Investigating Turbulence Transport in the Heliosphere

Lauren Kahre

Follow this and additional works at: https://louis.uah.edu/honors-capstones

Recommended Citation
https://louis.uah.edu/honors-capstones/432

This Thesis is brought to you for free and open access by the Honors College at LOUIS. It has been accepted for inclusion in Honors Capstone Projects and Theses by an authorized administrator of LOUIS.
University Honors Research/Creative Project Approval Form

Submit this form with a hardcopy of your final project. The Honors Office does NOT need an electronic copy of this form.

Student Name: Lauren Kahre
Department: Physics
College: Science
Degree: Bachelors of Science
Advisor Name: Dr. Nazirah Jetha

Full title of project as it should appear in Graduation Program and on transcript:

Investigation of Turbulence Transport in the Heliosphere

Abstract (should be included at the beginning of your project as well):

- Please see attached

Approved by:
Project Advisor: (Signature) Date: 11/29/11
Department Chair: (Signature) Date: 11/29/11
Honors Program Director: (Signature) Date: 11-29-11
Investigating Turbulence Transport in the Heliosphere

Lauren Kahre$^{1,2,3}$ and Nazirah Jetha$^{1,2}$

$^1$Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35805

$^2$Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899

$^3$Honors Program, University of Alabama in Huntsville, Huntsville, AL 35899
Abstract

The heliosphere is a bubble in space created by the interaction of plasma outflow from the Sun and the interstellar medium from the galaxy. Due to the dynamic nature of the Sun (coronal mass ejections, coronal holes, solar flares, etc.), this plasma outflow is turbulent. This project will investigate bulk properties of the solar wind by analyzing plasma and magnetic data from seven different spacecraft: Helios 1 and 2, Pioneer 10 and 11, Voyager 1 and 2, and Ulysses. Each spacecraft has its own unique trajectory, making it possible to study a different portion of the heliosphere with each data set. The ultimate purpose of this investigation is to be able to better characterize turbulence in the solar wind.

All of the calculations were done in MATLAB© using original code designed specifically for these data sets. For each data set, the variance of the magnetic field and plasma flow speed will be calculated, as well as certain averages. The results will then be used to test and improve upon the model developed by Zank, et al., which describes turbulence in the heliosphere.
# Table of Contents

1. Introduction 4
   1.1. Heliosphere
   1.2. Turbulence in the Solar Wind
   1.3. Spacecraft

2. Methods 8
   2.1. Data Collection
   2.2. Calculations and MATLAB© Code

3. Results 15
   3.1. Magnetic Data 15
   3.2. Plasma Data 20
   3.3. Ulysses’ Additional Analysis 25

4. Conclusions 28

5. References 30
1. Introduction

The Sun is a dynamic system that drives a plasma outflow known as the solar wind. The solar wind is contained by the local interstellar medium (LISM), but before this occurs, a vast region of space known as the heliosphere is created. While neutral atoms from the LISM can penetrate into the heliosphere, the majority of the material within the heliosphere emanates from the Sun. As such, the heliosphere is shaped by the dynamic nature of the Sun, and is anything but homogeneous. Within the heliosphere, the solar wind moves radially outward at supersonic speeds until it reaches the termination shock of the heliosphere (at approximately 75-90 AU), where it begins to slow down due to interactions with the LISM. Beyond the termination shock is the heliosheath, a region of subsonic plasma flow within the heliosphere. The heliosheath begins at approximately 80-100 AU and has a thickness of approximately 50 AU. The theoretical boundary to the heliosheath is known as the heliopause, and is defined as the region where the solar wind is completely stopped by the interstellar medium. The heliopause marks the boundary of the heliosphere, but theories also suggest that a region of turbulence, known as the bow shock, might exist at approximately 230 AU from the Sun. Similar to the way a boat makes a wake as it moves through the water, the Sun could be creating the bow shock as it moves through the LISM. Figure 1.1 shows a diagram of the general structure of the heliosphere.
Turbulence within the heliosphere is not well understood, and the dissipation of this turbulence is thought to be the cause of many unexplained solar phenomena, such as coronal heating and the observed radial temperature profile from 1 to 80 AU (Zank et al. (2011)). Understanding cosmic ray transport through the heliosphere requires an understanding of magnetic field fluctuations, which depends on the turbulence in the solar wind (Zank et al., 2011). Related to this is the transport of solar energetic particles (such as neutrinos) in the inner heliosphere, which can drive turbulence. A model created here at CSPAR to explain the ribbon of enhanced energetic neutral atom flux seen by the IBEX spacecraft also depends on an in-depth understanding of low frequency turbulence in the outer heliosphere and local interstellar medium (Heerikhuisen et al. (2010a,b)). An understanding of turbulence within the heliosphere
can give us insight into similar systems, such as the LISM itself or in magnetized accretion disks (Zank et al. (2011)).

