Response of the PUI Distribution To Variable Solar Wind Conditions

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Response of the Pickup Ion Distribution to Variable Solar Wind Conditions

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THESIS

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Abstract

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Jonathan Bower

University of New Hampshire, May, 2018

We present the first systematic analysis to determine pickup ion (PUI) cutoff speed variations, during general compression regions identified by their structure, shock fronts, and times of highly variable solar wind (SW) speed or magnetic field strength. This study is motivated by the attempt to remove or correct for these effects on the determination of the longitude of the interstellar neutral gas flow from the flow pattern related variation of the PUI cutoff with ecliptic longitude. At the same time, this study sheds light on the physical mechanisms that lead to energy transfer between the SW and the embedded PUI population. Using 2007-2014 STEREO A PLASTIC observations we identify compression regions and shocks in the solar wind and analyze the PUI velocity distribution function (VDF). We developed a routine to identify stream interaction regions and CIRs, by locating the stream interface and the successive velocity increase in the solar wind speed and density. Characterizing these individual compression events and combining them in a superposed epoch analysis allows us to analyze the PUI population under similar conditions and find the local cutoff shift with adequate statistics. The result of this method yields substantial cutoff shifts in compression regions with large solar wind speed gradients. Additionally, through sorting the entire set of PUI VDFs at high time resolution, we obtain a noticeable correlation of the cutoff shift with gradients in the SW speed and interplanetary magnetic field strength. We discuss implications for the understanding of the PUI VDF evolution and the PUI cutoff analysis of the interstellar neutral gas flow.
1 Introduction

Pickup Ions are created when neutrals moving through a magnetized plasma are ionized through photo-ionization, electron impact or charge exchange [Schwadron, 1998]. Once ionized, they experience a Lorentz force and undergo cyclotron motion, with a guiding center moving with the plasma. In the plasma’s reference frame the ions gyrate around the magnetic field lines, and depending on the direction of their initial velocity, they will move freely along the magnetic field as well.

In the Heliosphere, pickup ions (PUI) are generated from several different interplanetary and interstellar neutral sources which are ionized by the Sun’s radiation or interaction with the solar wind, and are picked up by the frozen-in interplanetary magnetic field (IMF). Once implanted in the solar wind the newly ionized particles are convected radially outward, typically occupying a velocity range from 0 km/s to twice the solar wind speed, associated with the ion’s cyclotron motion. Immediately after injection, the velocity distribution of the PUI population is highly anisotropic and forms a torus in velocity space [Kallenbach et al., 2000]. The population undergoes cooling processes (SW expansion and decreases in the IMF field strength) and achieves isotropy through scattering (pitch angle scattering and turbulence) [Kallenbach et al., 2000].

Interstellar pickup ions are particularly important in space science as they can serve as probes to study the composition and properties of the interstellar medium [Moebius et al., 1985]. The interstellar medium (ISM) is the diffuse gas, plasma and dust that exists between the stars and solar systems of our galaxy. This medium is of great interest in astrophysics, as it plays a crucial role in the formation of celestial bodies, and in our neighborhood, controls the size and shape of the heliosphere [Fichtner et al., 2006]. Issues arise in measuring the ISM due to its interaction with the magnetic field embedded in the solar wind. As the solar wind convects outward it slows, due to interaction with the LISM, until a distance of about 120 AU, where the SW and the ISM’s pressures balance. This interaction carves out the region known as the heliosphere, seen in Figure 1. As the solar wind convects out radially from the Sun, it stays magnetically connected to its source position and as the Sun rotates, this magnetic field becomes wound into the Parker spiral [Axford and Suess, 1994]. This radial expansion causes the solar wind density to decrease and become supersonic, where it continues to travel at supersonic speed throughout the solar system. Eventually, while the wind continues to expand, its ram pressure decreases, causing it to slow and become subsonic, forming the standing termination shock [Frazier and Garner, 2017]. Now that the SW is subsonic, information
about the SW interaction with the ISM is continuously translated through the medium, forming the Heliosheath, a region where the wind is slowed, compressed and turbulent [Axford and Suess, 1994]. As the solar wind slows and continues to expand, it eventually pressure balances with the interstellar medium and the flow is halted. This boundary is known as the Heliopause, beyond which lies the interstellar medium.

Scientists believe this boundary was measured directly by Voyager 1 in May of 2012 when it detected a rapid increase in the galactic cosmic ray flux, in conjunction with a decrease in the anomalous cosmic ray flux [Kallenbach et al., 2000]. Essentially, because of this interaction, charged particle populations are unable to penetrate far enough into the heliosphere to be measurable at 1AU. The consequence being that we must rely on direct observation of the neutral gas which penetrates almost unimpeded into the heliosphere. We diagnose the neutral gas in the inner heliosphere through solar UV backscattering, PUI measurement and direct neutral imaging [Moebius et al., 2004].

Interstellar PUIs accumulate in the SW out to the termination shock and increase in abundance relative to the SW density linearly with distance. Close to the Sun, the interstellar neutral population is reduced in density due to photo-ionization and charge exchange with the solar wind, depleting the interstellar neutral population [Kallenbach et al., 2000]. H, O and N have a large reduction in density compared to their native
abundance, while He and Ne survive much more readily due to their high ionization potential [Kallenbach et al., 2000]. At Earth’s orbit, He has the highest density of all the neutrals, making it the easiest to observe. The first observations of interstellar pickup ions were in fact He, measured by the SULEICA instrument on the AMPTE spacecraft [Moebius et al., 1985].

Because the solar wind plasma is largely collisionless, once injected, PUIs are only acted on by fluctuations in the local magnetic fields. These fluctuations can scatter the PUI populations and cause energy diffusion, leading to transport effects, such as pitch angle scattering, cooling and acceleration. Additionally, the expansion of the solar wind will result in a decreased magnetic field strength thus cooling the PUIs further [Saul et al., 2004]. If we can understand these transport effects and describe them accordingly we can build the PUI velocity distribution function (VDF) such that we can determine the underlying parameters of the PUI source population. The determination of physical parameters of the ISM has been one of the important scientific goals of several satellite missions in recent years, and is of continued interest to the scientific community.

The Interstellar Boundary EXplorer (IBEX) was launched on October 19, 2008 with the primary goal of probing the boundaries of the Heliosphere and to investigate the interaction between the solar wind and the ISM. IBEX is equipped with the IBEX-hi and IBEX-lo energetic neutral imagers that allow for all sky imaging of neutral atoms over a wide energy range (0.01 to 2 keV for IBEX-lo, 0.38 to 6 keV for IBEX-hi) [Fuselier et al., 2009], [O. Funsten et al., 2009]. IBEX measures the interstellar neutral flow distribution as a function of ecliptic longitude, resulting in a maximum neutral flux associated with the neutral flow perihelion. This bulk flow location thus provides a functional relationship between the neutral velocity and inflow direction. The hyperbolic trajectory equation describes the neutrals as they accelerate into the Sun’s gravitational well, but in order to determine their flow direction, one would need to know their flow speed and vice versa. This relationship extends to other measurements as IBEX observations yield approximately degenerate ISM parameters, meaning that measurements of the interstellar flow longitude, latitude, speed and temperature are tightly coupled, and their corresponding uncertainties result in a large 4 dimensional parameter tube [Schwadron et al., 2015]. Figure 2 shows two examples of this coupling, where the parameter relation between the flow longitude and velocity is seen on the left, and the coupled ISN temperature and inflow longitude is seen on the right. Complementary measurements, taken aboard IBEX, can refine the measurement error of any one parameter, but the error range is still large.
Independent determinations of individual parameters can be used to break the degeneracy and drastically increase the accuracy of all coupled parameters. Here we will discuss how He+ PUI measurements taken aboard the STEREO A satellite, can be used to determine the inflow longitude of the ISM to a great degree of accuracy and thereby break the degeneracy of the IBEX observations. This method, developed in Moebius et al. [2015], utilizes the variation of the radial neutral flow speed as a function of ecliptic longitude to determine the bulk neutral inflow direction. The longitudinal velocity variation of the neutrals manifests itself in the PUI velocity distribution by increasing or decreasing PUI cutoff (the point on the PUI VDF where the phase space density sharply decreases). Since the PUI cutoff is dependent on the radial neutral velocity at injection, the cutoff is increased upwind where the neutral flow is running into the solar wind, and decreased downwind where the neutral flow is running with the solar wind. Thus measuring the PUI cutoff as a function of ecliptic longitude and finding the max cutoff location will result in the neutral flow direction.

In the time between PUI injection to the solar wind and their measurement by STEREO-A, PUIs are bound to the magnetic field, convecting with the solar wind, and streaming along the IMF. At this time, they are essentially a secondary plasma population embedded in the solar wind, and as such they are subject to temporal changes in the solar wind parameters, resulting in magnetic heating, pitch angle scattering and adiabatic
Figure 3: Effect of a SW compression on the PUI VDF as seen by SOHO CELIAS CTOF. (a) shows solar wind parameters evolving across single compression region, where red designates regions before and after the compression and blue designates the region under compression. (b) shows the velocity distribution function, before, during and after the compression has passed. [Saul et al., 2004]

cooling. These interactions were first observed in Saul et al. [2004], where several compressions in the solar wind parameters were observed, resulting in positive cutoff shifts in the PUI VDFs. One such compression is shown in Figure 3. Here the compression is identified in blue, PUI VDFs are integrated in three time ranges, before, during and after the compression, and their cutoffs are identified. Prior to the compression arrival the PUI VDF has a sharp cutoff at $w = 2v_{sw}$, during the compression, the PUI cutoff was shown to be shifted to higher velocities, signifying a heating of the embedded PUIs. After the rapid increase in solar wind velocity is over, the PUI cutoff returns to pre-compression levels. All of this takes place over the course of hours, showing that these SW velocity changes can manifest themselves as large variations in the PUI cutoff.

These increases in the PUI cutoff manifest themselves as systematic error in the analysis of the PUI inflow direction. In order to improve the precision of the inflow detection these regions must be removed or accounted for. Additionally, this effect has its own importance in understanding PUI transport processes, as no survey of the PUI cutoff in compression regions has been possible before for a large number of events. A statistical study of these events allows the identification of the nature of these heating processes and to possibly correct for the such effects in the original data set. Therefore, the two goals of this thesis are to perform the first systematic study to understand PUI
behavior in compression regions and interplanetary shocks, and to develop criteria to remove or correct for these effects in the determination of the ISN flow direction.

This analysis is broken into four major components, section 2 begins with a discussion of PUI generation and transport and how these transport properties manifest themselves in the VDF. Section 3 describes the primary components and function of the STEREO satellites, and how the PLASTIC instrument aboard STEREO allows for PUI collection and selection. Section 4 describes the data structure, data treatment, and preliminary selection that is performed prior to the study of compressions. Section 5 contains the analysis of the evolution of the PUI VDF in SW compressions and shocks, performed with Python, with the goal of identifying systematic trends between solar wind parameters and the PUI cutoff. This is performed on three different solar wind structures, local high time resolution fluctuations, compression regions defined by their structure and interplanetary shocks. Section 6 is a discussion of the implications of these findings, as well as a statistical study of compression region removal on the inflow identification routine. Finally section 7 contains the conclusion which summarizes the primary findings of this study and outlines future research.
2 Generation and Transport of PUI’s

In order to have a functional understanding of the effects of PUI transport we need some background information about PUI origins, their velocity distribution functions and how they evolve under different solar wind conditions.

2.1 PUI Generation and Neutral Sources

As was briefly discussed, PUIs begin as neutral particles sourced from populations in the partially ionized interstellar medium, interplanetary dust, and planetary, lunar and cometary atmospheres. For this study, we will focus on PUIs generated from interstellar neutrals. The interplanetary magnetic field, frozen into the solar wind, prevents the ionized portion of the ISM from penetrating the heliosphere. As the solar system moves through interstellar space the neutral population in the ISM is able to flow unimpeded through the essentially collisionless solar wind and part of this population is thus readily available to be measured at 1au. This neutral flow is primarily comprised of H and He, but also contains trace amounts of, O, N and Ne when compared to H [Herbst, 1995]. As the flow passes through the heliosphere, neutrals are lost to ionization processes, namely photoionization and charge exchange collision, creating an ionization cavity close to the Sun. H, O and N have relatively low ionization potentials compared to He and Ne, resulting in a higher portion of these particles lost to ionization. This means that He and Ne exist in higher percentages at Earth’s orbit. Because He is the second most abundant neutral in the ISM, its survivability makes it the best test particle at Earth [Herbst, 1995]. The physical parameters of He held consensus values of $n_{He} = 0.015 \pm 0.002 cm^{-3}$, $v_{He} = 26.3 \pm 0.4 km/s$ and $T_{He} = 6300 \pm 390^\circ K$ [Moebius et al., 2004]. IBEX measurements have since shown that this temperature value is an underestimation, where $T_{He} = 8710 + 440/ - 80^\circ K$ for $v_{He} = 26.3$ [Moebius et al., 2015a]. A certain portion of the ions from the outer heliosphere undergo charge exchange to produce neutrals, some of these particles will yield velocity vectors that bring them into the inner heliosphere, generating a secondary neutral flow [Moebius et al., 2009]. The bulk of these particles charge exchange in the heliosheath, and as such, retain the velocity distribution of the compressed plasma. These secondary neutrals have a slower bulk velocity, but a higher temperature than the interstellar neutrals [Moebius et al., 2009].

