EFFECT OF COHERENT STRUCTURES ON ENERGETIC PARTICLE INTENSITY IN THE SOLAR WIND

by

Jeffrey A. Tessein

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics

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ABSTRACT

Solar energetic particles in the solar wind are accelerated in both solar flares and shocks associated with fast coronal mass ejections. They follow the interplanetary magnetic field and, upon reaching Earth, have implications for space weather. Space weather affects astronaut health and orbiting equipment through radiation hazard and electrical infrastructure on the ground with ground induced currents. Economic impacts include disruption of GPS and redirection of commercial polar flights due to a dangerous radiation environment over the poles. By studying how these particles interact with the magnetic fields we can better predict onset times and diffusion of these events. We find, using superposed epoch analysis and conditional statistics from spacecraft observations that there is a strong association between energetic particles in the solar wind and magnetic discontinuities. This may be related to turbulent dissipation mechanisms in which coherent structures in the solar wind seem to be preferred sites of heating, plasma instabilities and dissipation. In the case of energetic particles, magnetic reconnection and transport in flux tubes are likely to play a role. Though we focus on data away from large shocks, trapping can occur in the downstream region of shocks due to the preponderance of compressive turbulence in these areas.

This thesis lays the ground work for the results described above with an introduction to solar wind and heliospheric physics in Chapter 1. Chapter 2 is an introduction to the acceleration mechanisms that give rise to observed energetic particle events. Chapter 3 describes various data analysis techniques and statistics that are bread and butter when analyzing spacecraft data for turbulence and energetic particle studies. Chapter 4 is a digression that covers preliminary studies that were done on the side; scale dependent kurtosis, ergodic studies and initial conditions for simulations. Chapter 5 contains that central published results of this thesis, that there is a strong
association between energetic particle intensity and magnetic discontinuities and that
the correlation is can be attributed to transport and local acceleration.
The solar wind is a supersonic gas propagating throughout interplanetary space, an extension of the solar atmosphere being driven by the difference in gas pressure between the Sun and interplanetary space. The vast majority of the constituent particles are protons and alpha particles. In addition, heavier elements are up to Iron are routinely observed in the solar wind [Hundhausen, 1972]. The average density is about 10 particles per cm$^3$, however fast (slow) solar wind streams tend to be more less (more) dense. Wind speed can vary from 200 km/ to 1000 km/s, however, nominal speed during times of quiet solar wind is 400 km/s to 600 km/s. The average temperature is about 10$^5$ K. Like density, the temperature is correlated to solar activity. A table summarizing typical solar wind parameters is shown in Table 1.1. The solar magnetic field can be approximated as a dipole and is generated by the dynamo, which is thought to operate through rotating charged fluid in the interior. The solar magnetic field encompasses the entire solar system out to around 120 Astronomical Units (AU) and is known as the Interplanetary Magnetic Field (IMF) (one AU is the Earth-Sun distance, about 150 million km), beyond which is the Local Interstellar Medium [Burlaga and Ness, 2014]. Ions in the solar atmosphere occasionally accumulate enough energy to escape the Sun’s gravity and form the solar wind. Energetic particles in the solar wind follow

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the Sun’s magnetic field lines in the helical path of charged particles in a magnetic field. The drift has a characteristic radius given by

\[ r = \frac{mv_{\perp}}{qB} \quad (1.1) \]

where \( r \) is gyroradius, \( m \) is mass, \( v_{\perp} \) is velocity perpendicular to the magnetic field, \( q \) is charge and \( B \) is magnetic field. The path of these particles is sometimes complicated by turbulence, magnetic reconnection or cross field diffusion [Matthaeus et al., 2003].

The terrestrial magnetic field generates a protective bubble around the planet, known as the magnetosphere. When the solar wind reaches an object with a magnetic field the ram pressure of the solar wind equilibrates with the magnetic pressure of the magnetic field. In the case of the outer edge of the magnetosphere (magnetopause), its movement depends on the pressure from solar wind. Increased solar wind dynamic pressure can compress the magnetosphere. Likewise, during quiet solar wind conditions, Earth’s magnetosphere is able to push the bow shock Sunward. As the solar wind is diverted around the side of the magnetosphere, it forms a long, narrowing boundary on the night side of the Earth called the magnetotail. An artist’s depiction of the solar wind and magnetosphere in the inner heliosphere is shown in Figure 1.1. The bright spots on the Sun are solar flares, which are emissions of radiation, and the circular loop is a Coronal Mass Ejection (CME). Near Earth’s poles is a point separating field lines swept to the night side and those compressed on the day side. These indentations in the geomagnetic field are called the cusps.

The solar wind extends out to approximately 120 AU where it reaches the termination shock [Stone et al., 2005]. This is the point where pressure from the solar wind balances with the interstellar medium, and is the outer boundary of the supersonic solar wind. The termination shock forms an inner boundary and is approximately bullet-shaped [Matsuda et al., 1989]. The termination shock has become an object of study in recent years because we are getting our first in situ measurements from Voyagers 1 and 2 in this region. At this time, it is thought that Voyager 1 has crossed
the heliopause, thereby leaving the heliosphere, and is now within the local interstellar medium [Burlaga and Ness, 2014].

1.1 History of Solar Wind Observations

Studies of solar-terrestrial relations have a long history. Before the Space Age there were ways to remotely measure the effects of solar activity on our planet. Since cosmic ray flux is inversely proportional to solar activity (Forbush effect) one can look for the presence of isotopes like Carbon-14 and Beryllium-10 that are associated with cosmic rays. This is normally done with tree rings and ice cores. By linking isotopic records with the historical records, a lack of solar activity from 1645 to 1715 (called the Maunder Minimum) has been associated with unusually cold weather in Europe. Viking settlements in Greenland correspond to what is known as the Medieval Warm Period immediately preceding the Maunder Minimum. During the Maunder Minimum the Vikings abandoned Greenland, possibly due to climate change. Beryllium-10 concentration in ice cores allows us to trace back changes in solar activity for the past 100,000 years [Alexander, 2009]. The observations from such long time scale data sets show many different frequencies of oscillation in the solar cycle including the 2,300 year Halstatt cycle [Alexander, 2009].

In the twentieth century, studies of comet tails portended the existence of a solar wind. Astronomers found that comets contain a second tail made of ions that always points anti-Sunward. This observation meant that there might be a solar wind. At this time, most astronomers thought that the solar wind was intermittent, referred to as solar corpuscular radiation. In 1958 Eugene Parker predicted the existence of a continuous, supersonic solar wind. This was soon confirmed by in situ measurements from early spacecraft [Neugebauer and Snyder, 1962] and forms the basis for our current picture of the solar wind.

The arrival of the space age has greatly increased our knowledge of the solar wind. In the 1970s the Helios spacecraft went within 0.3 AU of the Sun; the closest of any spacecraft to date. Ulysses, launched in the 1990s did several orbits over the poles
of the Sun, revealing much about the properties of the solar wind away from the ecliptic plane for the first time [McComas et al., 2003]. The ACE spacecraft, launched in 1997, is at the L1 point (where gravitational fields of Earth and Sun balance) and provides an essential early warning system for space weather applications [Stone et al., 1998]. Space weather refers to the collective effects of solar activity on Earth including ground induced currents, increased radiation in the polar regions and temporary distortion of the geomagnetic field.

The IBEX mission, launched in 2009, is mapping the termination shock by measuring energetic neutral atoms (ENAs) coming in from the Local Interstellar Medium. An unexpected finding from the IBEX mission is the so-called ribbon composed of a swath of the sky that consistently has increased ENA flux [McComas et al., 2009, Dayeh et al., 2011, 2012, Desai et al., 2014]. Magnetospheric Multiscale Mission (MMS), launched in 2015, will obtain high resolution observations of magnetic reconnection in the magnetotail. Solar Probe Plus, launching in 2018, will get closer to the Sun than any other spacecraft and Solar Orbiter will get the first close-up observations out of the ecliptic plane.

1.2 Origin of the Solar Wind

A coronal hole is a structure on the Sun that is a source of hot, fast solar wind that is an area of lower density plasma in the solar atmosphere. At high solar latitudes there are permanent coronal holes known as polar coronal holes; they can also form at lower solar latitudes. High speed solar wind, $V_{SW} > 500 \text{ km/s}$, is fundamentally different from low speed solar wind, $V_{SW} < 400 \text{ km/s}$. High speed streams are hotter and more tenuous than slow wind, while low speed wind has a higher density.