The model developed by Zank et al., like all similar models, assumes that the turbulence in the solar wind behaves as a incompressible magnetized fluid, and derives a series of equations using a magnetohydrodynamic (MHD) approach that characterize this turbulence and its transport. The turbulence, according to the model, dissipates as it travels through the heliosphere, as other models also indicate, but the manner of this dissipation is under some debate. The data and calculations in this paper test and improve on the accuracy of this new model by looking at the properties of the solar wind in order to map the dissipation of turbulence in the heliosphere. Specifically, we will be focusing on the turbulence of the magnetic field and plasma flow speed, average plasma flow speed, and average plasma density. All calculations and data analysis were done in MATLAB®, a platform based on C programming that focuses on performing mathematical operations.

The magnetic field in the radial and tangential directions, i.e., the directions in the plane of the ecliptic, is twisted with the rotation of the Sun, causing any turbulence in these directions to be highly distorted. Thus, we limit our investigation of the turbulence in the magnetic field to the direction normal to the plane of the ecliptic. Such a limitation is not necessary in the plasma flow speed calculation because the rotation only causes distortion in the magnetic field. However, the plasma flow speed should show a certain dependency on latitude with respect to the ecliptic, particularly during solar minima. This latitude dependence is caused by the formation of polar coronal holes, which launch regions of fast solar wind due to open magnetic field lines. High latitudes will have faster
flow speeds (approximately 700-900 km/s); low latitudes will have slower flow speeds (less than 600 km/s). During solar maximum, the polar coronal holes tend to dissipate, causing the latitudinal dependence in the solar wind speeds to vanish. This effect likely will only be seen in the Ulysses data, which reaches extremely high latitudes and is relatively close to the Sun for the entirety of its mission. However, fast solar wind speeds are also possible in the other spacecraft data, particularly during solar maximum, when coronal holes can occur anywhere on the Sun, causing fast and slow streams to be intermixed.

In this research project, we analyze the data obtained by in-situ measurements from the Pioneer, Voyager, Helios and Ulysses missions. Each spacecraft has its own unique trajectory, and can therefore allow us to study turbulence of the solar wind in different regions of the heliosphere. The Pioneer and Voyager spacecraft are traveling on escape trajectories out of the solar system, while the Helios and Ulysses spacecraft orbited the Sun for the duration of their missions. While Pioneer 11 and the two Voyager spacecraft are traveling towards the nose of the bow shock, Pioneer 10 is traveling in the opposite direction, towards the tail of the heliosphere. The Voyager spacecraft also have their differences, with Voyager 1 currently traveling above the ecliptic and Voyager 2 below it. Both Voyager spacecraft traveled near the ecliptic until the encounter with Titan in the Saturn system bent the trajectory of Voyager 1 upwards (with respect to the ecliptic), and the encounter with Neptune bent Voyager 2’s trajectory downwards (with respect to the ecliptic). The two Helios spacecraft have similar orbits to each other, covering the region of the heliosphere from Earth to just inside the orbit of Mercury (0.29-1 AU), but Helios 1 was able to transmit usable data for several years longer than
Helios 2. Ulysses’ orbit, after the encounter with Jupiter, bent as planned, to angles of approximately 80 degrees from the ecliptic, at radii that ranged from approximately 1 to 5 AU. Figure 1.1 shows the trajectories of the two Voyager, the two Helios, and the Ulysses spacecraft.

![Figure 1.1: Mission profiles for the Voyager, Helios, and Ulysses spacecraft.](image)

In addition to the data collected by these seven spacecraft, we also took data that was collected by several spacecraft that orbited the Sun at L1, Lagrange point 1, which is approximately at 1 AU. This data was compiled by NASA into the Omnitape database, and is a record of solar wind conditions at 1 AU that spans from the mid 1960s to the present data. We use this data to normalize some of our calculations from the spacecraft data.

2. Methods

All data used in the analysis was obtained via NASA’s COHOWeb service, which supplies data for all missions studying the solar wind. A summary of each spacecraft’s mission information, including start and end dates for our analysis and trajectory...
information, is listed in Table 2.1 below. Also included in Table 2.1 is the information for the omnitape data, also obtained from COHOWeb. Each data set also has intermittent gaps within these date ranges caused by instrument failure or interference from various sources, particularly planetary sources (specifically Jupiter and Saturn).