Additionally, as the particles accelerate into the Sun’s gravitational well, their trajectories are bent into hyperbola, resulting in an increased in neutral particle density.
The ionization cavity coupled with the neutral particle acceleration result in the characteristic density structure seen in Figure 4. Here, sample trajectories of the neutral He are shown bending around the Sun, creating the gravitational focusing cone downwind. The variation of the neutral radial velocity manifests itself in the velocity distribution of PUIs, and can be exploited to measure the inflow direction.

When the interstellar neutrals or secondaries are ionized they are picked up by the solar wind, and although they are now an embedded plasma population, they are still separable from the SW plasma. PUI He is relatively easy to separate from the background SW due to its distinct mass per charge (M/Q) of 4. As He is ionized, primarily through photoionization at 1au, the relative motion between the He+ ions and the frozen-in magnetic field of the solar wind causes the ions to gyrate around the field line in the solar wind frame. In the observer frame, the He+ undergoes cycloid motion and is observed with a velocity between zero and twice the solar wind speed. Sampling many PUIs will result in a velocity distribution function where velocity states will be filled from 0 to a max velocity cutoff at twice the solar wind speed. Thus the cutoff of the PUI VDF can be used to infer the neutral injection velocity of the PUIs. The secondary neutral flow additionally adds to the PUI He+ velocity distribution, but since it has substantially lower flux and a lower velocity it results in a minimal contribution to part of the distribution and does not contribute to the cutoff.
Figure 5: Schematic view of the velocity distribution in the spacecraft frame for PUI injected with a perpendicular magnetic field (left) and a near parallel magnetic field (right) [Saul et al., 2004]. The x axis is associated with the Sun-spacecraft line or the radial direction.

2.2 PUI Gyration

The Lorentz force is fundamentally the most important transport effect that governs PUI motion as well as the least complex to describe. In the simplest terms the motion of the PUIs can be approximated by looking at the assumed stationary electromagnetic fields in the solar wind.

\[
F = q(\vec{E} + \vec{v} \times \vec{B})
\]

(1)

Where \(\vec{E}\) is the local convective electric field, generated by the moving SW. \(\vec{B}\) is the magnetic field vector and \(\vec{v}\) is the particle velocity. Transforming into the solar wind frame gives an initial velocity of the PUIs \(\vec{v} = \vec{v}_{\text{neutral}} - \vec{v}_{\text{sw}}\). Usually, at injection, the particle velocity is assumed to be near zero in the inertial frame which gives us \(\vec{v} = -\vec{v}_{\text{sw}}\), in order to determine the inflow longitude using the PUI velocity distribution we will have to consider the effect of non-zero \(v_{\text{neutral}}\), but for now this is a valid assumption. Transformation into the SW gives us \(\vec{E} = 0\), as there is no stationary electric field in a quasi neutral SW plasma. The result of this frame transformation yields:

\[
F = q\vec{v} \times \vec{B}
\]

(2)

Thus the injected PUI particles gyrate around the magnetic field with a speed determined by the initial velocity of the particles perpendicular to the field, and a gyroradius determined by the particle charge state, mass and the magnetic field strength. The particle
velocity along the magnetic field will be unaffected by the Lorentz force, and is simply
determined by the angle between the magnetic field and the SW velocity. Additionally,
the particle energy will be conserved in the solar wind frame, and the equations of motion
of the particles become.

\[ v_\parallel = \frac{\vec{v} \cdot \vec{B}}{B} \]
\[ v_\perp = \frac{|\vec{v} \times \vec{B}|}{|B|} \] (3)

Where \( v_\parallel \) is the particle velocity along the magnetic field, and \( v_\perp \) is perpendicular to the
magnetic field, with gyrofrequency \( \Omega = q|B|/m \) and gyroradius \( \rho = v_\perp/\Omega \). A coordinate
system is chosen where the x-axis is Sun pointing, the z-axis points out of the ecliptic
and the y-axis completes the right handed system (as seen in Figure 5), thus the particle
velocity can be expressed in terms of the pitch angle of the particles, \( \alpha \). The pitch angle,
\( \alpha \), is defined as the angle between the particle velocity and the magnetic field, as seen in
Figure 5. The simplified equations of motion now become:

\[ v_\parallel = |v| \cos(\alpha) \] (4)
\[ v_\perp = |v| \sin(\alpha) \]

For small angles of \( \alpha \) the magnetic field is close to radial, \( v_\perp \) will be small, leading to
a small gyroradius, resulting in particles that primarily stream along the magnetic field.
Conversely, for pitch angles \( \alpha \approx \pi/2 \) the particle will gyrate around the magnetic field
with little to no parallel velocity, and stay fixed at a max gyroradius, until acted on by
other transport effects.

2.3 Measurements of the PUI VDF

The first observations of the PUI VDF were limited to reduced 1d spectra in velocity
space. Figure 6 shows a sample of H and He spectra, taken aboard the Ulysses space-
craft in Dec, 1991. The density drop off is clearly visible in the particle distributions
characteristic of PUIs, associated with their max velocity \( 2V_{sw} \), and a relatively uniform
distribution at lower velocities. The distribution would ideally drop straight down at
\( 2V_{sw} \), but there will always be some small population of higher energy PUIs, either asso-
ciated with the energy diffusion of the particles or interaction with the solar wind. The
problem with these 1d velocity spectra is that transport effects acting on these particles
strongly influence the shape of the distribution but the related details of the distribution
Immediately after ionization the PUI VDF is assumed to resemble a torus in velocity space, as seen in Figure 5. The torus is rotationally symmetric about the magnetic field with a inclination subsequently defined by the local magnetic field direction [Drews et al., 2015]. If the magnetic field is perpendicular to the solar wind, which is assumed to be radial, the PUI velocity ranges from 0km/s to 2Vsw, creating a VDF that falls off at \( v^2 \). If the magnetic field points at small angles relative to the SW, the PUIs will gyrate only minimally, causing the VDF to have strong 1st order anisotropy in the SW frame [Saul et al., 2004]. This means that particles injected closer to the Sun will have higher parallel velocity components and smaller ring distributions in velocity space due to the Parker spiral of the interplanetary magnetic field being more radial.

### 2.4 Transport Effects on the VDF

The PUI VDF isotropizes when subject to interactions with Alfven waves that exist in abundance in the solar wind [Saul et al., 2004]. These Alfven waves affect the pitch angle of the PUI population, scattering the particles, which in turn create additional waves, all of which cause further isotropization of the Torus distribution. An illustration of this effect can be seen in Figure 7(1), where the torus is essentially smeared out around its shell in velocity space, eventually becoming fully isotropized. The effect of torus distributions at varying pitch angles can be completely mitigated by transforming the particle velocity to the solar wind frame, where the cutoff will still reside at \( v_{sw} \) even under incomplete
scattering and for different IMF directions. As the solar wind convects outward, it carries the magnetic field with it, causing the magnetic field and PUI population to expand as the solar wind expands. This effect results in adiabatic cooling of the SW, a decrease in SW density and a decrease in magnetic field strength. For slow variations of B, particles obey the first adiabatic invariant $\mu$:

$$\mu = \frac{v_\perp^2}{2|B|}$$  \hspace{1cm} (5)

Thus a slow decrease in the magnetic field strength will cause a corresponding decrease in $v_\perp$, shown in Figure 7(2), shrinking the torus, but still retaining its original orientation. Under these effects, PUIs fill the phase space within the shell, and the cutoff is less pronounced. These processes act over time, so measuring particles that were produced locally will have had less of an effect.

Additionally, PUIs can undergo strong acceleration through energy diffusion, expanding the torus, and creating high velocity tails in the 1D VDF [Drews et al., 2015]. Because the PUIs are directly dependent on the local magnetic field, changes in field strength orientation will result in changes in the orientation of the torus, as seen in Figure 7(3). Measurements of the PUI populations are generally integrated over long time scales due to lacking statistics, so these effects become difficult to measure directly without high time resolution. If the magnetic fluctuation happened locally and for a long enough time period, then they will be distinctly visible, otherwise they can be mistaken for Alfvénic fluctuations.

Figure 7: Velocity space diagrams depicting the He+ torus distribution under pitch angle scattering (1), adiabatic cooling (2) and rapid changes of the magnetic field vector (3) [Drews et al., 2015]
Figure 8: Velocity vector addition of PUIs with different initial radial velocities and the effect on their 1d PUI VDF. Case (1) shows an injection speed of zero in the inertial frame and a max velocity of twice the solar wind speed. Case (2) shows the effect of a positive injection speed, seen upwind where the interstellar neutral flow is ramming into the SW. Case (3) shows a negative injection speed, seen down wind where the interstellar neutral flow is running away from the SW, the max PUI velocity is lower than $2v_{sw}$ [Taut, 2018]

2.5 Longitudinal Variation of the Neutral Injection velocity

In the past, PUI distributions have typically been evaluated with the assumption that the velocity of their interstellar neutral source is negligible ($\sim 25$km/s at $\infty$, compared to an average SW velocity of $\sim 400$km/s). However, in this study the injection speed of the PUIs is very important [Moebius et al., 2015b]. Although the interstellar neutrals start from a speed of $\sim 25$km/s, as they get closer to the Sun they accelerate into the Sun’s gravitational well, increasing the speed of the neutrals to $\sim 50$km/s at 1AU and bending their trajectories (Figure 4). This effect was first discovered in [Moebius et al., 1999] using He+ observation taken with SOHO CELIAS CTOF. In the framework of just the Lorentz force transport, the motion of the PUI depends just on the magnetic field direction, strength and the relative velocities of the ions to the solar wind.

The PUI velocity is typically represented in terms of the PUI speed normalized to the solar wind speed; $w = v_{PUI}/v_{sw}$. Resulting in a cutoff of approximately $w_{cutoff} = 2$. The neutral injection velocity thus adds or subtracts to the cutoff value of the PUIs. This effect on the PUI gyration velocity (and the 1D VDF) in the spacecraft frame can be seen in three cases in Figure 8. With an initial injection of 0, shown in Figure 8 (1), the PUIs
Figure 9: Top: He+ PUI cutoff identified in 1deg longitudinal bins, the light blue line overlay is a model fitting of the neutral inflow speed, the blue line designates the upwind flow direction determined through the fit. Bottom: He+ PUI VDF observed by PLASTIC on STEREO-A, the white line designates the inflow direction determined through fitting [Taut et al., 2017].

gyrate around the field with a resultant $w_{\text{cutoff}} = 2$. Upwind, shown in Figure 8 (2), the SW and the interstellar wind are ramming into one another, this results in an increased relative speed between the neutral He and the SW and a cutoff velocity of $w_{\text{cutoff}} > 2$. Downwind, shown in Figure 8 (3), the opposite effect takes place, the interstellar wind is flowing in the same direction as the solar wind causing a reduction in their relative speed, and a cutoff velocity of $w_{\text{cutoff}} < 2$.

Transforming into the solar wind frame alleviates the need to worry about the motional electric field, the orientation of the IMF, and scattering due to Alfven waves; $w'_{\text{cutoff}} = (\vec{v}_{\text{PUI}} - \vec{v}_{\text{sw}}) / v_{\text{sw}}$, resulting in an approximate cutoff value of 1. Ignoring the motion of the particle along the field line, and assuming that the cutoff of the PUI distribution is largely unaffected by Alfven waves, the cutoff value is approximated as a function of the
radial velocity of the injected neutral \((v_r)\) as:

\[
w'_{\text{cutoff}} = \frac{v_{sw} - v_r}{v_{sw}}
\]  

(6)

Upwind, the radial injection speed is negative, resulting in the 1D VDF falling off \(w > 1\). Downwind, the injection speed is positive, yielding cutoff value at lower velocities. This effect is continuous as STEREO-A orbits the Sun, and the result is an approximately sinusoidal curve that is symmetric about the ISM flow direction. This effect can be seen in the phase space density plot in Figure 9 (bottom). The cutoff velocity is identified for each 1deg bin, resulting in a functional relationship between \(vr_{\text{cutoff}}\) and the ecliptic longitude, seen in Figure 9 (top). In [Moebius et al., 2015b] an analytical model of this effect of the radial neutral speed is derived,

\[
v_r^2 = 2 + v_{ISN\infty}^2 - (1 - \cos \lambda) - \left[\frac{v_{ISN\infty}^2 \sin^2 \lambda + \{v_{ISN\infty} \times \sin |\lambda|\sqrt{v_{ISN\infty}^2 \sin^2 \lambda + 4(1 - \cos \lambda)}\}}{2}\right]
\]

(7)

where the neutral particle speed at the observer is given by \(v_r = \frac{\nu_r}{v_E}\) and the neutral particle speed at infinity is given by \(v_{ISN\infty} = \frac{v_{ISN\infty}}{v_E}\). These values are normalized to \(v_E = \sqrt{\frac{GM_s}{R_E}}\), where \(G\) is the gravitational constant, \(M_s\) is the solar mass, and \(R_E\) is the Sun-Earth distance (1AU). The value \(\lambda\) contains both the interstellar flow longitude and the observed flow longitude: \(\lambda = \lambda_{\text{obs}} - \lambda_{\text{inflow}}\). This model can be fit directly to the measured relationship between \(v_r\) and \(\lambda_{\text{obs}}\), by varying the flow velocity and inflow direction in a least-square fit. Figure 9 (Top) shows the result of this fit as a light blue line overlaid on the measurements. This results in an upwind flow direction of \(\lambda_{\text{inflow}} = 255.5 \pm 0.5^\circ\), and is shown as a vertical blue line in Figure 9. A model free method of inflow determination is used in [Moebius et al., 2015b], where the authors instead performed a mirror correlation on the \(vr_{\text{cutoff}}(\lambda_{\text{obs}})\), resulting in a statistically identical inflow direction with similar error [Taut et al., 2017].
3 STEREO PLASTIC

Here we provide some background on PLASTIC, an instrument developed at the University of New Hampshire, which is aboard the STEREO spacecraft. This instrument provides PUI measurements in the solar wind frame and solar wind parameter measurements that we here use for analysis.