The Sun goes through eleven year cycles of activity, switching between stages of low activity with ordered magnetic field (solar minimum) and high activity with disordered magnetic field (solar maximum). This effect is thought to be a result of the differential rotation. Because low latitudes on the Sun rotate more rapidly than high latitudes, the magnetic field can quickly become twisted and mangled. It is thought
that as the field becomes increasingly distorted. There is an increase in solar activity and this is the rise toward solar maximum. Eventually, the field becomes so distorted that magnetic fields experience a change in topology to a more energetically stable state (magnetic reconnection), and the Sun returns to its quiescent stage, solar minimum. In 2008, the Sun came out of an extended minimum and Solar Cycle 24 began. The counting of the solar cycles started in the 18th century with the observations of Wolf and Schwabe. It is during the solar maxima that we see the most solar flares and Coronal Mass Ejections (CMEs), which can occur several times a week, as opposed to several times a year during solar minimum.

The Sun rotates with an average period of about 27 days. This causes the interplanetary magnetic field (IMF) to be wound in the shape of an Archimedean spiral. This shape applies on large scales only. Turbulence causes small scale distortions in the magnetic field and it can become completely distorted during the passage of a Coronal Mass Ejection (CME). The path length of a magnetic field line from Sun to Earth is typically approximated as 1.2 AU but, because of turbulent distortion can in reality be up to 1.7 AU.

This winding of the magnetic field plus the tilt of the solar dipole leads to the shape of what we know as the Heliospheric Current Sheet (HCS). This shape of the HCS is often described as a “ballerina skirt”. Smith and Bieber [1991] examined large scale structure in the solar wind by looking at winding angle statistics. Solar wind statistics such as correlation time and winding angle converge as the averaging time is increased, while distributions of these quantities are lognormal [Ruiz et al., 2014, Isaacs et al., 2015]. This will be discussed further in Chapter 4.

1.3 Interplanetary Transients

At low latitudes on the Sun, the solar wind is highly variable, producing both high and low speed streams. Magnetic reconnection in the corona, a change in topology of the magnetic field, can result in violent releases of energy, which is associated with solar flares and Coronal Mass Ejections (CMEs). CMEs often occur simultaneously...
with solar flares, intense releases of radiation from the Sun. The CME begins as a prominence, which is a magnetic loop with two points on the visible surface (photosphere). The footpoints of the prominence are areas of opposite magnetic polarity. In a typical CME, massive amounts of matter are released from the Sun in one giant burst. This release of energy triggers extremely hot and fast solar wind. When the CME reaches Earth it interacts with the day side of the magnetopause. The interaction sends current around to the night side of the magnetosphere and upon reaching the back, connects to the ionosphere, triggering a geomagnetic storm. The visible results of geomagnetic storms are auroras, however there are other effects as well. A geomagnetic storm can cause current to run through power lines, damaging them (Ground Induced Currents), and can throw off GPS signals and radio communication. One little known effect of geomagnetic storms is on racing pigeons. Since pigeons use the geomagnetic field for navigation, they lose their sense of direction during geomagnetic storms. The NOAA Space Weather Prediction Center in Boulder, Colorado warns pigeon racers to cancel any events that they have planned until the geomagnetic field settles.

1.4 Discontinuities

Turbulent dissipation processes tend to form coherent structures (localized regions of phase coherence), regions on the edge of magnetic structures where the gradients are high [Greco et al., 2012]. These form naturally in both hydro- (HD) and magnetohydrodynamic (MHD) turbulence and are connected to the intermittent nature of turbulent fields in which the structures are produced by nonlinear couplings [Matthaeus et al., 2015]. The solar wind is full of magnetic discontinuities, e.g. jumps in the magnetic field strength or direction. These discontinuities have been interpreted as coherent structures and are representative of current sheets, reconnection sites or filamentary structures associated with the interplanetary magnetic field [Retinò et al., 2007, Sundkvist et al., 2007, Borovsky, 2008, Servidio et al., 2011, Perri et al., 2012, Osman et al., 2014]. The tube-like structures, typically about a correlation length in width [Borovsky, 2008], form a region of constant flux called flux tubes that may or
may not connect back to the solar surface and act as pipes for energetic particles. Burlaga and Ness [1969] found that directional discontinuities (sudden changes in the magnetic field direction) are always present at 1 AU and emphasize a picture in which the solar wind is a series of discontinuities rather than one that is composed of flux tubes as in Borovsky [2008]. They also suggest that these discontinuities form in the IMF rather than advected outward from the corona frozen into the plasma. Finding the source of the discontinuities can help us answer open questions in the heliophysics field; for example, the non-adiabatic rate of cooling of the solar wind which may be the result of additional heating from turbulent dissipative mechanisms. Results from simulations have shown that most of the energy dissipation is confined to small scale magnetic structure [Wan et al., 2012a, Zhdankin et al., 2014, Wan et al., 2015]. Since magnetic discontinuities are regions of enhanced temperature [Osman et al., 2011a, 2012b, Wu et al., 2013]) studying them may provide an answer to this problem.

Methods for finding discontinuities include the wavelet and phase coherence. The wavelet method approximates the signal as a wave packet (wavelet) in order to locate structures or the same spatio and/or temporal scale of the wavelet. Wavelet coefficients are obtained and classified as passive (no coherent structure) or intermittent (lots of coherent structure). An intermittent wave packet is simply one whose amplitude exceeds some chosen value [Veltri and Mangeney, 1999]. The phase coherence method is related to the amplitudes of solitons constructively interfering at the sites of discontinuities where they will be in phase coherence [Hada et al., 2003].

Coherent structures are related to magnetic reconnection and may also be examples of flux tube boundaries and current sheets. They are important because they have been shown to be associated with increased plasma instabilities [Bale et al., 2009, Osman et al., 2012a, Servidio et al., 2014], heating [Osman et al., 2011b, 2012b] and energetic particles [Matthaeus et al., 1984, Ambrosiano et al., 1988, Dmitruk et al., 2004, Karimabadi et al., 2013, Tesein et al., 2013, Dalena et al., 2014]. Given all of this, there may be an association between coherent structures and suprathermal particles in the solar wind. This will be discussed further in Chapter 5. In order to address
these topics, we need a way to identify coherent structures.

1.4.1 PVI

Partial Variance of Increments (PVI) is a statistical measure used to identify discontinuities by relating large gradients to intermittency [Greco et al., 2009a]

\[
\hat{S}^{(2)} = \frac{\Delta B^2}{\Sigma^2}
\]  

(1.2)

where \(\Sigma^2 = \langle |\Delta B|^2 \rangle\), \(\Delta B\) is increment \(B(t + \tau) - B(t)\) and \(\langle ... \rangle\) denotes ensemble average. The lag, \(\tau\), is arbitrarily chosen. Since large values of PVI are created by large increments in the fields, they are related to a preponderance of coherent structures (intermittency) [Greco et al., 2008, Matthaeus et al., 2015]. Since these intermittent structures form the heavy tails of the distribution of increments, PVI is a good method for finding non-Gaussian, intermittent structures. When \(\text{PVI} > 3\), intervals corresponding to the tail of the non-Gaussian distributions of increments are selected. One way of using PVI statistics is to choose a certain threshold on the PVI beyond which is a strong coherent structure. PVI is simple, easy to implement and is useful for comparison to simulation.

Two possible interpretations of discontinuities include (1) that of Borovsky [2008] in which the discontinuities are seen as flux tube boundaries connected back to the solar surface and (2) the picture of Burlaga and Ness [1969] in which the solar wind naturally forms discontinuities that are not necessarily flux tubes. Different types include tangential discontinuities (TD) and rotational discontinuities (RD). A TD occurs when the magnetic field vector is parallel to the plane of the discontinuity and goes through a rotation in the plane while the magnitude changes by around 20% [Siscoe et al., 1968, Burlaga and Ness, 1969]. An RD is a propagating rotation about the normal component of the magnetic field, while the magnitude of the magnetic field stays roughly the same. Derivations of various discontinuities are given by Hudson [1970].
1.5 Solar Energetic Particles

Solar Energetic Particles (SEPs) are high energy particles sourced at the Sun. Numerous technologies can be impacted by energetic particles during geomagnetic storms [Lanzerotti, 2001]. There are two principal types of energetic particle events, impulsive and gradual [Reames, 1999], and they differ in their acceleration mechanism, timescale, and isotopic composition. Impulsive events are accelerated from a specific location through magnetic reconnection associated with solar flares. The mechanism operates at specific energies and has a relatively short time scale, hence the impulsive label. Gradual events are accelerated by shocks through DSA (Fermi acceleration at shocks). These collisionless shocks are formed by solar transients like Coronal Mass Ejections (CMEs) or Corotating Interaction Regions (CIRs). This process can accelerate particles over a time scale of days and in a much broader energy range than impulsive flares. SEPs tend to follow magnetic field lines through flux tubes, which have distinct plasma properties from neighboring tubes. Another difference between gradual and impulsive SEPs is the isotopic composition, for example, the presence of $^3\text{He}$ in impulsive flares which is orders of magnitude more abundant in the chromosphere than in the ambient solar wind.