Table 2.1: Summary of spacecraft time frames and trajectory information. Start and end dates mark the beginning and end of our analysis, though there may be gaps in data collection due to instrument failure or interference. Dates are in MM/DD/YYYY format. Note: Voyager 1’s magnetic data actually continues past this end date. The plasma instrument was damaged during the encounter with the Saturn system, making any calculations involving the plasma data impossible beyond that point. The omnitape data was obtained from various spacecraft, all of which orbited or are currently orbiting the Sun at L1. Most information courtesy of Wimmer-Schweingruber, et al. (2009), other information obtained from the 2004 Exploration report and COHOWeb.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Start Date</th>
<th>End Date</th>
<th>Trajectory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer 10</td>
<td>03/04/1972</td>
<td>11/15/1975</td>
<td>Escape towards heliotail in ecliptic</td>
</tr>
<tr>
<td>Pioneer 11</td>
<td>04/09/1973</td>
<td>05/30/1985</td>
<td>Escape towards bow shock in ecliptic</td>
</tr>
<tr>
<td>Voyager 1</td>
<td>09/15/1977</td>
<td>11/18/1980</td>
<td>Escape towards bow shock, initially in ecliptic, now above</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>08/31/1977</td>
<td>06/19/2004</td>
<td>Escape towards bow shock, initially in ecliptic, now below</td>
</tr>
<tr>
<td>Helios 1</td>
<td>12/14/1974</td>
<td>12/27/1980</td>
<td>Low-latitude orbit around Sun, 0.29-1 AU</td>
</tr>
<tr>
<td>Helios 2</td>
<td>01/17/1976</td>
<td>12/26/1979</td>
<td>Low-latitude orbit around Sun, 0.29-1 AU</td>
</tr>
<tr>
<td>Ulysses</td>
<td>11/22/1990</td>
<td>06/30/2009</td>
<td>High-latitude orbit around Sun, 1-5 AU</td>
</tr>
</tbody>
</table>

All data obtained from COHOWeb were hourly averages of the data obtained directly from the instruments, with some filtering to account for interference and computer errors. The COHOWeb team did this filtering before making the data widely available. Each data set was then run through individual MATLAB scripts for analysis. Both the Pioneer and Voyager sets were able to use the same algorithm for their analysis. The two Helios spacecraft required a minor modification to the algorithm to account for the extreme differences in fast and slow solar wind streams that close to the
Sun. Ulysses’ scripts are again a special case, this time accounting for the change in latitude of its orbit. The Omnitape data uses a script similar to the Voyager and Pioneer magnetic field script, as it did not require the fine detail that the Helios spacecraft demanded, and was only used for the normalization calculations, which were used to confirm that our trends were an actual property of the plasma and not a byproduct of our analysis. Each spacecraft has at least two different scripts, one for the magnetic calculations, and another for the plasma and energy calculations. Note that all calculations were done in CGS\textsuperscript{1}, not SI units, though the final plots may be in other units.

The first step in the analysis was to run the Omnitape data through its calculations. The script began with an algorithm designed to filter out shocks caused by CMEs. It essentially searched for a discontinuity in the plasma and magnetic data that marks a shock and removed it from the data. For each point, it calculated:

\[ T_{\text{ratio}} = \frac{T_1}{T_2} \] (1),
\[ u_{\text{ratio}} = \frac{u_1}{u_2} \] (2), and
\[ \rho_{\text{ratio}} = \frac{\rho_1}{\rho_2} \] (3),

where T is the temperature, u is the flow speed, and \( \rho \) is the plasma density. \( T_1, u_1, \) and \( \rho_1 \) each correspond to the parameters at a given point, while \( T_2, u_2, \) and \( \rho_2 \) correspond to the parameters at the next point. If \( T_{\text{ratio}} \geq 1.1, u_{\text{ratio}} \geq 1.045, \) and \( \rho_{\text{ratio}} \geq 1.1, \) the point was marked as a shock and removed from the data. For each usable data point, we calculated a running average over 10-hour segments, or bins. For each point, we took

\textsuperscript{1} CGS units are Gauss for magnetic field, cm/s for velocity, and g/cm\textsuperscript{3} for plasma density. The original data was in SI units, i.e., nT for magnetic field, km/s for velocity, and number of protons/cm\textsuperscript{3} for plasma density.
the difference of the average and the magnetic field value at that point and squared it to get the turbulence. Also included in this MATLAB script was a bi-monthly average of the variance, which was then analyzed for time dependence, along with the time dependence of the variance. This average and the two plots are intended as a check for physical reality and that the data matches observations at 1 AU.