3.1 Mission and Spacecraft Overview

The Solar TErrestrial RElations Observatory (STEREO), launched October 26, 2006, is comprised of two semi-identical, Sun orbiting spacecraft that are drifting apart by 45° a year in solar longitude [Galvin et al., 2008]. The primary purpose of the STEREO mission is to study the origin and evolution of Coronal Mass Ejections (CMEs) with a combination of imaging from two vantage points and in-situ measurements of the plasma, energetic particles, magnetic field, and electromagnetic waves [Galvin et al., 2008]. The two spacecraft are STEREO-A (AHEAD), which orbits at a slightly smaller radial distance from the Sun, when compared to Earth, and STEREO-B (BEHIND), which orbits at a slightly larger distance. Therefore, the two spacecraft drift away from the Earth’s orbital position at a rate of ≈ 22.5° per year [Galvin et al., 2008]. The increasing separation of the two spacecraft allows for multi-point observation of the solar wind’s magnetic topology, plasma temperature and density, and temporal evolution of CMEs [Kaiser and et al., 2005]. The STEREO science payload consists of 13 instruments, making up four experiment packages: two instruments suites and two single instruments, each with their own primary science goals [Kaiser and et al., 2005]. Figure 10 (a) shows a schematic depicting the placement of the instrument aboard STEREO-B. The experiment packages are known as [Kaiser and et al., 2005]:

- **SunEarth Connection Coronal and Heliospheric Investigation (SECCHI) Suite:**
  Comprised of 4 Remote sensing instruments, two White Light Coronagraphs, imaging in visible light, an Extreme Ultraviolet Imager, and a Heliospheric imager. The purpose of this suite is to study the 3D evolution of the structure of CMEs from the surface of the Sun to their impact at Earth [Howard et al. 2007].

- **In situ Measurements of PArticles and CME Transients (IMPACT) Suite**
  Comprised of seven instruments measuring the magnitude and direction of the
interplanetary magnetic field, energetic electrons and ions, and thermal and super-thermal electrons [Luhmann et al. 2007]

- **STEREO/WAVES (S/WAVES):**
  Three orthogonal monopole antenna functioning as an interplanetary radio burst tracker to observe the onset and evolution of radio disturbances between the Sun and Earth [Bougeret et al. 2007].

- **PLAsma and SupraThermal Ion Composition (PLASTIC):**
  Developed to study in situ, the properties of SW protons, the composition and properties of minor solar wind ions, and the distribution of pickup ions and suprathermal ions in interplanetary space [Galvin et al., 2008]

PLASTIC’s unique ability to resolve ion composition, velocity and incoming azimuthal and elevation directions have proved to be indispensable in the study of the PUI VDF. The design and measurement capabilities of PLASTIC are discussed in more detail below.
3.2 PLASTIC

PLASTIC is a time of flight mass spectrometer that is used to determine the flux, composition, and velocity of solar wind protons and suprathermal ions [Drews et al., 2015]. A photograph of PLASTIC can be seen in Figure 10b. The sensor is comprised of three primary elements: the entrance system, the Time-of-Flight chamber (TOF) and the particle detectors. The entrance system utilizes two subsystems to select particles by incoming elevation angle and energy-per-charge (E/Q). The E/Q is measured through a rotationally symmetric top hat ElectroStatic Analyzer (ESA), that has a 360 degree FoV in the ecliptic plane, and resolves E/Q by stepping through the analyzer voltage. Additionally, the entrance system is divided in three sections azimuthally, each optimized for a particular type of ion population [Galvin et al., 2008]. The 45° Sun pointing solar wind sector, equipped with a deflector system, resolves incoming particle angles out of the ecliptic up to ±20° in two channels. The Solar Wind Sector Small Channel is used to accumulate distribution function of solar wind protons and alphas. The Solar Wind Main Channel, resolves the charge states, composition, bulk and thermal speed of minor ions (e.g., C, O, Mg, Si, Fe) and PUIs. The Suprathermal Ions Wide-Angle Partition sector, covers the...
largest azimuthal FOV and as such has the largest geometrical factor, but lower angular resolution than the Solar Wind Sector [Galvin et al., 2008]. After passing the entrance system, particles leave the ESA, undergo post-acceleration and enter the Time-of-Flight chamber (TOF). As implied by its name, the TOF measures the flight time of the particle over a known distance, when coupled with the post acceleration, determines the particle’s Energy per Mass (E/M). Finally, the particle hits a Solid State Detector (SSD) that measures the total energy. A stop signal is provided by a microchannel plate (MCP) that is constructed using a series of resistive anodes to resolve the incoming direction in azimuth. Figure 11, left, shows a schematic cross section of the entrance system, TOF detector, and electrostatic analyzer. On the right is an illustration of the sensor system with the quadrants labeled (quadrant 0 resolves azimuth angle in the SW sector).

The PLASTIC solar wind sector provides the unique capability to measure the incident angle of ions in both polar $\theta$, and azimuthal directions $\alpha$ [Drews et al., 2015]. Azimuthal detection is achieved through a chain of resistive anodes behind the MCP, capable of resolving 32 different angles, with a total FOV of $\alpha \pm 22.5^\circ$, resulting in an angular bin width of $\Delta \alpha = 1.4^\circ$. The polar detection is achieved through an electrostatic deflection system, shown in Figure 11, left, attached to the top of the ESA [Taut, 2018]. This deflection voltage is stepped incrementally 32 times every 435 ms, resulting in a polar FOV of $\theta \pm 20.0^\circ$ and an angular resolution of $\Delta \theta = 1.3^\circ$. Additionally, PLASTIC provides the solar wind proton density ($n$), the solar wind speed $v_{sw}$ and the proton thermal speed $v_{th}$.

The PUI He+ data are measured through pulse height analysis, described in Drews
et al. [2010], used to resolve each particle’s E/M, E/Q, E, and incoming azimuth and elevation angle. The particle type is determined through the combination of E/Q and E/M resulting in a clearly defined $M/Q = 4$ for He+. With the particle type (mass and charge) determined, the incoming particle velocity can simply be calculated from the incoming energy determined with the ESA. For each incident He+, PLASTIC yields a measurement of the PUI velocity ($v_{He+}$) and incident angles ($\alpha, \theta$) on a 5 min time resolution. Traditionally, the PUIs have been measured by representing the PUI velocity measured in the spacecraft frame $w = v_{He+}/v_{sw}$, i.e. normalized to the solar wind speed. This measurement is fundamentally variable, as the PUI will have a $w$ value between 0 and 2, for a perpendicular field orientation (Figure 5, left), depending on where they are in their gyro-orbit. Additionally, the max cutoff value is dependent on the magnetic field direction, in the sense that for magnetic field orientations far from perpendicular the max cutoff value is also reduced. In the solar wind frame, the PUIs are injected onto a spherical shell in velocity space with a radius that equals the solar wind speed. Figure 12 (a) shows the PUI torus in the spacecraft frame (green) projected onto a shell in velocity space. Changes in the solar wind velocity will affect the radius of the torus by changing the radius of the shell. Changes in the IMF orientation will also change the radius of the torus by intersecting a different part of the shell. Figure 12 (b) shows a cross section of the shell and torus in the ($x,y$) plane. One can see that the torus diameter (green) will change its length depending on the field orientation. To account for this, PUI measurements can be considered in the solar wind frame, the equivalent of making the center of the circle the origin. From here, regardless of the IMF orientation, the Torus in the SW frame, seen as a gray line in Figure 12 (b), will always be located at a distance associated with the radius of the shell, or approximately the solar wind speed. Thus the PUI measurements should be expressed in the solar wind frame, by subtracting the solar wind velocity from the He+ measurement using their velocity vectors. The relative velocity of PUIs, $w'$, with respect to the local solar wind speed is given by [Drews et al., 2012]:

$$w' = \frac{vec v_{sw} - \vec{v}_{He+}}{v_{sw}} = \sqrt{w^2 - 2 \ast w \ast \cos(\alpha) \cos(\theta) + 1}$$ (8)

With the PUIs in the solar wind frame the injection speed is conserved for all IMF orientations [Taut et al., 2017]. Essentially, PLASTIC’s angular resolution is paramount as the transformation into the solar wind frame allows us to integrate over STEREO’s entire FOV. For any IMF orientation, the max cutoff velocity should fall at approximately $w' = 1$. 

20
4 PUI VDF Treatment and Data Structure

STEREO PLASTIC provides the unique ability to determine the three-dimensional velocity distribution of He+ at a resolution of $5^\circ$. This allows us to obtain radial cuts through the distribution in a frame that moves with the solar wind [Moebius et al., 2015b]. The center of STEREO PLASTIC’s SW sector constantly points radially at the Sun, with a field of view of $\approx \pm 20^\circ$ in the ecliptic and out of the ecliptic, restricting PUI measurements that include the torus to times when the magnetic field is near perpendicular to the radial direction. Because STEREO orbits near 1AU, where the Parker spiral is at $\approx 45$ deg, this torus configuration is not favored, but still readily accessible. An example of the two dimensional particle distributions, in viewing angle and energy, obtained by STEREO can be seen in Figure 13. Here the torus is shown measured in PLASTIC’s FoV on the right, where the magnetic field is quasi-perpendicular, and out of the FoV on the left, where the magnetic field is at small angles from the solar wind flow direction. When the torus is within the FoV it is clear that the cutoff falls on the shell at the solar wind velocity. Even though the torus is broad in angle around the shell, possibly due to pitch angle scattering, the cutoff remains intact. When the torus is outside of the FoV, PUIs are still observable, but they are heavily processed and have a greatly reduced cutoff.

It follows that measurements must be restricted to times when the torus falls into STEREO’s FoV so that only freshly injected PUIs are observed. This restrictive mask, is constructed using the magnetic field cone angle ($\beta$), which is defined as the angle between the $\vec{B}$, and the position vector $\vec{r}$, from the Sun to STEREO. This value is calculated using the IMF angle: $\theta$ out of the ecliptic, and the azimuthal angle $\phi$ from $\vec{r}$. Both angles in our data set are defined between $\pm 180^\circ$ so care must be taken with the signs.

$$\beta = \arccos(\cos(|\phi|) \cos(\pi/2 - \theta))$$

The mask is now defined using $70^\circ < \beta < 110^\circ$ for the times when the torus falls within PLASTIC’s FOV. A slightly different approach is used in Taut et al. [2017] where times are restricted using the average PUI guiding center motion. A comparative analysis between the two methods has been performed, and they have produced comparable results.

Due to the PUI process, the PUI speed is generally measured relative to the local ambient solar wind speed. Transformation of the PUI speed into the solar wind frame, as described in section 3.2, allows the PUI speed at injection to be conserved for any ecliptic longitude or IMF angle, but normalizing the PUI velocity to $v_{sw}$ introduces a fundamental dependence on the solar wind speed [Taut et al., 2017]. This fundamental dependence
Figure 13: Two dimensional VDF as seen by STEREO PLASTIC. Where \( w \) is the normalized PUI velocity, and \( \phi_B \) is the angle from the Sun-spacecraft line (radial) in the ecliptic. We can see on the left, for \( \phi_b \) angles far from 90° the torus falls outside PLASTIC’s field of view, and only heavily processed PUIs are observable. On the right the magnetic field is close to 90°, and the high particle flux of the torus can be seen.

of \( w' \) on \( v_{sw} \), needs to be considered and accounted for or it will add additional error to the inflow measurement. To eliminate the influence of varying SW speed, the cutoff is considered in terms of just the neutral radial velocity component \( v_r \):

\[
v_r = v_{sw} \cdot w' - v_{sw}
\]  

(10)

The first term in the definition, \( v_{sw} \cdot w' \), corresponds to the total PUI velocity in the solar wind frame. This essentially means that \( v_r \) is the difference between the measured PUI speed and the radius of the nominal torus shell.
4.1 PUI Cut-off Determination

Ideally, while looking at an energetically homogeneous PUI spectrum, the PUI cutoff would be a sharp well defined structure. Due to a various influences, such as the energy width of the neutral beam, local heating, acceleration processes and the finite resolution of the instrument, the PUI spectra are smoothed and the cutoff is less defined. Therefore, the exact location of the cutoff must be defined in a reproducible way. Here we discuss three methods of defining the PUI cutoff, each with benefits and disadvantages in different situations. A study was performed in Taut et al. [2017], where they measured the inflow direction, employing each of these techniques, and found that they all produce statistically similar accuracy.

4.1.1 Tanh Fitting

The first technique we will discuss involves fitting the drop off of the energy spectra with a hyperbolic tangent function, as described in [Moebius et al., 2015b]. This was originally used out of convenience, but has proved to be a statistically accurate and consistent measure of the cutoff provided there are adequate statistics. Initially, the maximum of the smoothed PUI spectra is identified, the spectra above this energy is taken and fit with the Tanh function using least squares minimization:

\[ c = \frac{1 - \tanh((v_0 - v_{cutoff}) * a)}{2} \]

Where \( c \) is the expected count rate, \( v_0 \) the measured PUI velocity (represented by \( w', v_r \) etc.), \( a \) is a scaling factor and \( v_{cutoff} \) the inflection point of the Tanh function, taken to be our cutoff value. The error value for this fitting technique is estimated from the fit confidence of the cutoff value. The result of this fitting can be seen in Figure 14a, where the velocity distribution of PUI measurements integrated over one longitudinal bin can be seen in red, the Tanh fit can be seen in blue, and the cutoff value determined through the fit is seen as a dashed black line.

