicity involves mainly the expansion of work for different components and elements of the sun and its relation to the solar wind. One area of expansion could be looking at the ion temperature of the solar winds and comparing that to the Alfvénicity. this would tell us if there was a relation with the solar winds and temperature and could give us key insights into what is heating the solar winds. Another topic is comparing the other components of velocity such as tangential and normal components to see if there is any relation. Furthermore, adding to the catalogue of Alfvénicity by doing more days throughout the years over more years as Parker Solar Probe heads closer towards the sun. All of these potential future works could provide excellent data on why certain aspects of the solar winds behave the way that they do.

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