After analyzing the Omnitape data, we analyzed the Voyager and Pioneer data sets. For the magnetic calculations, we again started by running the shock-finding algorithm, and then calculating running averages for each point over 10 hours, then using that running average to calculate the turbulence. These calculations depend on the assumption

$$B = <B> + b$$

where \(B\) is the total magnetic field in a given direction, \(<B>\) is the time averaged magnetic field, and \(b\) is the turbulent field. The timestamp, which was in year, day of year, and hour format initially, was converted to an hour timestamp for the purposes of normalization. Each script then began the normalization calculation by comparing the plasma data to match a flow speed to the turbulence in \(b_n\) for each point, where \(b_n\) is the magnetic field normal to the plane of the ecliptic. Once the data was matched, the time it took that plasma packet to travel from 1 AU to its median radius was calculated. We assumed no acceleration for a packet, so the time was simply the distance traveled (its median radius minus 1 AU) divided by the flow speed. For our data, this resulted in a time scale in seconds. This time scale was converted to hours, and then subtracted from the time (in hours) for each point, so that we had the time each point was at 1 AU. This time was then compared to the Omnitape data to match the Omnitape magnetic
variance to the spacecraft magnetic variance. Once matched, the normalized magnetic
turbulence was defined by the ratio of the spacecraft’s magnetic turbulence to the
Omnitape magnetic turbulence when the plasma packet was at 1 AU. Finally, both
scripts plotted both the turbulence in $b_n$ and the normalized turbulence in $b_n$ with an $R^{-3}$
line to show the expected trend as predicted by the earlier non-MHD model. Once these
plots are created, the scripts then calculated a radial average for the normalized
variance in $b_n$. All radial bin sizes in this calculation were 0.5 AU. These averages were
then plotted against radius.

We then calculated the plasma quantities for both the Pioneer and Voyager
spacecraft. This script performed a running average over 10 hours, this time calculating
the average flow speed, temperature, and density for each point, as well as the
magnitude of the turbulence in flow speed for each point. The turbulence calculation
included a similar assumption to equation 4, replacing the magnetic field values with
flow speed values. Using a similar calculation to the magnetic variance normalization,
the normalized density was found for each point, and the values calculated were
analyzed for radial dependence. As a check, the plasma flux (flow speed times density)
and pressure (temperature times density) were also calculated and analyzed for radial
dependence. The density and normalized density plots included $R^{-2}$ and $R^{-3}$ lines to
highlight any trends. We would expect the density plots to follow a $R^{-2}$ trend based on
an adiabatic thermodynamic profile. After these plots, the script executed another radial
average similar to the one in the magnetic variance scripts with all the values calculated
above. These averages were also analyzed for radial dependence.
The Helios scripts used all the same calculations as the Pioneer and Voyager scripts, with the exception that before the magnetic data was checked for shocks, it was split into fast and slow stream solar wind. For our calculations, we defined fast solar wind as streams with a flow speed greater than 500 km/s. After the division into fast and slow streams in the magnetic data script, the Helios scripts ran the exactly the same way as the Voyager and Pioneer scripts. However, due to the much smaller radii of the Helios data, the bin size for the radial average is reduced to 0.01 AU in the magnetic script and 0.05 in the plasma script. This radial average gives us a general idea of what the heliosphere is doing at a given radius over several years, not a snapshot of a month or so.

The Ulysses data set was again more complicated than the Helios data set, due to the wide range of latitudes and the oscillating radii caused by its orbit. Therefore, we performed an additional time average before the radial average, as well as a split into high and low latitudes. Due to Ulysses’ trajectory, this not only ensured data would be averaged over similar latitudes, but over the same orbit as well. The division again occurs before the 10-hour binning, at which point the script followed a dual path, one making the calculations for the high (greater than 20 degrees) latitudes, the other making the calculations for the low latitudes. These two paths converged when it came to plotting the data, where both sets were on the same plot, but in different colors. Radial averages for the Ulysses data were calculated in bin sizes of 0.1 AU, since the radii are larger than those of the Helios data and much smaller than those of the Pioneer and Voyager data.
Once we reduced the Ulysses data, we noticed some discrepancies (which will be discussed later in Section 3.2) and performed a more in-depth analysis, this time splitting the data into the three solar cycles that Ulysses covered. This splitting did not perform any magnetic calculations, it merely took the plasma flow speed and density averages found in the previous calculations and plotted them against radius and time, with respect to the solar cycle that it corresponded to. After these plots, it performed a latitudinal average for each solar cycle’s data, with bin sizes of 2 degrees. The data is then plotted against latitude, then time, after which we split solar cycle 23, the only full solar cycle in the Ulysses data and the one that showed the most discrepancies. This split was only performed on the 10-hour averaged flow speed, which was placed into bins depending on latitude. Each bin was 10 degrees in size, i.e., one bin contained latitudes between 0 and 10, the next contained 10 to 20, and so on, up to 90 degrees. No distinction was made between latitudes above or below the ecliptic. After plotting the data against time, with colors distinguishing the latitude for each data point, the script then performed another average, this time over approximately 3 weeks. After performing the average, the data was then plotted against time with respect to its latitude, so that we could check for time and latitude dependence simultaneously.