4.1.2 Cutoff Fitting Using the Average DeModulated VDF

In order to analyze the cutoff shift specifically in shock regions we needed to develop a fitting routine that is stable when fitting PUI VDFs with large accelerated tails. The method using the Tanh function breaks down for PUI VDFs with low statistics and/or high velocity tails. To solve this problem we opted to average the demodulated PUI VDF (VDF with the longitudinal dependence removed, discussed in next section) over the
Figure 14: Three separate techniques for identifying the cutoff location (black dashed line). (a) shows fitting using the tanh() function (blue line). (b) shows identification using the 1/2 max function, where the blue line indicates the smoothed interpolated vdf. (c) shows fitting using the average, interpolated VDF, and tends to yield lower cutoff values since a substantial amount of the acceleration is accounted for by flattening the fitted function.
entire 7 year data set, and performed an interpolation, giving us a continuous function that can be fit using the least squares method. The maximum count rate is identified and the distribution function beyond the max location is made continuous through polynomial interpolation. We then introduce variation parameters for fitting, defining the slope \((m)\), the shift in height associated with the high velocity tail \((\Delta h)\) and cutoff \((\Delta vr)\). This gives us a fitting equation for the count rate \(c(vr)\), defined using the interpolated average PUI VDF \(f(vr)\).

\[
c(vr) = A \ast f(m \ast vr - \Delta vr) + \Delta h
\]  

(12)

A sample fit that is a stress test for this method is shown in Figure 14. The PUI VDF has undergone considerable heating, indicated by the overall horizontal shift in the VDF and quantified by the \(\Delta vr\) value. Additionally, acceleration processes result in a massive high velocity tail, greatly reducing the steepness of the drop off, and a vertical shift accounting for the large fluxes in the tail. Aside from being stable in such extreme conditions, this method to quantifies the steepness of the cutoff, which can be used as a proxy for the amount of accelerated particles in the tail.

4.1.3 Half Max

The half max technique is fairly self explanatory, and is by far the most rudimentary of the three methods. Essentially this method defines the PUI cutoff as the point in the high energy drop off where the count rate reaches half of its max value. While quite simple, this method has proved to be quite accurate, low cost computationally, and is by far the most stable with low statistics. This means that this technique can be used successfully at the highest time resolution, making it ideal when measuring the PUI cutoff for fast variations of compressions when statistics are low. This method begins by smoothing the VDF with a running average, interpolating the histogram and identifying the maximum in the count rate, in both velocity and count rate magnitude. Using the interpolated VDF, the half maximum height is identified on the side of higher velocity and the velocity at that point is recorded. Figure 14b shows a sample of this routine on a one degree integrated VDF, where the blue line is the smoothed, interpolated VDF and the black line represents the velocity where the half max point was determined. The error of the half max point is estimated by adding, in quadrature, the velocity bin width error to the count rate error superimposed in velocity.

\[
\delta vr_{1/2max} = \sqrt{\delta vr^2 + (vr_{1/2max} - f(N_{1/2max} + \delta N_{1/2max}))^2}
\]  

(13)
Where $\delta v_{r1/2max}$ is the cutoff error, $\delta v_r$ is the bin width error, $v_{r1/2max}$ is the cutoff determined through this routine, $f(N)$ is the interpolated VDF, relating the count rate and the PUI velocity (seen in blue in Figure 14b), $N_{1/2max}$ is the count rate at the half the max height, and $\delta N_{1/2max}$ is the count rate error at the half max position. Since the half max routine has been found to be the most stable with low statistics it will be the only cutoff identification method used for the rest of this study.

### 4.2 Removal of Longitudinal Dependence

To reduce the error of the neutral inflow measurement, and to study PUI heating in solar wind compression regions, we will identify solar wind compressions, in several forms, and measure their effect on the PUI cutoff. Due to the fact that PUI count rates are relatively low when using PLASTIC, large integration times must be considered to build a PUI VDF with adequate statistics to confidently measure the cutoff. Compression regions in the solar wind generally happen too fast to effectively build a VDF, thus compression events need to be superimposed in order to identify their effects. But, the PUI cutoff speed is dependent on the longitude of measurement, which varies up to 100 km/s over one orbit. This is a large enough variation that combining PUI counts without accounting for their longitudinal variation will introduce considerable error to a PUI compression parameter study. Therefore, the longitudinal dependence of the PUI cutoff must be removed.

The steps to remove the longitudinal dependence of the cutoff follow the sequence of the analysis to determine the inflow direction. First, for each of the longitudinal bins (in 1° increments), the cutoff is obtained from the PUI VDF, using the fitting routine of choice. In this study the half-max routine is used throughout. Second, the deduced cutoff values as a function of longitude are fit to the model for the radial component of the ISN flow velocity $v_r$ at Earth’s orbit, eq. 7 [Moebius et al., 2015b]. This provides an approximate inflow direction ($\lambda_{inflow}$) and velocity at infinity ($v_{ISN\infty}$) for the data set. Using these parameters in a third step, the PUI data at the highest possible time resolution (10mins) are transformed by subtracting the modeled velocity ($v_r(calc) (\lambda)$) found by the fit to equation 7, which results in a “demodulated” radial velocity for the PUI VDF ($v_r^*$):

$$v_r^* = v_r - v_{r(calc)}$$  \hspace{1cm} (14)

As can be seen in Figure 15, this procedure yields a flat relationship for $v_r^*$ as a function of $\lambda$, with an average cutoff near $v_r^* = 0$. But, due to interplanetary conditions that affect the PUIs, there are still considerable deviations around zero. Since the goal of this
Figure 15: The two dimensional VDFs integrated in longitude over the 7 yr data set in STEREO’s $v_r$ frame, with and without longitudinal dependence. On the top in Figure (a) the longitudinal dependence is intact and increased cutoff speed upwind around the 250deg mark can be seen. On the bottom, in Figure (b) the longitudinal dependence of the data set is removed, and the cutoff position lies approximately at $v_r = 0$ for all longitudes.
study is to analyze specifically the effect of the solar wind variations on the PUI cutoff, the PUI measurements are normalized again to the solar wind speed. This results in a demodulated data set as a function of the dimensionless velocity $w^*$, which allows a direct comparison with a nominal PUI VDF independent of the solar wind speed value.

$$w^* = \frac{v_r^*}{v_{sw}}$$  \hspace{1cm} (15)

The rest of this analysis will be performed using the $w^*$ parameter. Combining the frame transformations, normalization and removal of the ISN flow pattern, $w^*$ is expressed in terms of the measured PUI speed, $v_{PUI}$, the solar wind velocity, $v_{sw}$, ecliptic and latitudinal direction of the PUI velocity vector (described in section 3.2), $\alpha$ and $\theta$, and the radial cutoff velocity as a function of ecliptic longitude, $v_{r(calc)}(\phi)$:

$$w^* = \frac{\sqrt{\frac{v_{PUI}^2}{v_{sw}} - 2 \frac{v_{PUI}}{v_{sw}} \cos \alpha \cos \theta + 1 - \frac{v_{r(calc)}(\phi)}{v_{sw}}}}{v_{sw}} - 1$$  \hspace{1cm} (16)

Like $v_r^*$ this should have a nominal cutoff value $w^*_{cutoff} = 0$. However, the choice made in the cut-off determination method does not necessarily provide the original injection speed of the PUIs, because of the smoothing effects on the cutoff discussed above. Thus the average cutoff value for the entire data set is found as $w^*_{cutoff}(average) = .027$. Because for the determination of the ISN flow longitude and for the study of the variations of the cut-off with solar wind parameters only changes of the cutoff around the average value are important, an offset from 0 does not influence the results presented here.
4.3 Data Structure

Preprocessing of raw STEREO-A PLASTIC data has been performed at the University of Kiel, Germany to consolidate the measurements to a workable format. Pulse height analysis is used in [Drews et al., 2010] to identify ion type and to measure the PUI velocity vector. These individual PUI velocities are transformed into the solar wind frame, and SW parameters, measured by PLASTIC and IMPACT, have been consolidated and averaged to meet PUI measurement cadence. IMF direction measurements, in elevation and azimuth, have been used to calculate the IMF cone angle, and PUI velocity measurements have been transformed and normalized to \( w^* \). Finally, all individual PUI counts are binned in \( w^* \) to produce an easily manipulatable VDF for every measurement period. This results in a consolidated data set comprised of averaged SW parameter measurements and He+ VDFs (in \( w^* \)) determined at a 10min time resolution, spanning STEREO-A’s operation from 2007-2013. Additional years are available to add to the consolidated data set, and are undergoing preprocessing. Each 10 min measurement period contains the following:

- \( t \): Time (in days from 2007)
- \( \phi \): Spacecraft longitude (in Ecliptic longitude defined from the Sun-Earth line at the spring equinox)
- \( v_{SW}(km/s) \): solar wind speed
- \( n(1/cm^3) \): solar wind number density
- \( |B|(nT) \): Magnetic field strength
- \( \beta \): Magnetic field cone angle (section 4)
- PUI phase space density measured in \( w^* \), binned in 75 sectors in the range \([-1 < w^* < .74]\)

For this analysis, the data set is manipulated using Python’s numPy package, all fitting routines are built using sciPy, and plots produced using pyPlot. Aside from the preprocessing, all analysis routines here have been developed for the sake of this study.
5  PUI Cutoff in Variable Local and Global SW Conditions

The solar wind can undergo considerable changes of local speed, composition, density, magnetic field strength, and temperature, that occur on different time scales. On average these fluctuations are driven by global structural variations, such as stream interaction regions (SIR), coronal mass ejections (CME), interplanetary shocks, or IMF reconnection events, but more local structures, such as transient interaction regions or turbulence can drive changes on a shorter time scale as well. Fundamentally, we don’t care about the classification of structures when analyzing the effects that these solar wind fluctuations have on PUI VDF. Since the primary goal is to simply remove or correct for these effects, it is important to identify all changes in the SW parameter as obtained aboard STEREO. The analysis begins with an unbiased assessment of parameter dependencies of the PUI cut-off at the highest time resolution (5.1). This technique that has been shown to be effective at identifying systematic trends in the PUI cutoff shift in a previous study [Taut et al., 2017], where the authors analyze the dependence on the magnetic field angle. As a next step, the study moves on to generic compression structures. In order to analyze the effect of these generally defined compression structures, it is statistically pertinent to identify as many compression regions as possible, whether they are considered co-rotating interaction regions or transient interaction regions. These events are characterized and identified automatically with a selection routine, allowing for similar compressions to be integrated in a superposed epoch analysis, to find a parameter dependence between the PUI cut-off and the compression strength (5.2). Finally, the most extreme compressions are considered. With shock fronts identified separately, and used as the epoch, solar wind parameters and PUI counts are superimposed according to their shock propagation direction (5.3). This results in a maximum PUI cut-off at the shock front passing.

5.1  Local Fluctuations of SW Parameters

The analysis begins by looking at correlations between indiscriminate, instantaneous changes in the solar wind and the effect that these factors have on the PUI cutoff. In a similar manner that the data set is evaluated in longitude to isolate the effect of longitudinal variation, which yield the ISN flow direction, this process is now repeated as a function of solar wind parameters, which yield other systematic dependencies. Each parameter \(v_{sw}, np, |B|, dv_{sw}/dt, dB/dt\) and PUI velocity spectra are resolved on a 10 min
Figure 16: PUI VDF as a function of $w^*$ for different values of local velocity gradients. The VDF for the largest local gradients (red) is shifted to larger $w^*$, while for gradients close to zero (blue, purple) the VDF has the lowest cut-off value.

resolution. The 7 year data set is sorted in one of the SW parameters and divided into sections with increasing parameter value. In each of the sections, the SW parameter is averaged and the PUI counts are integrated, giving a single 1D VDF. The cutoff value for each of these spectra is then determined using one of the Half-Max routine. This analysis results in a measurement of the PUI cutoff as a function of a single SW parameter and is used repeatedly to de-construct systematic trends in the cutoff shift due to the local solar wind conditions. Being that the solar wind is an incredibly dynamic environment, one must recognize that solar wind parameters may be linked in some way, and thus one must be careful when trying to determine the effect of a single parameter. Toward the goal to improve the ISN flow measurement, simply identifying criteria in solar wind measurements that result in a shifted PUI cutoff results in a filter to remove highly perturbed PUI times.

The derived-parameters, $dv_{sw}/dt$ an $dB/dt$, are first be calculated using the parameters from the data set. These gradient values are important in that they essentially measure the solar wind variability and yield information on the local compression or rarefaction properties. Due to the discrete nature of the data set, the gradient parameters are calculated in 10 min increments over 20 min periods using Euler’s approximation,
Figure 17: Variation of the PUI cut-off with interplanetary magnetic field strength (a), solar wind speed (b) and their gradients (c) and (d), and with solar wind density (e) at high time resolution. The cut-off shift shows a trend toward larger values of $w_{\text{cutoff}}$ with $B$, $Vsw$, and $nsw$, $|dv_{sw}/dt|$ and $|dv_{sw}/dt|$.
such that at a specific time increment $n$, the solar wind speed and field gradients are:

$$dv_{sw}^n/dt = \frac{v_{sw}^{n+1} - v_{sw}^{n-1}}{2\Delta t}$$  \hspace{1cm} (17)

and

$$dB^n/dt = \frac{B^{n+1} - B^{n-1}}{2\Delta t}$$  \hspace{1cm} (18)

$B$ is the field strength, $v_{sw}$ is the magnitude of the solar wind speed and $\Delta t$ is the time step associated with the time resolution of our data set (for this operation: 10 min).