With the launch of the Advanced Composition Explorer (ACE) spacecraft it has become increasingly more difficult to tell the difference between the two types of events, and a strict dichotomy appears to be an oversimplification [Kallenrode, 2003].

A puzzling observation in SEP events has been the wide longitudinal spread of observed events [Cane and Erickson, 2003]. Energetic particles are generally confined to magnetic field lines and one would expect some field line meandering as well as particles sampling other magnetic field lines. In general, the Potential Field Source Surface Model [Schatten et al., 1969] predicts a spreading of no more than 60° at 1 AU. However, a spread of 120° is observed by the ACE and STEREO spacecraft which together observe a wide longitudinal swath of the solar wind [Wiedenbeck et al., 2011]. Possible explanations for this include field line spreading, disruption of the magnetic field by transients and multiple sources.
SEPs also have the interesting phenomenon of the so-called $v^{-5}$ suprathermal tail in which the scaling of the velocity distribution function is power law at suprathermal energies. The velocity distribution function has a Maxwellian thermal distribution peaking around the typical solar wind velocity. At higher velocities, extending up to hundreds of MeV in energy is a “suprathermal tail” that scales as $v^{-5}$. This has been observed in the solar wind by Gloeckler et al. [2000] and in simulation by Le Roux et al. [2001]. The mechanism that produces this effect is unknown and still up for debate but a possible mechanism involving turbulent compressional acceleration has been described by Fisk and Gloeckler [2006]. Acceleration mechanisms will be described further in Chapter 2.

1.6 Dropouts

Dropouts are sudden changes in energetic particle flux commonly observed in the solar wind [Giacalone et al., 2000, Mazur et al., 2000, Chollet and Giacalone, 2008, 2011, Trenchi et al., 2013]. These dropouts are thought to be the manifestation of filled and empty flux tubes being convected past the spacecraft. An example of dropouts in the solar wind is shown in Figure 1.2. The y-axis is $1/v$ of the energetic particles. When plotted this way, one observes the particles arriving to the detector in order of speed with the faster particles arriving earliest. This velocity dispersion indicates acceleration that is happening somewhere else. The gaps in the energetic particles are the dropouts.

Because of observations of wide longitudinal spreading of SEPs [Wiedenbeck et al., 2011, Cohen et al., 2012] there is an apparent contradiction with the observation of dropouts. This could be resolved by topological trapping in which magnetic field lines starting in a region of high magnetic vector potential will be confined to a magnetic flux tube while particles farther away will diffuse away much more quickly [Ruffolo et al., 2003, Chuychai et al., 2007].
Figure 1.2: Example of dropouts in the solar wind, with $1/v$ of the energetic particles plotted. When plotted this way we can see the particles arriving to the detector in order of speed with the faster particles arriving earliest. When plotted this way, one observes the particles arriving to the detector in order of speed with the faster particles arriving earliest, indicating acceleration at a remote location. Image courtesy of ACE Science Center.
1.7 Interplanetary Shocks

Collisionless shocks in the interplanetary medium are analogous to shocks found in a hydrodynamic system. These interplanetary shocks can be driven by disturbances of solar origin like CMEs or CIRs. When the sound speed in the frame of the fluid is exceeded a shock is formed. Most familiar shocks, such as those in the atmosphere formed by a supersonic jet when the jet moves faster than the speed, are collisional shocks. In the case of collisionless shocks, electromagnetic interactions substitute for collisions.

Interplanetary shocks are identified in the solar wind by a strong discontinuity in the magnetic field and plasma data. The discontinuous jump in the plasma and magnetic field time series all change with the same sense (i.e. rise together or fall together). One exception to this is the rarely observed slow mode shock, in which the magnetic field magnitude will do the opposite of what the plasma data does (i.e. magnetic field rises while proton density and/or temperature decrease and vice versa). It can be difficult to determine whether or not a discontinuity is a shock. In fact, it may be possible that a tangential discontinuity is the limiting case of a weak shock (a shock with a relatively small density or magnetic field ratio). One additional constraint in shocks is pressure imbalance and entropy. A discontinuity will be pressure balanced and conserve entropy. One can also look for the expected energetic particle profile of diffusive shock acceleration near a shock. This features a steep rise in energetic particle flux leading up to the shock then a slow drop off behind. However, this is not always the case as shocks have been observed to have varying energetic particle flux time intensity profiles [Lario et al., 2003]. A sample of an interplanetary shock in the solar wind is shown in Figure 1.3. Shocks can accelerate particles through the processes of Diffusive Shock Acceleration (also known as First Order Fermi Acceleration) and Shock Drift Acceleration, which will be described further in Chapter 2.
Figure 1.3: An example of Diffusive Shock Acceleration (DSA) showing PVI (top panel), energetic particle flux (middle panel) and magnetic field (bottom panel). PVI (Partial Variance of Increments) is a measure of non-Gaussianity and will be explained further in Chapter 5. There is a steep increase in energetic particle intensity along with a strong discontinuity in magnetic field before the shock (upstream) and a slow drop off in flux after (downstream). This is typically what we see in the data at DSA events, but it varies [Lario et al., 2003].
1.8 Turbulence

Turbulence is a non-linear fluid phenomenon characterized by dissipation, efficient mixing, vorticity, and structure across a wide range of length scales. The momentum equation for turbulence is the Navier-Stokes equation

\[
\frac{\Delta u}{\Delta t} + u \cdot \nabla u = -\nabla p + \eta \nabla^2 u + F 
\]  

(1.3)

where \( u \) is velocity, \( p \) is pressure, \( \eta \) is viscosity and \( F \) represents other forces that may be present in the system of interest. The forces contained in \( F \) provide the energy injection that is required to maintain a turbulent flow. Turbulence is found in the solar corona, solar wind, outer heliosphere, interstellar medium, weather systems, wind tunnels and fusion plasmas. The Reynolds number is the ratio of the nonlinear term to the viscous term in Equation 1.3 and can be thought of as the “level of turbulence”.

The nonlinear term gives rise to the turbulent cascade in which the energy cascades without dissipation from large to small scales through nonlinear coupling until a dissipative length scale is reached. Kolmogorov [1941] (hereafter referred to as K41) showed using dimensional analysis that this cascade \( E(k) \), where \( E \) is energy and \( k \) is wave number associated with a particular length scale, is a power law. This was done by starting with the Reynolds number, \( R = LV/\nu \) where \( L \) is a characteristic length scale, \( V \) is a velocity scale and \( \nu \) is viscosity and cascade rate \( \epsilon = V^3/L \) and assuming that at the smallest scale (dissipative) \( \epsilon = v_d^3/l_d \). This gives us the typical size and velocity of the smallest eddies, \( l_d = (\nu^3/\epsilon)^{1/4} \) and \( v_d = (\nu \epsilon)^{1/4} \). We can use dimensional arguments to establish energy as a function of length scale \( E(k) \) (power spectrum).

\[
E \propto \frac{m^3}{s^2} 
\]  

(1.4)

\[
E = C v^2 l = C 
\]  

(1.5)
Rearranging the characteristic velocity equation and making the change $l \rightarrow 1/k$

\[
E(k) = C v^2/k = C \left(\frac{\epsilon/k}{k}\right)^{\frac{2}{3}} \tag{1.6}
\]

This spectral form of the inertial range energy must then be

\[
E(k) = C \epsilon^{2/3} k^{-5/3} \tag{1.7}
\]

where $C$ is a universal constant of order unity. This result ignores intermittency (see Matthaeus et al. [2015] for a review on this topic), shown to be present in simulations and observations of turbulence at small scales. Thus, the dissipation rate used by K41 is not constant. There are also the predictions of Iroshnikov [1963] and Kraichnan [1965] which predict a spectral scaling of $-3/2$ known as Iroshnikov-Kraichnan scaling.