Again, there were some discrepancies in the Ulysses data, this time narrowed down to solar cycle 23 (this will be discussed in more detail later). We then attempted to match these discrepancies with any shocks associated with coronal mass ejections (CMEs) during this time frame. This involved creating a file with the position and velocity data from 18 shocks measured by Gopalswamy et al. (2009), then comparing that position and velocity data with Ulysses’ trajectory and plasma data and looking for any
significant effects from a particular shock. To this end, we wrote another script that loaded the CME data file, then performed a calculation using its position and velocity data to calculate (assuming constant velocity) when it would cross Ulysses’ path, based on Ulysses’ position at the time the shock began. Using this time, we examined the plasma flow speed data from Ulysses and looked for increased values. The results from this analysis are discussed in the next section.

3. Results

3.1. Magnetic Data

The Omnitape data, which was used in all the following calculations, generally behaved as expected, particularly when it came to oscillations in the bi-monthly average plot, as seen in Figure 3.1 below. As seen in the figure, both the variance in $b_n$ and the variance of the total $b$ oscillate with time, with the variance of the total $b$ being somewhat lower, as expected. The variance tends to peak when the Sun is near solar maximum, which is also expected.
According to a basic model, we would expect the magnetic variance to decrease as a function of $R^{-3}$, which is what we observe in all the data sets, with some error. Smaller variances do occur, which are discussed below, but in general, all data holds to this inverse radius cubed trend remarkably well.

The Pioneer data sets are an example of this, but there are differences from the trend in both, as seen in Figure 3.2 below. Pioneer 10 shows considerable variation from the trend, mainly in the spread of the data. This could be caused by shocks that were not removed by the shock finding algorithm. Pioneer 11 follows the trend better, but shows a marked increase near Saturn, then decreases down to expected levels. This increase can likely be attributed to Saturn’s magnetosphere. Pioneer 11 also shows a considerable spread around the trend line, but this spread is far less than that of Pioneer 10.

Figure 3.2: A side-by-side comparison of the average variance in $b_n$ plots for both Pioneer 10 (left) and Pioneer 11 (right). Radial average variances are plotted in blue with error bars corresponding to the standard deviation for each radial bin. The trend line corresponding to a $R^{-3}$ dependency is plotted in red. The y-axis on each plot is on a log scale and corresponds to the variance in $b_n$, with the heliocentric distance on the x-axis on a linear scale. Gaps near 4-5 AU correspond to bad data caused by interference from the Jovian magnetosphere.
The Voyager data is again close to the expected trend of $R^3$, with the Voyager 1 data being incredibly close to the trend except for two locations, as seen in Figure 3.3. As stated earlier, the Voyager 1 magnetic data continues far past the plasma data, reaching approximately 120 AU. For the entire set of data, there are only two real variations from the expected trend, one at 40 AU and another after the spacecraft passes 80 AU. This second increase is most likely due to Voyager 1’s crossing of the termination shock; plasma flow speeds sharply decrease at this point, and since the plasma is ionized, this causes an increase in magnetic flux, and thus, the variance in $b_n$. The first, like certain variations in the Pioneer data, offers no readily available explanation. This distance does correspond to the Kuiper Belt, but given the low population density of the region, the fact that Voyager 1 was at approximately 30 degrees inclination with respect to the ecliptic during this time, and that most objects within the belt are composed of ices, an interaction that would cause interference in the magnetic data is extremely unlikely. However, it is possible that latitude transitions made by Voyager 1 at this time could be responsible. Voyager 2 is also relatively close to the expected trend, but with more variation than is found in the Voyager 1 data, particularly around 20 AU. The increase in variance around 20 AU is likely due to Voyager 2’s encounter with the Uranus system.
As mentioned earlier, the nature of the Helios data required a split into fast and slow streams, and then separate radial averages for both sets. These averages resulted in data that somewhat matched the $R^{-3}$ trend line, as seen in Figure 3.4. However, the spread in the data is fairly wide, unlike most of the variations in the Pioneer and Voyager data, so we cannot say with certainty that it does follow the expected $R^{-3}$ trend. Transient effects from solar activity could explain these variations in the Helios data. The averages for the Helios data were performed over a far shorter time frame than those for the Pioneer or Voyager data sets, and the effects would be far more intense at the radii involved in the Helios data than at those from the Pioneer or Voyager data. While the Helios data is roughly centered over the minimum between solar cycles 20 and 21, with data for both spacecraft beginning in the declining phase of cycle 20 and ending near the maximum of cycle 21, it is possible these variances from the trend occurred near the end of the data because of increasing solar activity. It is also possible that one or more of the orbits by the Helios spacecraft encountered Mercury’s magnetosphere, causing some small interference; however, since the spread of the
data is over the entire span, it is unlikely that Mercury could have caused all of the interference.