The PUI counts are binned for all five parameters. Each list is sectioned into 20 bins of the parameter of interest, such that there are similar statistics in each parameter range. This results in different bin widths in parameter space, as there are fundamentally lower statistics for the largest and smallest values of each parameter. In each range, the parameter is averaged, and the PUI counts are accumulated. This results in 20 PUI VDF’s, each with an associated parameter average. As an example how the PUI PSD varies with interplanetary parameters, Figure 15 shows five of these PUI VDFs sorted in ranges in $dv_{sw}/dt$. Each of the PUI VDF’s are normalized to the max count rate, and the cutoff is identified using the half max routine. Figure 17, shows $w^*_{cutoff}$ binned in 20 ranges as a function of $d|B|/dt$ (17c), $dv_{sw}/dt$ (17d), $|B|$ (17a), $n(17e)$ and $v_{sw}$ (17b).

In Figure 16 the most negative $dv_{sw}/dt$ value, seen in red, has a visible shift to higher $w^*$ values, and the lowest magnitude $dv_{sw}/dt$, seen in purple, yields the lowest cutoff value. This essentially means that for decreasing $dv_{sw}/dt$, where one would expect a cooling, the PUI’s are seeing a heating. Additionally, for a positive $dv_{sw}/dt$ of smaller magnitude (yellow), the VDF exhibits a relatively smaller positive shift. This observation is consistent with the $dv_{sw}/dt$ parameter dependence in Figure 17 (b), which shows a clear positive $w^*_{cutoff}$ shift for both positive and negative $dv_{sw}/dt$. A similar response is visible in Figure 17 (a) where $w^*$ also shows a positive shift for large gradients in $|B|$. The strongest linear trend is associated with $|B|$ (c), where $w^*_{cutoff}$ also drops below its average of .025 for small values of $|B|$. The solar wind density (d), seems to be a poor indicator of PUI heating. With the exception of very high densities, no trend is observed. The largest range between the max and min $w^*_{cutoff}$ is found for the solar wind velocity (e), with a minimum near 400km/s, which is close to the most frequent value for $v_{sw}$.

5.1.1 Parameter Coupling

After identifying cutoff dependences associated with each one of the parameters separately, one must note that each one of these parameters changes do not occur in isolation.
(a) PUI cutoff as a function of field strength for different ranges of SW velocity fluctuations.

(b) Slope of the $w^*_{\text{cutoff}}$ and $|B|$ correlation as a function of SW velocity gradient. Each of the points in the colored regions are slopes associated with the plot and fit-line of the corresponding color. During times with large PUI velocity fluctuation (blue/green), the cutoff shift shows a more substantial correlation with the field strength.

Figure 18: (a) Linear relationships between the PUI cutoff and B field strength in four different ranges of $dv_{sw}/dt$ (b) Slopes of the cutoff-field strength correlations as a function of SW velocity gradient. Each of the points in the colored regions are slopes associated with the plot and fit-line of the corresponding color. During times with large PUI velocity fluctuation (blue/green), the cutoff shift shows a more substantial correlation with the field strength.
Therefore, similar trends of PUI cutoff with SW velocity and field strength gradients are likely connected with natural coupling between the two parameters. For the SW velocity and field strength gradients this is a fairly intuitive result for quasi-perpendicular IMF orientations that we are restricted to measure. If we measure an increase in the SW velocity, then it follows geometrically that the SW parcel being measured is being compressed, as the SW compresses the magnetic field strength in the packet increases because the field lines are being brought closer together. For this reason, these trends cannot be taken at face value and must be further dissected.

Therefore, we will be looking at the relationship between the PUI cutoff, the magnetic field strength and the solar wind velocity fluctuations in combination next. To perform this task, the data is initially as described above to identify cutoff dependence on the velocity fluctuations. The time series of $dv_{sw}/dt$, $|B|$ and PUI counts in $w^*$ are all sorted in increasing $dv_{sw}/dt$. Each of these variables are then broken into 14 sections of similar statistics, according to $dv_{sw}/dt$, and $dv_{sw}/dt$ in each range is averaged. This results in lists of $|B|$ and PUI $w^*$ counts associated with the average $dv_{sw}/dt$ values. Each of these sub-lists are sorted according to $|B|$, and broken up into 10 ranges of field strength. For each of the ranges of this sub-list, $|B|$ is averaged, the PUI counts are accumulated into a single VDF which is normalized, and a cutoff value is identified using the half max routine. This results in a relationship between $|B|$ and $w^*_{cutoff}$, that changes for each $dv_{sw}/dt$. The slope of each of these linear trends is found by fitting a linear function through least squares minimization. Four of these sample dependencies, between $w^*_{cutoff}$ and $|B|$, in ranges of $dv_{sw}/dt$ can be seen in Figure 18 (a). The relationship between the slope of the cutoff-field strength correlation ($dw^*_{cutoff}/d|B|$) and $dv_{sw}/dt$ is shown in Figure 18 (b).

An approximately linear trend is identified between the PUI cutoff and $|B|$ in Figure 17 (c). While Figure 18 (a) shows that a linear trend between $w^*_{cutoff}$ and $|B|$ for any $dv_{sw}/dt$, the slope of the correlation is largely dependent on the magnitude of the velocity fluctuations. In the blue trend (top left) of Figure 18 (a), there are large negative velocity gradients which result in a cutoff shift of $\bar{w}^*_{cutoff} = .05$ on average. This value is consistent with 17 (d), but when the PUI are sorted for $|B|$, $w^*_{cutoff}$ shows a range of $\pm .06$. This is juxtaposed against the red trend (bottom left), where the magnitude of the SW velocity fluctuations are at a minimum, the trend is essentially flat and the cutoff has a range of $\Delta w^*_{cutoff} \approx .01$. This relationship between $dw^*_{cutoff}/d|B|$ and $dv_{sw}/dt$ seems to be approximately continuous and occupies mostly associated with the magnitude of the
Figure 19: Schematic view of a SIR in the ecliptic plane, showing the sequence of compression and rarefaction regions. Red indicates the approximate region of the compressed slow wind, purple, the compressed fast wind and blue, the rarefaction region. The black arc indicates STEREO’s trajectory through the SIR. Radial arrows indicate the local solar wind speed. The two large arrows that emerge from the stream interface indicate the compression region expansion into the slow and fast wind. Figure adapted from Pizzo [1978].

velocity gradient. The effect of the coupled negative and positive gradients on the PUI cutoff has not yet been identified, but some information deconstructing the effect of these gradients will be revisited in section 6. after we evaluated the variation of the cut-off shift across identified compression regions and as a function of their strength in the next section.

5.2 Large Scale Compression Regions in the Solar Wind

As opposed to SW variations on a fast time scale that may include waves and turbulence, we now look at the effects of time periods with sustained compressions or rarefactions on time scales of hours to days. One such compression type, known as the stream interaction region, depicted in Figure 19, is created when fast wind runs into preceding slow wind [Gosling and Pizzo, 1999]. Due to the frozen in magnetic field, the plasma populations of the two SW types are prevented from interpenetrating [Gosling and Pizzo, 1999]. As a consequence, a compression region forms between the fast and slow wind. As the
compression region evolves, matter piles up at the interface between the two plasmas, separating the high density compressed slow wind (seen in red) and the relatively low density compressed fast wind (seen in purple) [Gosling and Pizzo, 1999]. This pile up, known as the stream interface, is characterized by a large peak in density and increase in proton temperature [Gosling and Pizzo, 1999]. The density maximum is often defined as the stream interface, and we will follow this definition here. Figure 20, shows a sample sequence of three compressions in the SW velocity, number density and magnetic field strength. The sequence of a fast wind and trailing slow wind creates the rarefaction region (seen in blue) where the velocity and pressure decrease and the plasma is cooled. To evaluate the effect that these large compression structures have on the PUI VDF with sufficient counting statistics, we perform a superposed epoch analysis across all compression regions identified in the STEREO data between 2007 and 2013. This analysis is explained in the following.

5.2.1 Compression Region Identification

The process of identifying these compression regions utilizes the SW number density and velocity. SW measurements, which are synchronized with our PUI data sets are measured in 10 min increments. This high time resolution results in substantial local fluctuations that must be removed to see more global structures. Density and speed are averaged in 100 min increments using a nearest neighbor running average. The compression regions of interest occur on time scales on the order of 2 days. Thus, 100 mins is still a relatively high resolution. Peaks, which represent the stream interface are identified in the number density by performing a numerical differentiation of the smoothed time series and identifying the zero crossings [?, Gosling et al., 1996] After the peak finding routine is performed, the most prominent peaks in the number density are selected (top 20%, which are deemed "large compressions).

Using the stream interface as a reference point, the local structures of the stream interaction region can be identified. The stream interaction region begins at the local minima in the solar wind velocity, preceding the stream interface, and continues until the solar wind speed stops increasing. This region encompasses measurements of the compressed slow solar wind, which the spacecraft measures first, and the compressed fast solar wind that is running into it. The region from the well to the peak of the stream interface, represents the slow solar wind, and encompasses the large increase in SW density where the matter of the fast solar wind piles up with the slow solar wind.
Figure 20: Solar wind speed and density (top) and magnetic field strength (bottom) as a function of time for a sample of three consecutive STEREO crossings of compression regions. Each compression is subdivided into four regions of interest, the compressed slow wind in red, the compressed fast wind in purple, the peak region in white and the rarefaction region in blue, matching the colors in Figure 19.
The compressed fast wind is defined from the stream interface up to the point where the SW velocity stops increasing. The peak region spans between the compressed fast wind and the rarefaction, where $v_{sw}$ is approximately constant. Finally, the rarefaction region begins when the SW velocity starts to decrease, and continues as long as there is a negative slope. The result of this identification scheme can be seen for a 20 day span in Figure 20.

Here three compression regions are identified, with each section highlighted, red for the compressed slow wind, purple for the compressed fast wind, white for the peak region, and blue for rarefaction region. The red line overplotted on the $v_{sw}$ measurements and the blue line on the density measurements represent the smoothed time-series used in the peak finding routines. The three compression regions vary in a number of ways. The first compression is rather large, with a solar wind velocity increase of $\approx 300 km/s$, a peak density value of nearly 50 $1/cm^3$, and a large magnetic field peak. This compression is followed by a long rarefaction region, spanning nearly 5 days, where the density and magnetic field strength are low and calm. The second compression, is much smaller, and is not really considered a SIR at all. While there exists a substantial build up in density, there is only a small increase in the solar wind velocity, and the magnetic field does not return to pre-compression levels in the rarefaction. The third compression, is of comparable magnitude to the first, but instead of a long drawn-out rarefaction region, a second parcel of fast wind arrives.

The compression regions are classified using four different identifiers, the relative change in solar wind velocity ($v_{sw2}/v_{sw1}$), where $v_{sw2}$ is the solar wind velocity at the end of the compressed fast wind, and $v_{sw1}$ is the minimum solar wind velocity at the start of the compressed slow wind. The compression region steepness ($\Delta v/\Delta t(km/s^2)$) (which is essentially the solar wind acceleration), is determined separately for the compressed fast wind, compressed slow wind, total compression and rarefaction. A proxy for the total magnetic flux in the compression $|B|s$ is determined by integrating the magnetic field over the compression. Finally, the peak height of the stream interface ($\Delta n p(1/cm^3)$) is used. The PUI count measurements are also accumulated in each one of these regions, yielding four separate VDF’s, one for each of the compressed slow wind, compressed fast wind, peak region, and rarefaction region. This sample of large scale compressions allows for a parameter study of the PUI cutoff based on compression strength. To see the effect, on the PUI cutoff, adequate statistics are required. This is achieved through a superposed epoch analysis (SPE), where multiple compression events are accumulated and averaged.
to see underlying trends. We construct an average time series that shows the evolution of the solar wind parameters across the SPE compression region. The start and end times of the slow compressed wind, the fast compressed wind, the peak region, and the rarefaction region (the limits of the colored regions in Figure 20) are used as time stamps for the SPE analysis. Then we stretch or compress the sections of each event in time so that they are all compiled on a similar time scale, referred to as the SPE time. The matching of the times is achieved through performing a running average on the SW parameters of each compression and through binning the PUIs, such that each compression has the same relative time resolution. These time series for each compression are averaged to create the SPE compression, with the end of the compressed fast wind as the epoch. We have chosen $v_{sw}, \, n, \, |B|$, the PUI count rate, and $|dv_{sw}|/dt$ as our SPE SW parameters. Section 5.1 has shown that the PUI cutoff varies substantially with $v_{sw}, \, n, \, |B|$, and $|dv_{sw}|/dt$, thus evaluating these parameters across the SPE compression should provide additional insight. Additionally, the PUI count rate will provide insight into the compression effect on the PUI population. The result of this routine, after averaging the largest 20\% (based on the steepest SW velocity increase) compressions can be seen in Figure 21.