Lower frequency oscillations are associated with stream structure and make up the energy containing range in which most of the power is contained. The next higher frequency range, corresponding to the nonlinear cascade, is the inertial range. At high wave numbers, viscous dissipation processes produce a steeper spectrum known as the dissipation range. A schematic of the power spectrum is shown in Figure 1.4 and an actual measured power spectrum from the solar wind is shown in Figure 1.5 [Tessein et al., 2011]. We see that the power law is not exactly $-5/3$ in the solar wind but is close, and that the spectrum steepens between 0.1 Hz and 1 Hz to form the dissipation range. Note that it is closer to the prediction of hydrodynamics than it is to the $-3/2$ prediction of magnetohydrodynamics.

1.8.1 Solar Wind Turbulence

Solar wind turbulence has been studied since the early days of the space age and has implications for heating, energetic particle acceleration and cosmic ray modulation [Bieber et al., 1994, Matthaeus et al., 2015]. Belcher and Davis Jr. [1971] observed Alfvénic fluctuations in the solar wind. Burlaga and Ness [1969] suggested that
the commonly observed magnetic field discontinuities in the solar wind are a manifestation of turbulent processes rather than a filamentary structure of solar origin. Matthaeus and Goldstein [1982a] measured correlation length, cross helicity and magnetic helicity in the solar wind. Solar wind autocorrelation functions plotted on a 2D plane where direction denotes angle to the mean magnetic field, inspired by the experimental result of Robinson and Rusbridge [1971], show that correlation persists longer in the quasi-perpendicular and quasi-parallel directions, rather than at oblique angles [Matthaeus et al., 1990]. This suggests that solar wind fluctuations are dominated by quasi-perpendicular and quasi-parallel fluctuations and has been dubbed the “maltese cross”. Dasso et al. [2005] extended this result by subsetting for slow and fast, in which it was found that fast (slow) streams are dominated by quasi-parallel (quasi-perpendicular) fluctuations. A two-component model in which 2D (slab) fluctuations are assumed to be perpendicular (parallel) to the mean field useful for particle diffusion [Ruffolo et al., 2008] arises naturally from the maltese cross. The third order law relating the cascade rate to longitudinal fluctuations was recast into MHD form.
Figure 1.5: An example of a solar wind power spectrum from the ACE spacecraft [Tessein et al., 2011]. This power spectrum estimate is taken from 10 hours of data. Note the inertial range at low frequency and the spectral break around 1 Hz. The bottom panel is the magnetic helicity spectrum, a topological quantity defined by $\int A \cdot B dV$ where $A$ is magnetic vector potential and $B$ is magnetic field.
Figure 1.6: Means and variances of $n$ and $q$ (inertial range power law index) as a function of the angle between the mean magnetic field and the solar wind velocity. The two quantities are related by $q = -(n + 1)$. This is done for the trace (a sum over spatial components) of magnetic field and velocity as well as the $N$ (out of plane component). See Tessein et al. [2009] for more details.
by Politano and Pouquet [1995].

Scaling of inertial range fluctuations have been looked at since the early days of the space age. Coleman [1968] found a −3/2 magnetic field power spectrum that appeared to be closer to the −5/3 scaling predicted by K41 than the Iroshnikov-Kraichnan scaling. Horbury et al. [2008] and Wicks et al. [2010] found, using wavelets, an anisotropic scaling matching the prediction of Goldreich and Sridhar [1995]. Tessein et al. [2009] used second order structure functions to estimate inertial range scaling and obtained an isotropic spectrum most closely matching the prediction of K41. This result is described briefly below.

In Figure 1.6, the scaling index $n$ of the second order structure function (multiplied by constant $A$),

$$S_2(L) = \langle [Z(x) - Z(x + L)]^2 \rangle \propto AL^n$$

(1.8)

where $S_2$ is second order structure function, $Z$ is a field and $L$ is lag, has, as we change the angle between the mean magnetic field and solar wind velocity, an unchanging power law slope as a function of temporal lag $L$ [Tessein et al., 2009]. The power law index $n$ of the second order structure function is related to the slope of the power spectrum by $n = (q + 1)$ where $q$ is the slope of the power spectrum. Thus, $n = 2/3$ corresponds to $q = -5/3$. However, note that when local averaging is used, the spectrum is found to be anisotropic in the inertial range [Horbury et al., 2008, Podesta, 2009, Wicks et al., 2010].

This discussion brings up the notion of local and mean fields. The reason for the apparent discrepancy between the results of Tessein et al. [2009] and Horbury et al. [2008] is the definition of the mean field. Tessein et al. [2009] used a global mean field (longer interval used to accumulate statistics), while the wavelet method of Horbury et al. [2008] is a local mean field (shorter interval used to accumulate statistics). Because of the availability of high resolution solar wind measurements in recent years, local mean fields have become increasingly popular [Chen et al., 2010, Sahraoui et al., 2010,
However, it should be kept in mind that typically at least a correlation time is required for statistics to converge.

### 1.8.2 Turbulent Simulations

No discussion of solar wind turbulence would be complete without mentioning the simulation efforts. MHD simulations take the fluid approximations and give insight into magnetic reconnection and intermittency. There are various implementations of MHD that make assumptions to save computational time, such as reduced MHD [Strauss, 1976] or stringent requirements that can increase computational time like compressibility, Hall term and finite Larmor radius corrections [Oughton et al., 1998, Ghosh and Parashar, 2015]. Particle-in-Cell (PIC) codes push distribution functions and are more expensive than MHD but are able to probe kinetic scales where the fluid limit breaks down. PIC simulations sometimes decrease the proton to electron mass ratio to ease the computational burden. Hybrid simulations can be thought of as a compromise between MHD and PIC, treating electrons as fluid and ions as PIC [Parashar et al., 2009]. Gyrokinetic simulations solve the gyrokinetic equation that comes from the Fokker-Planck equation and push the distribution function averaged over a gyroperiod [Howes et al., 2008]. Hybrid Vlasov-Maxwell solves the collisionless Vlasov-Maxwell system [Valentini et al., 2007] and is an excellent albeit computationally expensive method for probing kinetic scale turbulence [Servidio et al., 2012]. There are also test particle simulations in which particles follow magnetic fields from snapshots of MHD simulations [Ambrosiano et al., 1988, Dalena et al., 2014]. Test particles are not self-consistent but can be used to show particle acceleration in dynamical magnetic fields. There are also global heliospheric simulations which can look at acceleration of the solar wind, and interaction of the solar wind with planetary magnetospheres and the interstellar medium [Usmanov et al., 2000].
1.8.3 Non-adiabatic Cooling

As the solar wind expands outward from the Sun and rarefies, it is expected that it will cool. Assuming adiabatic expansion predicts that this radial temperature profile will be proportional to the distance from the sun, $R^{-4/3}$ [Gazis and Lazarus, 1982]. A derivation of this result is given by Williams et al. [1995]. Observations from the Voyager spacecraft show that this radial temperature profile is much shallower, $T \propto R^{-0.49\pm0.01}$ [Richardson et al., 1995], suggesting an additional heating source. This heating may be due to turbulent dissipation mechanisms [Coleman Jr, 1968] and Matthaeus et al. [1999] shows that such a model fits the observations. The precise nature of turbulent dissipation at kinetic scales remains an open research topic.

1.9 Corotating Interaction Regions

A CIR occurs in the solar wind when, due to the spiral nature of the IMF, a fast solar wind stream collides with a slow solar wind stream, forming a compression and a rarefaction region. They are corotating because they recur every 27 days due to solar rotation. CIRs can create forward and reverse shocks beyond 1 AU and have been associated with energetic particles.

CIRs are known to be sources of energy. Tessein et al. [2011] look at the energy injection of five CIRs in the solar wind. They apply various turbulence diagnostics and find no known signatures of generation of turbulence at the CIRs. For example, see Figure 1.7 in which the spectral slopes of the CIRs are what one might expect in a region occupied by both fast and slow solar wind streams. This analysis does provide evidence of energy injections by the CIRs but it may be too weak or slow (in comparison with ambient turbulent time scales) to rewrite the spectrum. In a companion paper, Smith et al. [2011] find that the energy injection at CIRs is slow enough to be assimilated into the ambient turbulence without changing the underlying dynamics. Abreviation and acronyms used in the thesis are listed in Appendix C.
Figure 1.7: Distribution of power law indices for fast wind, slow wind, and CIRs. The spectral slopes of the CIRs are what one might expect in a region where fast and slow wind collide.
There are a variety of mechanisms by which energetic particles can be accelerated in the solar wind. One topic that has yet to be fully explained is that of the suprathermal tail, in which the velocity distribution has, at suprathermal energies a power law tail with a slope $v^{-5}$. This occurs both in observation and simulation [Gloeckler, 2003, Le Roux et al., 2001]. Schwadron et al. [2010] suggest that this power law tail may be the result of a superposition of processes acting simultaneously.