![Figure 3.4: Radial average normalized variance in $b_n$ for Helios 1 (left) and Helios 2 (right). Blue crosses indicate data points, and the red dotted line is the $R^{-3}$ trend line. The error bars indicate standard deviation for each radial bin. The y-axis is on a log scale and indicates average variance in $b_n$, while the x-axis is on a linear scale and indicates heliocentric distance in AU.](image)

Ulysses, as stated above in the methods section, also required some special treatment for averages. Not only did it require the same multiple averages that the two Helios data sets required, the Ulysses data set also had to be split according to the latitude of the spacecraft at the time the measurement was taken. That being said, the data again held close to the $R^{-3}$ trend line, with some variances, as seen in Figure 3.5. Like the variances in the Helios data, transient events could explain the variances closer to the Sun, but the multiple variances closer to 5 AU are more easily explained by Ulysses’ encounter with Jupiter as it performed a slingshot maneuver to enter its polar orbit around the Sun. Ulysses’ mission took place over multiple solar cycles, with data beginning close to the maximum of cycle 22 and ending with the extended minimum between cycles 23 and 24, so transient events due to solar activity causing the variances closer to the Sun is entirely possible, as Ulysses’ mission encompassed two
solar maximums. Ulysses will be discussed in more detail later, as problems with the plasma flow speeds indicated the data required a closer look.

Figure 3.5: Radial average normalized variance in $b_n$ for Ulysses. Red and blue crosses indicate data points, with error bars indicating standard deviation in each radial bin. Red indicates low latitudes (less than or equal to 20 degrees) with respect to the ecliptic, while blue indicates high latitudes (greater than 20 degrees). The green line indicates the $R^{-3}$ trend.

3.2. Plasma Data

The plasma data examined for all the spacecraft included a number of values: flow speed, density, temperature, pressure, flux, and variance in flow speed. This investigation focused on the density and flow speed parameters, while the other plasma values were used as checks to ensure the MATLAB script was handling the data properly. In general, the density was expected to follow a $R^{-2}$ trend while the flow speed fluctuated with no radial dependency. This is what was observed, with some variance, particularly with the Voyager data. The Ulysses data in particular showed odd variations, which forced a more in-depth analysis (also discussed in Section 3.3).
The Pioneer data held to the expected trends fairly well. Both the plasma flow speed and density plots for both Pioneer spacecraft can be seen in Figure 3.6. For both spacecraft, the gaps in data can be clearly seen; for Pioneer 11 particularly well near Jupiter and Saturn, but both appear to follow the expected inverse radius-squared trend for the plasma density. The flow speed also fluctuates with no radial dependence between approximately 300-700 km/s, which are typical values for the fast and slow solar wind. This indicates that we are sampling multiple solar wind streams.

The two Voyager data sets also follow our expected trends well. Voyager 1 appears to have some spread, but Voyager 2 follows the trend with little to no variance.
The flow speeds for both plots also seem to behave as expected, with both plots varying between expected values for the solar wind with no apparent radial dependence.

Figure 3.7: Average plasma density (top) and flow speed (bottom) plots for Voyager 1 (left) and Voyager 2 (right). Blue marks data points, with error bars on the density plots marking standard deviation in each radial bin. The red dotted lines on the density plots indicate the $R^{-2}$ trend line, while the green lines indicate the $R^{-3}$ trend line. The density plots have a y-axis on a log scale that corresponds to the average plasma density in number per cm$^3$ while the flow speed plots have a regular scale that corresponds to the average flow speed in km/s. The x-axis on all plots is on a regular scale and shows heliocentric distance in AU.