In the SPE average compression region, the solar wind speed gradient steepens in the slow compressed wind and further into the fast compressed wind. In the fast compressed solar wind the velocity gradient is steepest, and approximately linear across the region. The SW density is decreasing during this entire span, and returns approximately to pre-compression levels. The magnetic field strength continues to increase into the compressed fast wind, which places the peak here. The field strength starts to decrease in the compressed fast wind, and remains slightly above pre-compression levels in the peak region and into the rarefaction region. The rarefaction region is characterized by a linearly decreasing solar wind velocity, low density and magnetic field strengths. The PUI count rate approximately follows the solar wind density, with a max at the stream interface, but the function appears to be slightly asymmetric with increased PUI count rate into the rarefaction region. The velocity fluctuation magnitude increases through the compression region, reaching a peak at the end of the compressed fast wind. This peak is sustained through the peak region and the fluctuations decrease in the rarefaction region, although they are still well above pre-compression levels.
Figure 21: Average temporal evolution across the superposition of compression regions, shown here for, SW velocity, density, magnetic field strength, PUI count rate, and magnitude of the local solar wind velocity gradient (from section 5.1). Shown is the result from a superposed epoch analysis of 100 compressions selected for large total increases in solar wind velocity. The compression region (blue & purple) shows increasing $v_{sw}$, peaks in the density and field strength, and high average PUI count rate and local solar wind velocity gradients.
Figure 22: PUI cutoff (top) and 2D count rate density (bottom) evolution across the SPE SIR event. The max PUI cutoff comes at the end of the compressed fast wind, and drops off substantially going into the rarefaction region. The beginning of the rarefaction region still yields substantially shifted cutoff values.

5.2.2 Evolution of PUI VDF across the SPE Compression

The same SPE averaging across the compression region is also performed on the PUI measurements to see how the PUI VDF and cutoff evolve as a function of time from the end of the compressed fast wind, shown in Figure 22 (bottom). The cutoff in each of the bins in SPE time is now identified using the half max routine, which yields a time-series of $w^{*}_{\text{cutoff}}$ across the SPE compression that can be seen in Figure 22 (top). Evidently, more PUI counts will be accumulated in longer compressions. Which means that they will have a larger effect on the PUI SPE time series.

The PUI cutoff shows a large increase beginning in the compressed slow wind, increasing from a below average cutoff values of $w^{*}_{\text{cutoff}} \approx .015$ to $w^{*}_{\text{cutoff}} \approx .055$. The cutoff value reaches its peak at the end of the compressed fast wind with a value $w^{*}_{\text{cutoff}} \approx .075$, where the average SW velocity gradient is steepest, and the magnetic field strength is near
Figure 23: PUI VDF as a function of $w^*$ for four different sample of compressed fast wind, compression strength ($\Delta v_{sw}/\Delta t$) is shown for each distribution in the top right corner. At the highest compression strength (black), the VDF shows a substantial shift to higher $w^*$ values and a more substantial high velocity tail.

its peak. The cutoff remains elevated through the peak SW velocity into the rarefaction region, where it bottoms out toward the end, slightly below the average cutoff. Figure 21 also shows that large values of $dv_{sw}/dt$ exist in the peak region and persist into the rarefaction region. The VDF evolution, seen in Figure 22, shows a visible shift to higher $w^*$ in the compressed fast wind and rarefaction region, but an apparent broadening in the compressed slow wind. Additionally, there is an increased flux of high velocity tail particles starting in the compressed slow wind and continuing into the very beginning of the rarefaction region.

5.2.3 Compression Region Parameter Dependence

With the compression regions identified and characterized, the next step is to perform a parameter dependence study, similar to the one performed on the local fluctuations. Each compression region contains a compressed slow wind, compressed fast wind and rarefaction region, that are characterized by the average steepness of the solar wind speed gradient across the region. For each of these regions, the PUI counts are accumulated into separate VDFs. This results in lists of compression/rarefaction strengths, and the corresponding VDFs, which are sorted in increasing $\Delta v_{sw}/\Delta t$ and sectioned into 10 ranges. $\Delta v_{sw}/\Delta t$ (not to be confused with $dv_{sw}/dt$ from the high time resolution
Figure 24: (a) PUI cutoff shift as a function of the compression strength in the compressed fast (purple) and compressed slow (red) wind. (b) The PUI cutoff shift as a function of the rarefaction region $\Delta v_{sw}/\Delta t$. The compressed slow wind, fast wind and rarefaction regions all seem to show a correlation with $|\Delta v_{sw}/\Delta t|$ parameter study) is the average gradient over the region, calculated using the smoothed $v_{sw}$. A sample of four of these VDFs are seen in Figure 23, where a large $\Delta v_{sw}/\Delta t$ (green) results in a substantial shift to higher $w^*$. The VDF’s show that for the steepest compressions $\Delta v_{sw}/\Delta t = 2.9$ there exists a substantial bulk heating of the PUIs. The separation here is visibly more prominent when compared to the VDF separation of the high time resolution $dv_{sw}/dt$ seen in Figure 16. When compared to the less substantial compression regions the VDF is shifted to higher $w^*$ without any flattening that is seen in the local fluctuations.

The cutoff values are plotted as a function of the average $\Delta v_{sw}/\Delta t$ in Figure 24, where (a) shows the $w^*_{cutoff}$ dependence on $\Delta v_{sw}/\Delta t$ in the rarefaction region, and (b) shows the $w^*_{cutoff}$ dependence in the compressed fast (purple) and slow (red) wind. The cutoff shifts drastically for large compressions and appears to be linearly related to the slope of the compression. In the second plot in Figure 24, the cutoff in the rarefaction region, sorted and accumulated for the rarefaction gradient strength ($\Delta v_{sw}/\Delta t$), appears to be increasing the steeper decline of the rarefaction region.

To identify if this unexpected trend is restricted to PUIs at the beginning of the rarefaction region, the region is subdivided into two sections, one closest to the compression peak and one in the tail of the rarefaction. This essentially draws a new dividing line.
through the rarefaction region, where the PUI counts are accumulated in the top of the
rarefaction region separately from the tail of the rarefaction region (dashed vertical line
in figure 21). The resulting cutoff values are shown in Figure 25. In the section of the
rarefaction region immediately following the compression peak (a), the cutoff varies lin-
early with the compression strength, while in the rarefaction tail (b)) there is almost no
trend, but the average cutoff is similar to the one in (a).

5.3 Interplanetary Shocks

Fast collisionless shocks lead to some of the most substantial acceleration processes that
are observed in the solar wind. The vast majority of interplanetary shocks are the result
of compressive interactions driven by stream interaction regions or coronal mass ejections
(CMEs) [Kilpua et al., 2015]. Fast shocks in interplanetary space are divided into two
categories dependent on their propagation direction with respect to the solar wind, where
shocks that propagate with the solar wind, radially away from the Sun, are deemed fast
forward shocks (FF) and shocks that propagate toward the Sun, but still outflowing with
the solar wind, are deemed fast reverse shocks (FR). The majority of shocks at 1au are
driven by CMEs, and forward propagating [Berdichevsky et al., 2000]. A given CME
has a 66% chance of developing a shock at 1au [Jian et al., 2008]. A FF shock forms in

Figure 25: The PUI cutoff in the rarefaction region, in the time immediately following
the compression (a), and in the tail end of the rarefaction (b), revealing a more substan-
tial negative correlation between the cooling strength and the cutoff in the top of the
rarefaction region than in the tail.
Figure 26: Diagram showing the creation of forward and reverse shocks around the interaction region of a compression in a stream interaction region. The Forward shock propagates with the solar wind flow direction into the slow wind and the reverse shock propagates against the solar wind flow direction into the fast wind [Steinberg et al., 2005].

front of a CME if the relative motion between the CME and the preceding solar wind exceeds the magnetic sound speed. Because CMEs are such violent events, they are more likely to meet this criterion compared to an SIR [Kilpua et al., 2015]. Additionally, since the occurrence of CMEs correlates with solar activity, so does the total number of FF shocks [Lindsay et al., 2000]. Because the STEREO data set covers solar minimum around 2009, there are fewer FF shocks in the first half of the data set than in the second. The shock normal of the CME-driven shocks on average points more often into the radial direction, while SIRs have a broader distribution of shock normals [Lindsay et al., 2000]. Coupled with the fact that STEREO’s FoV is limited to quasi-perpendicular field directions, FF shocks, associated with CMEs, will be statistically favored when measuring PUIs in shock regions.

Stream interaction regions, as described in section 5.2, are created through a fast stream running into a preceding slow stream where they develop a compressive interaction region between the two. This interaction region creates two pressure waves expanding forward into the compressed slow wind and reverse into the compressed fast wind. As soon as the pressure wave velocity that expands into either one of these regions increases past the magnetosonic sound speed shocks develop [Gosling and Pizzo, 1999]. Thus,
stream interaction regions may be bounded by both a FF shock propagating into the slow wind and a FR shock propagating into the fast wind. The basic structure of this interaction and shock development can be seen in Figure 26. Here, one can see the forward and reverse shocks bounding the interaction region of the SIR at distances beyond 1au. Approximately 24% of SIRs have developed shocks at 1au, and many more of these SIRs will develop shocks as they propagate outward due to the decrease in SW density. [Jian et al., 2006]. Additionally, Figure 26 shows an effective spacecraft trajectory as the interaction region passes over the spacecraft. The effective trajectory means that the spacecraft will pass from the pristine slow wind through the shock front and into the interaction region in a FF shock, and from the interaction region through the shock front and into the pristine fast wind in a FR shock.

As in section 5.2, for compression and rarefaction regions, we superimpose all forward and all reverse shocks so that there is sufficient PUI statistics to determine heating of the torus particles. Creating an SPE time-series for interplanetary shocks is more straightforward than for compression regions, because the shocks only have one relevant structure (the shock front), the times around the shocks can be mapped 1:1. The shock times for STEREO A were taken from IPshocks.com for the entire time of operation of the satellite. With the shock fronts as a reference point, the solar wind parameters 200 mins before and after each shock are considered. The time series for each parameter can then just be averaged point by point with all of the other shocks. The PUI accumulation is similar, for each parameter measurement there is a PUI VDF, so at each measurements in time around the shock front, the PUIs are accumulated, normalized and the cutoff is determined using the half-max routine.

5.3.1 VDF of Fast Forward and Fast Reverse shocks

As discussed in the previous section, fast Forward (FF) and Fast Reverse (FR) shocks are classified by their propagation direction, where FF shocks propagate away from the Sun (with the solar wind), and fast reverse shocks propagate toward the Sun (against the solar wind). For this study the directional designation of the shock front is provided with the data set, but the propagation direction can be seen clearly in changes in the solar wind parameters. With these designations, PUI counts are integrated and SW parameters are averaged based on the shock propagation direction. So, all FF shocks (154 events) and all of the FR shocks (41 events) are accumulated separately, allowing for the time and directional dependence of each of these shock structures to remain intact.
Figure 27: Time series of the solar wind parameters, $v_{sw}$, $n_p$ and $|B|$ the PUI cutoff and VDF across the average FF shock. The PUI cutoff, and 2d VDF now show the directional dependence of the shock, there is a clear max cutoff value at the shock front which decreases as the shock get further away.
Figure 28: Time series of the solar wind parameters, $v_{sw}$, np and $|B|$ the PUI cutoff and VDF across the average FR shock. The direction of the FR shock can be seen in the density in field strength which decrease as the velocity increase, this is expected as the shock front is propagating into the fast wind. The PUI cutoff is massively shifted by the shock up to 200 mins before the spacecraft passes through the shock front, and very quiet after it passes.
Figure 29: Velocity distribution functions averaged 200 mins before and after the average FF (a) and FR (b) interplanetary shock passes, compared with the 7yr averaged VDF (purple). The VDF downstream of both shock fronts shows considerable heating.

The velocity distribution functions before and after the FF and FR shocks are shown in figures 29a and 29b respectively. The SPE SW parameter PUI cutoff time evolution across the FF and FR shocks can be seen in figures 27 and 28. In the FF shock (Fig. 27), the spacecraft is passing from the upstream region, or the pristine slow wind, into the downstream region where the SW has undergone the shock compression. In the FR shock (Fig. 28) the opposite sequence occurs, where the spacecraft starts in the downstream interaction regions. Then the shock and SW are swept past the spacecraft, revealing the upstream pristine fast wind. All transitions from the upstream to the downstream regions are associated with large increases in the number density, and field strength, along with massive cutoff shifts at the discontinuity.

The VDFs in Figure 29a show that there is a high flux of accelerated particles both before the shock arrives as well as after it passes, but after the shock passes, there is a much larger bulk heating. The directional dependence of the FF shock is seen affecting the PUI cutoff in Figure 27, as there is bulk heating in the VDF immediately after the shock passes, while there is minimal heating before the shock arrival. In the $w^*$ cuto$ff$ time-series, this causes a defined peak at the shock passage, followed by a slow decrease in the cutoff after. The PUIs remain heated until about 100m after the shock passes. The directional dependence is also clearly visible in the SW parameters. As the shock front propagates into the slow wind, there is a drastic increase and discontinuity in the
solar wind velocity as the particles experience the massive shock compression. The field strength and density also have discontinuities at the shock front and both increase by about a factor of 2.