SEPs in the solar wind consist of the high energy particles accelerated in shocks (gradual) and flares (impulsive). The SEPs observed in the paper by Tessein et al. [2013] (hereafter referred to as T13) are from the EPAM instrument aboard ACE in the energy range 47 keV to 4.75 MeV. This corresponds to a speed which allows them to traverse the Earth-Sun distance in several hours. The highest energy particles have a radius of gyration given by the equation

$$r_L = \frac{mv_{\perp}}{qB} \tag{2.1}$$

In Chapter 1, gradual and impulsive flares were mentioned briefly. This concept of two separate mechanisms goes back to an influential paper entitled “The Solar Flare Myth” [Gosling, 1993]. Prior to this revelation it was thought that SEPs originated primarily at solar flares despite evidence for two different mechanisms at work [Kahler et al., 1978, Reames, 1999].
2.1 Diffusive Shock Acceleration

Diffusive shock acceleration occurs when a particle is accelerated back and forth across a shock through repeated reflections off turbulent fields, gaining energy from the shock each time it passes the shock front. Figure 2.1 is a schematic of a typical parallel shock in which the shock is propagating parallel to the mean magnetic field. In the case of a shock propagating perpendicular to the magnetic field a different mechanism, shock drift acceleration, will act. In the schematic the shock front is represented by a vertical line in the middle and the mean magnetic fields are the lines pointing left to right. The upstream plasma (left of the shock) is moving faster than the downstream plasma driving a shock. This creates discontinuities in the fields across the shock. The shock itself propagates faster than the downstream plasma but slower than the upstream plasma resulting in a pileup and a peak in density at the shock. An example of this pileup is shown in Figure 2.2, showing time series and proton density and speed at a shock. At the shock there is a spike in proton density. This will also result in converging flow in the frame of the shock. Because of converging flow in the shock...
Figure 2.2: Time series of proton density and speed at a shock. The spike in density at the shock (denoted by vertical dashed line) is typical of compression seen at shocks.

reference frame there is small increase in the energy of the particle after a full cycle, leading to a large increase after many cycles. This process is analogous to two table tennis paddles being brought together accelerating a ball between them. Note that we have to assume that the particle moves much faster than the shock to begin with without explaining how it obtained that speed. This is known as the injection problem of DSA.

In this process the downstream spectral index depends only on the shock compression ratio

$$\alpha \propto (r+2)/(r-1) \quad (2.2)$$

where $\alpha$ is spectral index of the energy spectrum $f(E) = E^{-\alpha}$ and $r$ is compression ratio. In addition to this it has been shown that many shocks do not accelerate particles Lario et al. [2003].
2.2 Other Acceleration Mechanisms

Trapping of particles in magnetic fields may accelerate particles. For example, simulations in which test particles interact with snapshots from MHD simulations show that particles can get trapped by magnetic fields and accelerated in current sheets, magnetic O-points and reconnection sites [Matthaeus et al., 1984, Ambrosiano et al., 1988, Drake et al., 2006]. Further, it was shown by Dmitruk et al. [2004] that protons and electrons are affected differently; protons (electrons) are energized perpendicular (parallel) to the magnetic field. Another study allowed particles initially trapped and accelerated in coherent magnetic structures move into a larger simulation domain which accommodates their larger gyroradius [Dalena et al., 2012, 2014]. In the larger simulation domain, the particles are evenly spread throughout the box since their gyroradii are too large to be confined by the structures; there were also different pitch angle distributions between the small and large boxes, hinting at different physics occurring at different energies.

Betatron acceleration is energization due to the conservation of magnetic moment in a time varying magnetic field. Recently, evidence for betatron acceleration has been found in test particle simulations Dalena et al. [2012, 2014].

Fisk and Gloeckler [2006] propose a method using a compressible turbulence to explain the observed suprathermal tail. The method may explain the observed suprathermal tail and acceleration of galactic cosmic rays [Fisk and Gloeckler, 2012].

2.3 Application to Turbulent Dissipation

Some of this acceleration may be due to turbulent dissipation mechanisms in which energy is stored in the fluctuations; for example, the heating, dissipation and plasma instabilities described in the previous chapter. Could it also be the case that this energy deposition mechanism operating in current sheets could accelerate particles? Something like this could be occurring in and around reconnection jets [Sundkvist et al., 2007, Zank et al., 2014, Le Roux et al., 2015, Zank et al., 2015]. Khabarova et al. [2015] find evidence for trapping and acceleration of particles in the
HCS away from shocks and other sources. Inspired by the superposed epoch analysis of Osman et al. [2012b], the main topic of this thesis, after more preliminary material, will be the effect of coherent structures on energetic particle intensity. Using data from ACE, a significant temporal correlation has been found between magnetic discontinuities and energetic particles [Tessein et al., 2013, 2015]. A summary of that result, a superposed epoch analysis shown in Figure 2.3, shows that there is increased energetic particle intensity associated with stronger coherent structures and further, there is a temporal peak in energetic particle intensity at the coherent structures. This is described more fully in Chapter 5.
Chapter 3

SPACECRAFT AND DATA ANALYSIS METHODS

This chapter will cover basic data analysis methods used in the study of solar wind data, data sets, and instrumentation. There are various basic techniques that are essential to the analysis of solar wind data, for example, the Taylor Hypothesis in which the spacecraft takes temporal measurements and uses the solar wind speed to convert to spatial measurements. This is only valid if the characteristic fluctuation speed is much slower than the solar wind speed. This condition is met reasonably well in the solar wind but not necessarily in the terrestrial magnetosphere.

It would be a serious omission to write a chapter on measurement techniques without a proper discussion of error analysis. While proper error analysis is crucial when working with any data, it is beyond the scope of this thesis. Error-of-the-mean is a simple error calculation [Tessein et al., 2009]

\[ \sigma_{\text{err}} = \sigma / \sqrt{N} \]  

(3.1)

where \( \sigma \) is standard deviation and \( N \) is the number of samples going into the computation. A comprehensive discussion of error analysis can be found in Bevington and Robinson [2003].

3.1 ACE

The Advanced Composition Explorer (ACE) is the spacecraft used for the results shown in Chapter 5.[Stone et al., 1998]. ACE was launched in 1997 and is in a stable orbit at the L1 Lagrange point, roughly 1.5 million kilometers away from Earth on a Sun-Earth line. Its spin rate is 5 times per minute and the spin axis is within
20° of the Sun-Earth line. Because of its location ACE is useful as an early warning system for space weather forecasting. ACE is also an excellent workhorse for solar wind studies because of the diversity within its suite of instruments which include composition, energetic particle and plasma data. The studies shown here, requiring energetic particle and plasma data made ACE an obvious choice. A useful place to obtain the data is from the ACE Science Center\(^1\). The magnetic field instrument (MAG) is a triaxial fluxgate magnetometer that measures magnetic field vector. The plasma instrument is the Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) [McComas et al., 1998]. SWEPAM measures proton density, temperature, velocity vector as well as alpha to proton ratio at 64 second resolution in the energy range 0.26-36 keV. The Electron, Proton and Alpha monitor (EPAM) measures energetic particles and includes several sensors pointing in various directions [Gold et al., 1998]. The LEMS30 and LEMS120 (Low Energy Magnetic Spectrometer) which measure ion fluxes between 45 keV and 4.8 MeV. The measurements come from 8 logarithmically spaced energy channels. LEMS30 and LEMS120 are oriented 30° and 120° away from the spacecraft spin axis respectively. The data set for this instrument has a 5 minute temporal resolution.

The coordinate system used for vector quantities is known as the RTN coordinate system. R stands for radial and is the Sun-Earth line. T (tangential) is the cross product of R with the solar rotation axis and N (normal) completes the relation \(R \times T = N\).