The Helios data, as stated above, was split into fast and slow streams before running any averages or calculations. These data sets show little to no variation from the expected $R^{-2}$ trend. The small increase around 0.6 AU in the Helios 1 plot could be explained by a shock that was not detected by the shock finding algorithm, while the decrease soon after that could be explained by the faster flow speeds indicated on the corresponding flow speed plot. Helios 2, meanwhile, shows some fluctuation
throughout, but remains close to the trend line. Again, flow speeds fluctuate with no apparent radial trend, again showing that we are sampling multiple solar streams. Our variances from the trend could also be caused by either Helios spacecraft crossing from fast to slow streams, or vice-versa.

![Plasma Density and Flow Speed Plots](image)

**Figure 3.8:** Average normalized plasma density (top) and flow speed (bottom) plots for Helios 1 (left) and Helios 2 (right). Blue crosses indicate data points, while the red and green lines on the two density plots indicate the $R^2$ and $R^3$ trends, respectively. Error bars in the density plots indicate the standard deviation for each radial bin. Y axes for the density plots are on a log scale and indicate average normalized plasma density while the y axes for the flow speed plots are on a regular scale and indicate flow speed in km/s. X axes on all four plots indicate heliocentric distance in AU.

The Ulysses data was split further than the Helios data, not just into years, but also into high and low latitudes. However, while most of the data seemed to follow expected trends, there was a definitive split in the data, as seen in Figure 3.9. This split, however, seems to be limited to the high latitude data in both the density and flow
speed plots. For the density, most of the data (including some at high latitudes) seems to follow the expected $R^{-2}$ trend. The split into lower densities that occurs at the high latitudes, however, is consistent with our expectations when you consider that regions outside the ecliptic may not follow the $R^{-2}$ trend. For the flow speed, most of the data does oscillate with no apparent radial dependence, but there is an upper section with flow speeds that are consistent with the fast solar wind, and most of the other data does not show any averages with flow speeds this high. However, because these speeds seem to occur only at high latitudes within Ulysses’ data, they are easily attributable to high-latitude coronal holes. Taking the data from the flow speed plot, the low density split at high latitudes is even more easily explained, as high flow speeds result in lower densities. However, the timescale of Ulysses’ is over multiple solar cycles (22, 23, and 24), including two maxima, during which the high latitude coronal holes should have dissipated. Therefore, Ulysses’ data was examined in greater detail, as is described in Section 3.3.

**Figure 3.9:** Average normalized plasma density (left) and average flow speed (right) plots for Ulysses. The magenta crosses on the density plot and the blue crosses on the flow speed plot correspond to low latitude (less than or equal to 20 degrees) data, while the blue crosses on the density plot and the red crosses on the flow speed plot correspond to high latitude (greater than 20 degrees) data. The red and green lines on the density plot correspond to the $R^{-2}$ and $R^{-3}$ trends, respectively. Error bars on the density plot indicate the standard deviation for each radial bin. The y-axis for the density plot is on a log scale and displays the average normalized density, while the y-axis on the flow speed plot is on a linear scale and displays average flow speed in km/s. Both x axes display heliocentric distance in AU.
3.3. Ulysses’ Additional Analysis

Since the Ulysses data showed significant variation, particularly the seemingly characteristic split that apparently cannot be explained solely by low and high latitudes, it was split yet again into three different solar cycles. Ulysses started with solar cycle 22, which (according to the solen.info site maintained by Alvestad) continued until May 1996, when cycle 23 began. Cycle 23 peaked in April 2000 and continued into the extended minimum until cycle 24 began in December 2008. As seen in the plots of Figure 3.13, during solar cycle 22, there is a generally well-behaved trend for higher flow speeds at higher latitudes, but for solar cycle 23, the data seems to be trending both towards high and low flow speeds with higher latitudes. There is some minor deviation during cycle 22 around 10 to 30 degrees, but it is possible at these latitudes that solar activity created this deviation. Stream shear between fast and slow streams is also possible. After 30 degrees, the trend becomes obvious, which is not the case for cycle 23. There is not sufficient data to draw a good conclusion for solar cycle 24, but the initial trend appears to follow that of cycle 22, and did not show any particular splits. Therefore, the investigation from this point forward focused on solar cycle 23.
Figure 3.13: Plots of plasma flow speed against latitude. The top plot shows solar cycle 22, the middle solar cycle 23, and the bottom cycle 24. All three x-axes show latitude in degrees from the ecliptic, while the y-axes all show flow speeds in km/s. No distinction is made between degrees above and below the ecliptic.

Figure 3.14 shows the plasma flow speed plotted against time, with each color corresponding to a different 30-degree range in latitude. There are two main areas of concern: one peak in flow speeds around 2001-2002, and another range of fluctuations around 2003-2004. The two peaks at the beginning and end of solar cycle 23 are expected, as both peaks coincide with solar minimum and values are consistent with those expected of the polar coronal holes that form during solar minimum.