The evolution of the SW parameters, PUI VDF, and cutoff across the SPE average FR shock front can be seen in Figure 28. Here the PUI cutoff is positively shifted as the SPE begins at -200 mins, and shifts the cutoff up to $w_{\text{cutoff}}^* = .4$, an even larger heating than the PUIs have undergone in the FF shock. This increase in the PUI heating is consistent with the shock propagation direction, as the shock is ramming into the fast solar wind flow, the shock speed adds to the solar wind speed. Immediately after the shock convects past STEREO, the PUIs are back to pristine SW levels. Due to the shock propagation direction, STEREO sees particles that have passed through the shock before the shock arrives at the spacecraft. This results in a massive increase in the PUI cutoff before the shock front arrival, and no effect afterward. Additionally, this effect is seen in the SW parameters, as the shock is propagating into the fast wind, the solar wind velocity increases, while the magnetic field strength and density go down. This is consistent with the view that the matter is flowing through the shock from the fast wind toward the preceding slow wind. Additionally, the directional dependence of the FR shocks is seen in the PUI VDFs in Figure 29b. Before the shock arrives there is a huge flux of highly accelerated PUIs, as well as massive bulk heating, both of which are expected since the spacecraft is in the downstream region. As soon as STEREO passes the shock front it encounters an unaffected PUI population because it transits from the downstream region, where the shock has affected the particle populations into the upstream region, which is still unaffected.
6 Discussion

Several different systematic effects have now been identified, but still need to be digested and placed in context. In review, section 5.1 identified $w_{\text{cutoff}}^*$ as a function of 5 solar wind parameters, $dB/dt, dv_{sw}/dt, |B|, n, \text{ and } v_{sw}$. An approximately linear relationship between the PUI cutoff and $|dB/dt|, |dv_{sw}/dt|$ and $|B|$ was discovered, seen in figures 17c, 17d, and 17a respectively. $w_{\text{cutoff}}^*$ seemed to yield no trend with the solar wind density (17e) while there appears to be a correlation between $w_{\text{cutoff}}^*$ and $v_{sw}$ at least for large $v_{sw}$ (17b). Additionally, in section 5.1.1, coupling between $|B|$ and $dv_{sw}/dt$ in their effect on $w_{\text{cutoff}}^*$ was studied, showing that very large shifts in $w_{\text{cutoff}}^*$ occur for large $|B|$ and $|dv_{sw}/dt|$. Section 5.2 presented an automated procedure to select for compression regions in the solar wind using established patterns in solar wind speed and density. When superimposed, these events create an average compression time-series, seen in the solar wind parameters in Figure 21, and seen in the PUI cutoff and VDF in Figure 24. These compression events were characterized by there $\Delta v_{sw}/\Delta t$, and binned for a parameter study, resulting in a positive linear correlation between $w_{\text{cutoff}}^*$ and $\Delta v_{sw}/\Delta t$ in both the compressed fast and slow wind, and a negative correlation in the rarefaction region. The rarefaction region was subdivided into one region immediately following the peak in the solar wind velocity and one regions making up the tail, showing that the cutoff shift in the region comes from the section following the peak. Finally, in section 5.3, FF and FR shocks were superimposed to analyze how $w_{\text{cutoff}}^*$ and the PUI VDF evolve as the shock passes. Here the maximum $w_{\text{cutoff}}^*$ was identified just downstream of the shock front. The FR shocks proved to have a stronger effect, though there are fewer of these events to analyze.

The high time resolution parameter dependencies seen in Figure 17, reveal some counter intuitive trends between $w_{\text{shift}}^*$, $dv_{sw}/dt$ and $|B|$. Figures 17c and 17d show that $w_{\text{shift}}^*$ shows a positive increase for large magnitude gradients in both solar wind velocity and field strength. Naively, one would expect the solar wind to undergo a compression and associated heating when $dv_{sw}/dt$ is positive, and an expansion and associated cooling when $dv_{sw}/dt$ is negative. If this were the case, $w_{\text{shift}}^*$ would continue decreasing for more negative $dv_{sw}/dt$, resulting in a linear relationship between $w_{\text{cutoff}}^*$ and $dv_{sw}/dt$. The fact that $w_{\text{cutoff}}^*$ scales instead with $|dv_{sw}/dt|$ and $|d|B|/dt|$ in a similar manner leads us to two possible scenarios. Either the field strength gradients and the solar wind gradients are correlated and indicative of some compressional turbulence that drives heating in the PUIs, or the PUIs are being heated by some large scale compression that brings
with it large velocity and field strength gradients.

If these large velocity gradients are associated with a global compression then this dependency would actually be the result of a selection bias. If we analyze the parameter dependencies in Figure 17 in conjunction with the SPE compression structure in the solar wind parameters (Figure 21) some important relationships come to light. Firstly, looking at the relation between $v_{sw}$ and $w_{cutoff}$, there appears to be a clear minimum of the cutoff value around 400km/s, while the value increases to lower and higher speeds. At low $v_{sw}$ the cutoff values are strongly variable with no clear trend. The minimum may be related to the fact that 400 km/s is the most frequently occurring speed and thus more likely steady. The large variability at the lowest solar wind speeds, could be due to their occurrence at the end of a rarefaction region and thus be actively cooled, or in the compressed slow wind and thus actively compressed. The clear trend toward large cutoff values for high $v_{sw}$ may be understood looking at the SPE time series, and at the individual compression events (Figure 20). It is evident that the highest solar wind speeds inherently come in and around the compressed fast wind. This is magnified by the fact that the PUI count rate increases inside of compressions, where matter piles up. Additionally, due to the limited FoV of the STEREO SW sector, the PUI torus is only observable when the magnetic field is close to 90° from the Sun-spacecraft line, limiting PUI measurements to a times with special field orientations. Perpendicular field orientations actually favor compression regions, as the fast wind rams into the slow wind, where the IMF becomes more perpendicular, see Figure 19 [Gosling and Pizzo, 1999]. This logic can also be extrapolated to the other parameters. Large magnetic field strengths and densities are associated with large cutoff shifts, but the SPE time series shows that large field strengths and densities generally come in the heart of these global compression regions. So, rather than the density and field strength acting as drivers of the PUI heating, it is possible the general topology compression affects both PUIs and SW parameter measurements alike.

Additionally, this result could be a property of the way the cutoff is measured, where a deformation of the torus could appear as an increase in the cutoff. For an example of how this could work, we consider the possible generation of local motional electric fields through changing SW speeds. In any local velocity change, there is relative motion between the two SW parcels that could induce a local electric field. If the field is induced perpendicular to $B$ for a brief time, then a portion of the gyrating PUIs would be accelerated while others would be decelerated, depending on their phase in the gyroperiod.

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This could result in a measurable cutoff shift since the fitting routines are more sensitive to higher velocity PUIs that make up the cutoff of the VDF.

Looking at the high time resolution cutoff shifts in conjunction with the PUI cutoff evolution across the large scale SPE compression may yield some additional insight into the heating processes. In Figure 22, the PUI cutoff and VDF are seen evolving across the SPE compression. Prior to the compression arrival, the VDF appears to be cooled, dipping below the average values of \( w_{\text{cutoff}}^* = 0.02 \) and increasing rapidly in the compressed slow wind. The cutoff in the compressed slow wind alone reaches a value \( w_{\text{cutoff}}^* \approx 0.055 \), which is approximately the maximum cutoff value seen in any of the high time resolution parameter dependencies. The compressed fast wind continues to higher cutoff values, reaching a peak of \( w_{\text{cutoff}}^* \approx 0.075 \), notably higher than any of the high time resolution dependencies, before decreasing in the peak and rarefaction region. Though the cutoff is less than in the compression region, for the majority of the rarefaction region the cutoff is still shifted positively, signifying a sustained heating in the PUIs.

The heating in the rarefaction region could be the result of PUIs leaking from the compression into the following rarefaction region. Similar particle transport has been observed by Steinberg et al. [2005] where counter streaming electrons were identified in the rarefaction region of a CIR using ACE and Genesis data, the geometry of such a situation can be seen in Figure 26. Initially, the counter streaming electrons are accelerated by a shock front that is well formed at larger radial distances beyond the spacecraft orbit. Due to the magnetic field geometry, the spacecraft remains magnetically linked to the upstream shock and the accelerated electrons are able to stream along the field line to the spacecraft [Steinberg et al., 2005]. This mechanism could also apply to PUIs as they are also magnetically bound to the solar wind, they are also able to move freely along the field lines. Initially this hypothesis appears to be supported supported by observations seen in Figure 25, where the cutoff shift in the rarefaction region is seen as correlated with the \( \Delta v_{\text{sw}} / \Delta t \) value of the preceding compression. Since the relationship between the solar wind gradient in the compression region has already been shown to produce an approximately linear relationship with the cutoff shift, this behavior could be explained by the heated PUI distribution leaking into the rarefaction region. A substantial problem with this idea is that PUIs are substantially less mobile than electrons. Steinberg et al. [2005] observed counter streaming electrons up to 2.5 days after ACE passed through the interaction region. Since particle mobility scales with the particle mass PUIs potentially streaming along the IMF toward the Sun would be expected to be observable up
to $\tau = \sqrt{M_e/M_{He+}} \ast 2.5$ days, where $M_e$ is the electron mass and $M_{He}$ is the helium PUI mass. Since the PUIs are so much more massive than the electrons, they would only be expected to be observable for less than 100 min after leaving the interaction region. Since the PUIs are bound to the magnetic field, there appears to be no way for them to leak so far into the rarefaction region that they would produce measurable cutoff shifts up to a day after the compression passed. Instead, the fact that the cutoff in the rarefaction region scales with $\Delta v_{sw}/\Delta t$ in the preceding compression is likely tied to the compressional turbulence.

This positive cutoff shift in the rarefaction region instead, seems to suggest that the dependencies found in the high time resolution study might not simply be due to selection bias placing large $|v_{sw}|$ and $|dv_{sw}/dt|$ in compression regions. The solar wind in this region is known to be expanding and to have relatively low density. With just this structure considered, the PUI’s should undergo a cooling instead of a compression, and as such there must be other mechanisms at work. If the solar wind velocity gradients do translate to turbulent heating acting on the PUIs this effect could be explained by the fact that $|dv_{sw}/dt|$ is still large following the compression front and into the rarefaction. Figure 21 shows that $|dv_{sw}/dt|$ and $v_{sw}$ have a similar response in the SPE time series, resulting in the magnitude of the solar wind velocity gradient scaling with the solar wind velocity. For compressions with large $\Delta v_{sw}/\Delta t$, the solar wind velocity has to increase considerably, and as such so do the velocity gradients, resulting in the PUI’s in the rarefaction being heated by the compressional turbulence, and not the preceding compression.

Upon a return to Figure 22, which shows the PUI cutoff and VDF across the SPE compression, several other questions are raised. Not only is there an apparent heating in the rarefaction region, where cooling is expected, but the heating in the compressed fast wind is actually higher than expected as well. In an SIR, the stream interface represents the region of direct collision between the two streams, and as such the point where the solar wind undergoes the most substantial compression and heating [Gosling and Pizzo, 1999]. If the embedded PUI population follows the same principle, then this should also apply to the maximum $w^*_{\text{cutoff}}$. Instead, the maximum cutoff shift comes at the end of the compressed fast wind. Once again, this additional heating effect coincides with the maximum $v_{sw}$ gradient strengths. If these two effects are additive, the cutoff shift due to the turbulent heating can be estimated using the maximum $|dv_{sw}/dt|$ in Figure 21. The solar wind fluctuations reach a maximum value of $|dv_{sw}/dt| \approx .015$ so the cutoff shift due to the turbulent heating could account for approximately $\Delta w^*_{\text{cutoff}} \approx .01$. This effect
reduces the magnitude of the peak PUI heating at the end of the compressed fast wind, but does not reduce it below the cutoff shift at the stream interface. This supports the idea that PUIs undergo a slightly different heating process in the compression than the solar wind. When Saul et al. [2001] first observed PUI heating in the solar wind compression, they found that the most substantial heating that took place was associated with strong gradients in the solar wind speed. This process is also seen in Figure 24a, where the cutoff shift in the compressed fast and slow wind scale approximately linearly with the slope of the compression region. Because shocks are just strong, violent compressions, we can investigate to see if the PUI cutoff responds with a similar trend associated with the velocity gradient.

Like the compression region, the cutoff in the FF shock, seen in Figure 27, also reaches its maximum at the shock front where the solar wind velocity increases rapidly. At the shock discontinuity, the PUIs are heated to a much higher level compared with the largest velocity gradients at high time resolution or the average gradients in the large compression regions. This makes sense because the velocity gradient at the shock front is massive \( \Delta v_{sw}/\Delta t \approx 55 \text{ m/s}^2 \), where the max compression region velocity gradient was only \( \Delta v_{sw}/\Delta t \approx 3.5 \text{ m/s}^2 \). This seems to suggest that the steepness of the gradient in the solar wind velocity is fundamentally important for PUI heating. This process is not necessarily linear, as is suggested by the linear fit in Figure 24a. By comparing the max \( w^*_{cutoff} \) at the shock crossing in Figure 27 to the linear fit we see that this process might have a nonlinear dependence. The linear fit in the parameter relation between \( \Delta v_{sw}/\Delta t \) and \( w^*_{cutoff} \) in Figure 24a, yields:

\[
 w^*_{cutoff} = 0.21 \Delta v_{sw}/\Delta t + 0.01
\]

The measured solar wind velocity gradient resulted in \( \Delta v_{sw}/\Delta t \approx 55 \text{ m/s}^2 \), plugging this value into the linear fit results in \( w^*_{cutoff(calc)} = 1.1 \), while the measured cutoff value was \( w^*_{cutoff(measured)} = 0.2 \). So there is a substantial discrepancy between the two that either suggests that this relationship is nonlinear, or that efficiency of PUI heating due to compressions may be different for the two cases.