Because of the mismatch in measurement frequency between MAG/SWEPAM and EPAM the data sets have to be resampled. Two ways of doing this are merging (averaging the data to a lower frequency) and decimating (strategically removing data points to end up with a lower frequency data set). In this case I have chosen to merge the data set mainly because 300 seconds is not an integer multiple of 64 seconds. The added advantage of merging in this situation is a reduction in the intermittency of the data.

\(^1\) http://www.srl.caltech.edu/ACE/ASC/
magnetic field and plasma data. This will add weight to our results which show that intermittency in the magnetic field is an important effect.

3.1.1 ACE Shock Listing

The ACE shock list contains a list of shocks observed by ACE including density, shock normal, upstream to density magnetic field and density ratios and Mach number. It is good for analyzing individual shocks but does not contain weak (low magnetic field/density ratio) shocks [Vorotnikov et al., 2008]. There are also cases of strong shocks in which there was no plasma data available, so shocks of this nature will not appear in the list. The WIND spacecraft has a similar list maintained by the Center for Astrophysics that is quite comprehensive and can be used in tandem with the ACE list during times when WIND is near ACE ².

3.2 Probability Density Function

A probability density function (PDF) shows the likelihood of occurrence for a measured variable with the area normalized to one. Three types of PDF include linear bins (bins linearly spaced), logarithmic bins (bins logarithmically spaced) and equal statistical weight (same number of samples in each bin). Typically, we use equal statistical weight most frequently. A sample PDF of magnetic field fluctuations is shown in Figure 3.1.

3.3 Increment Based Statistics

Increment-based statistics are commonly used in the solar wind. PVI, structure function, skewness and kurtosis all make use of increments. In a turbulent flow the distribution of increments tends to be non-Gaussian, with wider tails than a Gaussian distribution. This is an effect called intermittency, characterized by a preponderance

² http://www.cfa.harvard.edu/shocks/
of discontinuities in the data [Matthaeus et al., 2015]. An example of this is shown in Figure 3.1. The increment is a simple quantity, defined as

$$\Delta B = B(t + \Delta t, r + \Delta r) - B(t, r)$$  \hspace{1cm} (3.2)$$

where $B$ is a time series measurement (it may or may not be a vector), $r$ is spatial location, and $t$ is temporal location. We define $\Delta t$ and $\Delta r$ as the temporal lag and spatial lag respectively for which they are arbitrarily chosen. The spatial lag can only be used with multipoint measurements.

### 3.3.1 Structure Function

The structure function makes use of increments between two points in the data

$$S_n(\tau) = \langle |b(t + \tau) - b(t)|^n \rangle$$  \hspace{1cm} (3.3)$$

where $\langle ... \rangle$ denotes ensemble average. The second order structure function $S_2$ can be used to infer the slope of the power spectrum $k^q$ if $S_2(\tau) \sim A\tau^q$ where $q = -(n + 1)$. The third order structure function is related to the cascade rate $\epsilon$ by the so-called 4/5 law

$$S_3(L) = -\frac{4}{5}\epsilon L$$  \hspace{1cm} (3.4)$$

where spatial lag $L$ replaces temporal lag $\tau$.

### 3.3.2 PVI

PVI (Partial Variance of Increments) is a statistical measure used to identify discontinuities by relating large gradients to intermittency [Wan et al., 2012b]

$$\delta^{(2)} = \frac{||\Delta B||^2}{\Sigma^2}$$  \hspace{1cm} (3.5)$$

where $\Sigma^2 = \langle ||\Delta B||^2 \rangle$ and $\Delta B$ is increment $B(t + \tau) - B(t)$. Large increments are indicative of intermittency. Since large values of PVI are created by large increments,
large values of PVI are related to intermittency [Greco et al., 2008]. PVI is handy because of its ease of use and convenient comparison between simulation and solar wind observations.

Another useful statistical quantity used in PVI studies is waiting time (WT). WT is the minimum time between two PVI events exceeding a chosen threshold [Greco et al., 2008]. It can be used to examine whether the system has “memory” - that is, if past fluctuations affect the nature of the turbulence at a later time [Greco et al., 2009c]. There is evidence that the distribution of waiting times is described either by an exponential function or by power law. If the system were to have no memory, it would be described by Poisson statistics and have an exponential form. Using simulations it has been shown that the distribution of waiting times has a power law form [Greco et al., 2008]. In the solar wind Greco et al. [2009a] found that waiting time distributions are better described by a power law for spatial increments smaller than the correlation scale while waiting times for increments larger than the correlation scale are best fit by an exponential form, indicating lack of memory [Greco et al., 2009c]. They conclude that the turbulent fluctuations in the solar wind are related to large structures and the discontinuities are probably current sheets or magnetic flux tube boundaries.

Non-Gaussianity can be observed in a distribution of the magnetic field increment (see Figure 3.1). Osman et al. [2011a] identify three regions in this distribution. It has a super-Gaussian core (region I), sub-Gaussian midregions (region II) and super-Gaussian tails (region III) corresponding to high intermittency and PVI. Greco et al. [2009b] separated the results of an MHD simulation into the three regions described above and looked at where in the simulation’s magnetic structures these three regions of the distribution occur. It was observed that region I corresponds to the low-level fluctuations between magnetic structures, region II corresponds to the centers of magnetic islands and region III are the sharp boundaries at the edge of magnetic structures where gradients are high.

Osman et al. [2011a] further investigated the connection between solar wind
Figure 3.1: PDF of magnetic field increments in the solar wind. A Gaussian distribution is superimposed for comparison. The super-Gaussian tails represent the highly intermittent fluctuations.
discontinuities and inhomogeneous dissipation. One way of looking for this is by finding regions of enhanced heating in non-Gaussian structures. The discontinuities were found by looking for high values of PVI and again the distribution of increments is divided into three regions. When looking at temperature and dissipation rate distributions for each region it was found that ion temperature and dissipation rate increase going from region I to region III. In addition, when the analysis is conditioned on PVI threshold, they find increasing temperature and dissipation rate with increasing PVI threshold. This indicates that discontinuities identified by the PVI statistic are regions of increased heating. Given that there also has been found increased wave power along instability thresholds [Bale et al., 2009], and their association with cascade rate and heating [Osman et al., 2012a, 2013] there is ample evidence that coherent structures are important areas of energy deposition in general. Considering the pool of suprathermal particles in the solar wind and that their origin is still considered an open problem this begs the question of whether energetic particles are associated with coherent structures.

One feature of PVI statistics is its dependence on its surroundings. Thus, the interval of averaging used in the denominator affects the observed values of PVI. An example of this effect is shown in Figure 3.2. Here we show the same period of time in 2003 using three different intervals of averaging: 1 day, 10 days and 200 days. The time around day 149.8 of 2003 was a time in which there were a lot of strong coherent structures. Thus, using the one day averaging interval for the PVI calculation, we are looking at mostly strong coherent structures throughout the entire 24 hours period, thus the PVI values reach a maximum of around 4. However, using the 10 day average, there are less coherent structures, so the strong one around day 150 will be much stronger in comparison, elevating the PVI above 10. Similarly, using the 200 day average, the effect of amplified further, increasing PVI to above 15.
Figure 3.2: PVI time series for the same period of time in 2003 using three different intervals of averaging: 1 day, 10 days and 200 days. The time around day 150 of 2003 was a time in which there were a lot of strong coherent structures.
3.3.3 Skewness and Kurtosis

Skewness is the third-order central moment of the probability distribution and is a measurement of the asymmetry of the probability distribution.

\[ S = \frac{\langle (x - \bar{x})^3 \rangle}{\langle (x - \bar{x})^2 \rangle^{3/2}} \] (3.6)

where \( \bar{x} \) is mean. Skewness is negative in the solar wind because of the 4/5 law.

Kurtosis measures the “peakedness” of the distribution function

\[ K = \frac{\langle (x - \bar{x})^4 \rangle}{\langle (x - \bar{x})^2 \rangle^2} \] (3.7)

and proves useful for intermittency statistics [Bruno et al., 2001]. Intermittency manifests itself through scale dependent kurtosis, wherein as one adjusts the increment the smaller scales, the kurtosis becomes larger. An example of this scale dependent kurtosis (SDK) is shown in Figure 3.3 in which PDFs of SDK are calculated for three different lags. As the lag is increased the peak of the distribution increases from its nominal (Gaussian) value of three.