The 2001 peak nearly coincides with solar maximum, meaning solar wind speeds should not nearly be as high as they are shown to be. While Ulysses is at high latitudes at this time, the Sun’s coronal holes usually dissipate during solar maximum (Webb, 1984), meaning the trend towards faster flow speeds at high latitudes shouldn’t be very
pronounced (if it exists at all). This lack of high flow speeds at high latitudes is
evidenced earlier (late 2000, early 2001) by consistently slower flow speeds from the
time that Ulysses entered lower latitudes until it passed over one of the poles. However,
according to the paper by Miralles et al. (2002), in the summer of 2001, a large high-
latitude coronal hole was detected by the Solar and Heliospheric Observatory (SOHO),
despite the fact that the Sun was still close to maximum. The paper also states that
Ulysses detected fast solar wind in July 2001, confirming both the presence of a polar
coronal hole at the time and the peak in our data now.

The peaks and fluctuations in 2003 offer no immediate explanation, as Ulysses
was at low latitudes and the Sun was in the declining phase of cycle 23 at the time.
However, in late 2003, Earth was impacted by what became known as the “Halloween
Storm,” a series of 17 major solar flares and CME eruptions that occurred from late
October into early November. According to COHOWeb trajectory data, Ulysses was on
the opposite side of the Sun as seen from Earth when this storm occurred. However,
according to the official NOAA report, the storm only ended on Earth because the active
region producing the flares rotated away from Earth. The report further states that the
active region continued to produce flares as it rotated out of Earth’s view. Taking this
new information into account, it is possible that those active regions produced the
fluctuations we see in the data, despite the fact that the Sun was approaching solar
minimum. The timing of both the storm and the fluctuations in the Ulysses data seems
to support this conclusion, as the fluctuations begin around the time the storm on Earth
ended.
Figure 3.14: Plot of average plasma flow speed against time for solar cycle 23. Different shapes and colors correspond to different latitudinal bins, where each bin is 10 degrees in size. Blue corresponds to low latitudes (less than 30 degrees), green to mid-latitudes (greater than or equal to 30 degrees and less than 60 degrees), and red to high latitudes (greater than or equal to 60 degrees). Within each color, there are three shapes, where '+' corresponds to the lowest 10-degree bin in that color range, '*' to the middle bin, and 'x' to the highest bin. For example, a blue '*' corresponds to a measurement taken within 10-20 degrees latitude, while a red 'x' corresponds to a measurement taken within 80-90 degrees. Areas of concern are circled.

In addition to this analysis, we examined the 18 shocks found in Gopalswamy, et al., using the methods described in Section 2. After performing this analysis, there was no evidence that any of the shocks affected the Ulysses data significantly. This seems to contradict our earlier assumption that the Halloween Storm caused the peak in flow speeds in late 2003 and early 2004, but it is possible that a single shock event could not cause a significant variation in the data like that the Halloween Storm called. Also, our analysis did not take into account the latitude at which these shocks originated. Even shocks that occurred on the same side of the Sun could have originated at significantly different latitudes than Ulysses’ position, causing it to miss detection of faster flow speeds caused by the shock. These shocks would therefore cause no concern to the integrity of our analysis, as Ulysses’ measurements would be unaffected.

4. Conclusions

Our analysis of observations made by the Pioneer 10 and 11, Voyager 1 and 2, Helios 1 and 2, and Ulysses spacecraft are consistent with previous models for
turbulence dissipation that were built on by Zank et al. (2011). For the variance in the magnetic field normal to the plane of the ecliptic, there is a clear $R^3$ relationship for all seven spacecraft, as is described in Zank et al. (1996). The plasma density values also appear to match the expected adiabatic expansion ($R^2$) relationship.

The Ulysses spacecraft’s orbit presented a unique problem when it came to reducing the data because of its large shift in latitude and the different plasma environments outside of the ecliptic. There was also a major split in the data that required a closer inspection, which showed evidence of the unusual solar features during the 23rd solar cycle, in particular the polar coronal hole that appeared around solar maximum and the intense geomagnetic storm during the declining phase of this cycle. However, while these large-scale events cause significant shifts in the data that are easy to spot, single events such as CMEs either do not affect the data or their effects are extremely difficult to predict. We were unable to find any evidence that the 18 CMEs that we examined affected the Ulysses data significantly with our analysis. Our analysis for all spacecraft did include a shock finding algorithm, but this used a general method for finding discontinuities in the data, not the shocks themselves. It is possible, however, that a more in-depth analysis that takes both latitude and plasma acceleration into account may be able to locate events such as these within the Ulysses plasma flow speed data.
5. References