Besides PUI heating due to the effect of solar wind compressions and shocks, we must also discuss some other systematic effects that can change the cutoff velocity without heating or cooling. Stream interaction regions are defined by the geometry of a high speed solar wind packet running into the preceding slow speed stream, creating a high density compression between the two streams where the primary SW heating occurs [Gosling and Pizzo, 1999]. Using the knowledge of these compression structures one must rectify
their response in a single point observation as seen on STEREO. Ideally, a single solar wind parcel would be followed as it enters the interaction region, and actively sample the PUI VDF as it undergoes the heating, but due to the fact that the solar wind is flowing past STEREO, this is impossible. This results in the fundamental problem that the history of the PUIs must be inferred instead of measured. This problem manifests itself when looking into the fast and slow streams of a compression. An increase in the solar wind velocity is interpreted as a compression geometrically, regardless of the response of the other solar wind parameters. One should be careful to note that a positive $dv_{sw}/dt$ does not necessarily mean that the solar wind packet is positively accelerating. In the compressed slow wind, the high speed wind, drives the compression and in simple momentum conservation, it accelerates the slow speed stream. Conversely, in the fast wind the momentum conservation means that the solar wind is being decelerated. This mechanic may also affect the PUI cut-off shift, as PUIs are continuously injected into these regions, they will be measured with a different solar wind speed than they were injected into. This effect will either manifest itself as an overestimation of the solar wind velocity at injection in the compressed slow wind or an underestimation in the compressed fast wind. Since $w^{*} \propto \frac{1}{v_{sw}}$, this is expected to manifest itself in systematically higher cutoff values in the compressed fast wind and systematically lower cutoff values in the compressed slow wind. Looking at Figure 24a, this effect does not seem to dominate the cutoff response. If this $v_{sw}$ history dependence did dominate one would expect a vertical offset between the compressed fast wind and slow wind parameter dependence, with the compressed fast wind resulting in higher cutoff values for each $\Delta v_{s}/\Delta t$. Figure 24a seems to show no meaningful separation between the two lines. In fact, the slow PUIs could possibly have a slight shift to higher cutoffs, which might be explained by the solar wind expansion.

In the solar wind, the proton and alpha particle temperatures decrease with radial distance ($R$) from the Sun. As a shell of solar wind particles expands, it’s flux is conserved and as such undergoes expansion and adiabatic cooling $Q \propto R^{-4/3} * v_{sw}$ [Hellinger and Trvncek, 2013]. The PUIs are also affected by this expansion, which will cool PUIs to inner shells in velocity space, reducing the cutoff. Since this effect scales with the solar wind velocity, PUIs in the compressed fast wind will be cooled more substantially, since the average $v_{sw}$ is inherently going to be higher than the compressed slow wind. This effect was first described in detail in [Vasyliunas and Siscoe, 1976].
Table 1: Interstellar neutral inflow measurements (λ), removing different ∆v_{sw}/∆t ranges and shocks. The error of the inflow measurement (δλ) is minimally effected by the quantity of compression regions removed.

<table>
<thead>
<tr>
<th>Comps Removed #</th>
<th>λ</th>
<th>δλ</th>
<th>min(∆v_{sw}/∆t)</th>
<th>max(∆v_{sw}/∆t)</th>
<th>Data Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>255.48</td>
<td>.48</td>
<td>-</td>
<td>-</td>
<td>0 %</td>
</tr>
<tr>
<td>115</td>
<td>256.03</td>
<td>.42</td>
<td>1.35m/s²</td>
<td>5.39m/s²</td>
<td>5.0%</td>
</tr>
<tr>
<td>288</td>
<td>255.00</td>
<td>.45</td>
<td>.70m/s²</td>
<td>5.39m/s²</td>
<td>14.3%</td>
</tr>
<tr>
<td>518</td>
<td>255.45</td>
<td>.46</td>
<td>.00m/s²</td>
<td>5.39m/s²</td>
<td>23.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shocks Removed #</th>
<th>λ</th>
<th>δλ</th>
<th>FF Shocks</th>
<th>FR shocks</th>
<th>Data Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>242</td>
<td>256.06</td>
<td>.46</td>
<td>196</td>
<td>46</td>
<td>.8 %</td>
</tr>
</tbody>
</table>

6.1 Removal of Shock and Compression times

Aside from learning about the response of the PUI VDF to compression regions, the original reason for studying PUI heating sites has been to correct for, or remove, these regions from the data set in order to more precisely identify the inflow longitude of interstellar neutral flow. This task is completed by excluding the compression times that have been identified using the program developed in section 5.2. Using the PUI evolution across the SPE compression as a guide, we will exclude times beginning from the start of the compressed slow wind until the beginning of the rarefaction region. There is some additional heating that should be excluded in the beginning of the rarefaction region, but without a well defined reference point, they will be left in the data set, a point of refinement for this routine will be to additionally remove those times. With boundaries of removal for each compression region defined in time, all PUI counts within those boundaries are ignored. The inflow measurement is achieved through binning all PUI counts according to their placement in ecliptic longitude and \( v_r \). This results in 360 PUI VDFs that are normalized and each of the cutoffs are determined using the half max routine. With \( v_{cutoff} \) determined as a function of the ecliptic longitude, the function in equation 7 is fit to the data set using least squares minimization, varying the inflow longitude, \( \lambda \), the neutral velocity at infinity \( v_{ISN\infty} \) and a vertical offset. The PUI cutoff and VDF as a function of \( v_r \) and ecliptic longitude can be seen in Figure 30. The cutoff (top) also shows the model fit in turquoise. The vertical line in both the cutoff and VDF figures is associated with the inflow direction determined from fitting the model. To determine the effect that the compression regions have on the measurement
Figure 30: PUI cutoff and VDF in ecliptic longitude with compressions removed. Substantial high velocity tails are still visible.

of the inflow, the compressions are sorted for their $\Delta v_{sw}/\Delta t$ and they are excluded in incrementally larger groups from the data set starting with the compressions with the strongest velocity gradient. Table 1 shows four ranges of compression removal. The first inflow measurement is taken without excluding any compression events and results in an inflow of $\lambda \approx 255.5^\circ \pm 0.48$, the next measurement removes the largest 115 events, which amount to approximately 5% of the data and result in a slightly decreased error to $\delta \lambda = 0.42$. Removing additional compression events does not appear to reduce the inflow errorbar any further.

The removal of the compressions have a minimal effect on the inflow direction. Figure 31 shows the inflow direction plotted as a function of the amount of data, or essentially the number of compressions that are removed from the set. The blue line represents the inflow measured before any compressions were removed, and the green box is associated errorbar. The removal of the largest compressions, in a 5% removal of data, the inflow measurement shifts by half of a degree in ecliptic longitude. This shift in the inflow can simply be due to the fact that these events are randomly observed in ecliptic longitude, and if many of these large compression events happen to take place on one side of the inflow direction.
Figure 31: Variation of the ISN inflow direction with different numbers of compressions removed. The blue line represents the inflow direction as measured prior to removing any compression regions.

that can shift the measurement. Additionally, the fact that these compression events are stochastically distributed in longitude might explain why there is no substantial reduction in the errorbar of the inflow measurement. As the events are removed the variance of the cutoff measurements around the expected value is reduced, but this process also decreases the statistics one has to take the measurement. So while removing the compression might reduce variance, or noise, it does not appear to have a large enough positive effect to substantially outweigh the loss of statistics.

Shock times are also selected and eliminated in a similar fashion. With the shock passing time as a reference point, 10 mins upstream from the shock and 150 mins downstream are selected and removed. The results of this process are seen at the bottom of table 1, and yield a removal of .8% of the data set, but the removal of these shock times did not appear to reduce the error in the inflow measurement substantially. Figure 32 shows the effect that the removal of a single shock front can have on the VDF of a single longitudinal degree. The VDF before the shock removal takes place is seen in blue, the same longitudinal bin with the shock removed is seen in red. The removal of the shock has the largest effect on the high velocity particles, and there seems to be a slight reduction of the particles in the bulk cutoff region. Once again, the removal of the shock times also shifts the inflow direction up from $\lambda = 255.5^\circ$ to $\lambda = 256.0^\circ$ this likely means that the strongest compressions selected in the previous scheme encompass many of these shock events resulting in a similar shift of the inflow.
7 Conclusion and Outlook

In this thesis we have used STEREO PLASTIC observations from 2007 to 2013 to study the evolution of the He+ PUI velocity distribution in variable SW conditions within the overarching project to identify the neutral gas inflow direction from longitudinal variations of the PUI cutoff shift. There were two primary goals commanding the scope of this thesis. The first goal was, to perform the first systematic study of the PUI behavior in compression regions and at interplanetary shocks, to obtain information about heating processes and transport mechanisms of PUIs. The second goal was, to develop criteria to eliminate or correct for these effects, allowing for a more accurate measurement when determining the neutral flow direction through the longitudinal variation of the PUI cutoff shift. These two goals are fundamentally coupled, because understanding PUI acceleration and heating allows one to more accurately deconstruct and account for changes in the PUI velocity distribution when determining the ISN flow direction from PUI observation.

PLASTIC has proven to be indispensable to the study of PUI-SW interaction, as its high angular resolution allows for the PUI torus to be transformed to the SW frame. In the SW frame, the PUI cutoff can be considered for all IMF angles, and the two dimensional PUI distribution can be integrated in angle over the whole FoV, creating a 1D radial VDF. With all field orientations considered, and the longitudinal dependence of the PUI cutoff removed, PUI counts could be accumulated over any and all longitudes or time periods. This allowed for a high time resolution survey relating the PUI cutoff to
variations in several SW parameters, as well as SPE analysis of compression regions and shocks. A routine to identify and characterize these compression regions was developed, allowing for a compression region parameter study that resulted in a correlation between the steepness of the solar wind velocity increase and the cutoff shift. Additionally, accumulating compressions and interplanetary shocks in SPE time series resulted in the evolution of the PUI cutoff across the both interplanetary shocks and compressions.

Sorting and accumulating the PUI phase space density according to the high time resolution parameters, revealed approximately linear dependencies between the magnitudes of the velocity and field strength gradients, as well as with the magnetic field strength. The magnetic field strength correlation can be explained through recognizing that any changes in the local solar wind are communicated to the embedded PUI population through the magnetic field, thus a stronger field results in stronger coupling between solar wind and the PUI He+. The correlation between the velocity and field strength gradients and the PUI cutoff shift seem to either be attributed to a compressional turbulence driving heating in the PUI cutoff shift, or a selection bias, where large gradients of the SW parameters in quasi perpendicular field orientations come during times of larger scale SW compressions.

In the SPE compression region the PUI cutoff was shown to increase rapidly in the compressed slow wind, reach a max value at the end of the compressed fast wind, and decrease in the peak and rarefaction regions, where there was still a positive shift observed well into the beginning of the rarefaction region. This time series produced several important findings as the PUI cutoff did not reach a peak at the stream interface, where the solar wind experiences maximum heating. Instead the peak was found in the compressed fast wind, where the magnetic field strength and velocity gradient magnitudes are high. This signals that there are a number of processes at work, as there is a global compression, a tight coupling between the PUIs and the solar wind and a contribution of compressive turbulence. Additionally, positively shifted PUIs were identified well into the rarefaction region, where the solar wind is expanding and as such the PUIs were expected to be cooled. This result is either a remnant of PUI transport along the field line to the rarefaction region from the preceding compression, or once again due to heating by compressive turbulence. In order to deconstruct these processes and find the individual heating contributions, a sophisticated model must be employed that is able to resolve PUI transport as well as heating due to both compression structures and compressive turbulence. Such a model data comparison goes beyond the scope of this thesis and will
be taken up in the near future.

In a final step of this thesis, we tested the effect on the determination of the ISN flow longitude when compressions and shocks are removed from the data set, with increasingly lower threshold for the solar wind gradient. As the events are removed, the data is improved in fidelity, but at the expense of a decrease in statistics. These effects balance, and the errorbar does not change. Additionally, the inflow direction was shown to be stable in the removal of the compression regions, meaning that for such a large data set these events are minimally impactful. The compressions should still likely be considered when subdividing to smaller time periods, where individual events can have a larger effect. Since the compression regions are stochastically distributed in longitude, simply removing them does not increase the inflow measurement precision. If the mechanisms that drive the PUI heating can be well explained in a model, the effect of the heating could be corrected for without explicitly removing the times from the data set. Such a correction technique would be similar to the removal of the longitudinal dependence based on the model of the ISN flow that was used here to study the localized effects of the solar wind on the PUIs. Such a method could remove the effect of PUI heating by the solar wind without losing statistics. This preservation of statistics has been shown to be important in the removal of the shock and compression regions from the data set to reduce the errorbar of the inflow measurement.

With this thesis, we have provided the first systematic study revealing the effect of solar wind compressions and shocks on PUI velocity distributions, as a next step these results should be compared to simulation so that they may be deconstructed and better understood. In essence, PUIs have been shown to be effective diagnostic tools for the study of the ISM, but they are still highly subject to the changing solar wind conditions at injection. The PUI VDF thus tells a story about the population’s origin and its exposure to these solar wind structures. As such, the study of these effects is not only key to measuring the neutral flow direction and thus understanding the global heliosphere, but also to study the evolution of suprathermal particle distributions in the solar wind.
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