3.4 Superposed Epoch Analysis

Superposed epoch analysis is a technique in which many overlapping events are averaged together. For example, the superposed epoch analysis of T13 shows the average energetic particle flux time profile averaged over hundreds of shocks normalized to a common time axis in which \( \Delta t = 0 \) corresponds to the location of the shock and positive (negative) values of \( \Delta t \) correspond to time after (before) the shock (see Figure 3.4). The contents of the figure are described further in Chapter 5.

3.5 Pitch Angle Distributions

Pitch angle, the angle between the magnetic field and velocity vector is an important quantity in shock studies. Because we expect the angular distribution of pitch angles to isotropize in the event of diffusive shock acceleration, one can use
Figure 3.3: Scale dependent kurtosis in the solar wind for three different increments using 1 second ACE magnetic field data and normalized to the ion inertial length $d_i$. 
Figure 3.4: Superposed epoch analysis, showing average energetic particle flux at hundreds of shocks for various thresholds of PVI. This is described further in Chapter 5.
Figure 3.5: Sample data of high energy pitch angle distributions from ACE/EPAM/LEMS120.

Figure 3.5 depicts a sample of this data. There are five minute high energy pitch angle distributions from the LEMS120 instrument of ACE/EPAM, with cosine of pitch angle on the x-axis. The number at the top, ‘S=’ is the number used to normalize the distribution such that the maximum is 1. The points are the sectors of the instrument. In this case, LEMS120 has eight sectors pointing in eight different directions. For example, an isotropic pitch angle distribution would be flat across all sectors. Some common pitch angle distributions include pancake, bidirectional, beam and betatron. A pancake distribution is when the pitch angles are uniform at all angles and is associated with pitch angle scattering. A bidirectional PAD has a peak at $\alpha = \pm 1$. A situation like this would occur in a flux rope, with both footpoints at the Sun and particles passing through the flux tube from both direction. A beam-like PAD has a peak in the parallel or anti-parallel directions. If the PAD peaks at $\alpha = 0$ (perpendicular) this may be associated with betatron acceleration.

3.6 Detrending

There is often a trend associated with solar wind data, for example due to the solar cycles. This means that measurements in the solar wind can vary over a period of months and years in a way that is not relevant to the turbulence studies. Because it may or may not affect the analysis, it is sometimes necessary to detrend the data to check for this effect. Detrending is simply taking a linear fit of the data sample and
subtracting that line from the y-values. Detrending was performed by Tessein et al. [2009] in order to obtain cleaner statistics.

### 3.7 Correlation Statistics

The correlation function gives us information about how well correlated two signals are. The most common type is the Pearson correlation

\[
C(x, y) = \left\langle \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{\sigma_x \sigma_y} \right\rangle
\]  

(3.8)

where \(N\) is sample size, mean denoted by a bar and \(\sigma\) denotes standard deviation. Alternatively, the Spearman correlation may be useful for solar wind statistics [Maruca et al., 2013].

#### 3.7.1 Autocorrelation Function

For any randomly varying function we can look at the time or spatial lagged autocorrelation of that function. This is simply the correlation between two points in the signal, where the time (or distance) between them is the lag. In general, the autocorrelation function is

\[
R(\tau) = \langle b(r, t)b(r + \delta r, t + \tau) \rangle
\]  

(3.9)

In a turbulent flow this function will typically peak at zero lag and steadily decrease to \(1/e\), where it will oscillate about zero. The lag for which \(R(\tau)\) first reaches zero is known as the correlation time, for which the signal is decorrelated from itself. Alternatively, \(\tau\) can be expressed in units of length and we have the equivalent concept of a correlation length. The correlation length in the solar wind is typically \(10^6\) km but depends on the size of the interval used for averaging [Ruiz et al., 2014, Isaacs et al., 2015]. A sample solar wind correlation function is shown in Figure 3.6.
Figure 3.6: A sample solar wind correlation function.
Figure 3.7: Correlation length estimate as a function of various intervals of averaging in the solar wind.

3.8 Ergodic Theorem

The ergodic theorem is a statement about the averaging interval used to calculate a quantity [Panchev, 1971, Matthaeus and Goldstein, 1982b, Isaacs et al., 2015]

\[ B_T = \frac{1}{T} \int_0^T B(t) dt \quad (3.10) \]

In the limit \( T \to \infty \) the ensemble average \( B_T \) will converge [Matthaeus and Goldstein, 1982b]. An example of this effect can be seen in Figure 3.7, which shows the solar wind correlation length estimate calculated as a function of various intervals of averaging. The true solar wind correlation length should be of order \( 10^6 \) km, but note that for small intervals of averaging the correlation estimate is an order of magnitude lower. As the interval increases, the function will converge to the correlation length.
3.9 Power Spectral Density

By taking the Fourier transform of the zero-lagged autocorrelation function, we may obtain the power spectrum. This is known as a Blackman-Tukey autocorrelation function [Matthaeus and Goldstein, 1982a]. It is a measure of the energy in the system at various length and/or time scales. A sample solar wind power spectrum is shown in Figure 3.8 [Tessein et al., 2011].

In a turbulent medium, the power spectrum tends to have three frequency subranges: the energy containing range, the inertial range and the dissipation range. The energy containing range refers to the lowest wavenumber end of the spectrum and is dominated by structures beyond the causality limit. The causality limit is reached when wavelengths longer than 1 AU in the radial direction cannot be measured at 1
AU because the sunward end of the structure has not formed yet. These scales are predominantly due to structures of solar origin and are not related to the turbulence. For example, if the plot in Figure 3.8 were to extend to lower frequencies, one might expect a peak at the frequency corresponding to 11 years because of the 11 year solar cycle.

The inertial subrange is at higher frequencies, corresponds to the turbulent cascade, and is of power law form $P(k) \sim k^{-5/3}$ as in hydrodynamic turbulence. At dissipation scales where the inertial subrange ends, the spectrum steepens into the dissipation range, where fluctuations are dissipated into heat. Less is known about the solar wind dissipation range, mostly due to a historical lack of available high frequencies measurements, but this is changing as these measurements becomes more available (see, for example Alexandrova et al. [2009], Sahraoui et al. [2010]).

3.10 Cross Helicity and Alfvén Ratio

Cross helicity is the correlation between velocity and magnetic field fluctuations $\langle \delta v \cdot \delta b \rangle$. Matthaeus and Goldstein [1982a] calculated cross helicity as a function of wavenumber and found that it is often negative and near unity for most frequencies, indicating some anti-correlation between velocity and magnetic field fluctuations. Milano et al. [2004] further subset this analysis for $V \cdot B$ angle (where $V$ is solar wind speed and $B$ is mean magnetic field) and found very little change in the cross helicity spectrum with respect to angle. Tseisin et al. [2011] and Smith et al. [2011] used cross helicity to observe generation of turbulence in CIRs. Isaacs et al. [2015] found that cross helicity decreases with increasing averaging interval, most likely due to the increased probability of sector boundary crossings in a larger sample size. The sector crossing would introduce a mixture of signs on the cross helicity calculation and decrease the average. There is a tendency for high values of cross helicity in the solar wind known as dynamic alignment. The Alfvén ratio

$$r_A = E_v(k)/E_b(k)$$
where $E_v$ and $E_b$ are the energy in the velocity and magnetic fluctuations respectively is the ratio of energy in the kinetic fluctuations to the magnetic fluctuations. Isaacs et al. [2015] found that Alfvén ratio increases with increasing averaging time, most likely due to sampling sector structure in larger time intervals. However, there is an interesting unexplained minimum at smaller times for both this and the cross helicity analysis described that also appears elsewhere [Matthaeus and Goldstein, 1982a, Milano et al., 2004, Wicks et al., 2013]. Some distributions of Alfvén ratios for various averaging intervals are shown in Figure 3.9.

3.10.1 Cross Correlation

A cross correlation is similar to an autocorrelation but looks at the correlation between two signals. Equation 3.12 is an example of a lagged cross correlation in which one of the signals is shifted in time and one can find a corresponding correlation for each time shift.

$$C(a, b) = \frac{\langle a(t)b(t + \tau) \rangle}{\sqrt{\sigma_a \sigma_b}}$$  \hspace{1cm} (3.12)
Typically, one is interested in the time shift for which correlation is maximized.

### 3.11 Sector Rectification

A spacecraft moving in the ecliptic plane tends to observe a “sectored structure” of the solar wind in which it will alternatively sample inward and outward directed magnetic fields. There is a manifestation of the spacecraft crossing the HCS. When doing analyses like cross helicity that take into account the direction of the fields one must correct for this effect, known as sector rectification. A good method for sector rectification was set forth by Bieber [1988] in which sectors are defined relative to a nominal 45° magnetic field typical at 1 AU due to the Parker spiral. A line is drawn perpendicular to this direction which serves as a separatrix between toward and away sectors. Once a sector has been identified as “away”, the direction of the flow is reversed and the “away” sector has been rectified.
Chapter 4
PRELIMINARY STUDIES

This section contains various unpublished statistical side studies unrelated to the main project (energetic particles). There will be three main preliminary studies covered: (1) An examination of means and variances of various solar wind statistics, (2) Scale-dependent kurtosis in the solar wind and its connection to synthetically generated intermittent fields and (3) Generation of initial conditions for MHD simulations.

4.1 Distributions of Means and Variances

In solar wind data analysis, the time series data are often years long. It doesn’t make sense to use one long sample of data when working with statistics for many reasons. Breaking the data set down into sub intervals creates “ensembles” that can be thought of different realizations of the system. In addition, the solar wind contains transients stream structure, sector crossings and solar cycle effects all of which impose time dependence in the system. Thus, it is important to choose an interval of averaging that is smaller than the time scales of these stream structures; typically time scales of 1 to 10 hours have been used [Roberts et al., 1987, Horbury et al., 2005]. Due to recent usage of local averaging in solar wind studies, it is of interest to examine how basic quantities in the solar wind change as a result of varying the interval of averaging [Milano et al., 2001, Cho and Lazarian, 2003, Bale et al., 2005, Sahraoui et al., 2010, Alexandrova et al., 2012]. When looking at small intervals of averaging the ergodic theorem becomes relevant. The ergodic theorem states that as the interval of averaging increases, statistical realizations will converge [Panchev, 1971]. This provides the additional constraint that the chosen interval of averaging must be sufficiently large. Here we look at how varying the interval of averaging will affect basic solar wind statistics:
average magnetic field and fluctuating field. More in depth studies of this nature can be found in Ruiz et al. [2014] and Isaacs et al. [2015]. The plots shown below use the ACE merged MAG/SWEPAM data set from the years 1998 through 2009 [Gold et al., 1998, Smith et al., 1998].

Figure 4.1 shows distributions of correlation length for averaging times ranging from 1 to 16 hours. This plot was obtained by calculating a correlation time using the Blackman-Tukey method and converting to time using the Taylor hypothesis. The speed used as a conversion factor was the average speed for the particular interval. The maximum lag used was 10% of the sample. If the correlation did reach $1/e$ before the maximum lag we extrapolated it using a linear fit. Note that the distributions appear lognormal which is typical of solar wind quantities. As we increase the averaging time, the correlation length increases toward $10^6$ km, which is the typical value in the solar wind [Matthaeus and Goldstein, 1982b].

Figure 4.2 shows values for Alfvén ratio $r_A$ and normalized cross helicity $\sigma_c$ as a function of averaging interval. The increase in $r_A$ and the decrease in $\sigma_c$ may be related to larger structures (which are more likely to include sector boundaries) being sampled [Isaacs et al., 2015]. Figure 4.3 shows distributions of $r_A$ in the solar wind for 1 hour, 10 hours and 16 hours. What we learn from these studies is that an averaging time of 1-10 hours seems most reasonable. More results of this nature are shown in Isaacs et al. [2015] and Ruiz et al. [2014].

4.2 Scale Dependent Kurtosis

Kurtosis of the increments is useful as a measure of non-Gaussianity Frisch [1995]. It is useful to look at scale dependent kurtosis in the solar wind. We can do this by changing the lag in the increment. Figure 3.3 shows distributions of kurtosis of the increments for $10d_i$, $100d_i$ and $1,000d_i$, where $d_i$ is the ion inertial length. The data used are 1 second magnetic field from ACE/MAG and 64 second plasma from ACE/SWEPAM. Fine resolution magnetic field is required because we want to use $10d_i$ as the smallest lag where $d_i$ is typically 1 second or less in the solar wind. The data
Figure 4.1: Distributions of correlation length for averaging times ranging from 1 to 16 hours. This plot was obtained by calculating a correlation time using the Blackman-Tukey method and converting to time using the Taylor hypothesis [Matthaeus and Goldstein, 1982a]. The speed used as conversion factor was the average speed for the particular interval. The maximum lag used was 10% of the sample. If the correlation did not reach $1/e$ before the maximum lag we extrapolated it using a linear fit. Note that the distributions appear lognormal which is typical of solar wind quantities. As we increase the averaging time, the correlation length increases toward $10^6$ km, which is the typical value in the solar wind [Matthaeus and Goldstein, 1982a].
Figure 4.2: Values for Alfvén ratio $r_A$ and normalized cross helicity $\sigma_c$ as a function of averaging interval. The increase in $r_A$ and the decrease in $\sigma_c$ may be related to larger structures (which are more likely to include sector boundaries) being sampled [Isaacs et al., 2015].
Figure 4.3: Distributions of Alfvén ratio $r_A$ in the solar wind for 1 hour, 10 hours and 16 hours.

was broken up into 4 hour subintervals and the the kurtosis based on radial magnetic field was calculated for each one. The distributions are of all the subintervals. The ion inertial length was computed according to the equation $d_i = c/\omega_{pi}$ with

$$\omega_{pi} = 1.32 \times 10^3 Z n_i^{1/2}$$  \hspace{1cm} (4.1)$$

where $c$ is speed of light, $\omega_{pi}$ is ion plasma frequency, $Z$ is the charge state, taken to be unity for protons, and $n_i$ is ion density. Since the density has a 64 second cadence, we assigned 64 repeating values of density to each 1 second magnetic field measurement, updating the density after every 64 seconds. The procedure gives an ion inertial length, but our measurements are in the time domain, so we invoke the Taylor Hypothesis to convert ion inertial length to ion “inertial time”. We then used this time as a factor for the lag in computing kurtosis of the increments. Note that as the lag increases, the kurtosis decreases to its Gaussian value of 3, indicative of non-Gaussianity.
Figure 4.4: PDF of values returned from the Gaussian random number generator.

[Marsch and Tu, 1994, 1997, Sorriso-Valvo et al., 1999]. For more information on scale dependent kurtosis see Wan et al. [2012b] and Subedi et al. [2014].

4.3 Initial Condition for MHD Simulation

We have generated initial conditions for a $128^3$ data set in complex Fourier space, used an FFT to transform the fields into real space and done various calculations with the real fields. These initial conditions also have the magnetic and velocity fields uncorrelated because the fields were created independently using a Gaussian random number generator (Figure 4.4).

There are several checks to be done that allow us to know the code is working. Among the most important is that the total energy is equal to one.

$$E_{total} = E_v + E_b$$ (4.2)
<table>
<thead>
<tr>
<th>Total energy</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfvén Ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum wavelength</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum wavelength</td>
<td>100.0</td>
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<tr>
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</tr>
<tr>
<td>Spectral knee (b)</td>
<td>3.0</td>
</tr>
<tr>
<td>Hc/Hm correlation</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.1: Initial conditions.

\[ E_b = \sum_k \sum_{i=1}^3 \left[ Re(A_i)^2 + Im(A_i)^2 \right] \]  \hspace{1cm} (4.3)

where \(A\) is vector potential and corner modes are weighted by a factor of one half. Total kinetic energy is obtained in the same manner from the velocity fields. For this code the total energy is unity to a high level of precision (one part in \(10^{13}\)). We obtain this result both in Fourier space and real space.

Another important quantity is the mean square current density. The current in real space is obtained by twice taking the curl of the magnetic vector potential in Fourier space

\[ J = \nabla \times (\nabla \times A) \]  \hspace{1cm} (4.4)

where the curl (in Fourier space is)

\[ \nabla \times \mathbf{B}(r) = -i\mathbf{k} \times \mathbf{\overline{B}}(k) \]  \hspace{1cm} (4.5)

The mean square current density was computed using a finite difference method to compute the curl of the real space magnetic field.

4.3.1 Fourier Transform

We have obtained real space fields by using the FFTW (Fastest Fourier Transform in the West) software package [Frigo and Johnson, 1998]. We know that the FFT has been done properly because upon an inverse Fourier transform using FFTW back
Table 4.2: Table of computed values.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Magnetic Energy</td>
<td>0.503</td>
</tr>
<tr>
<td>Total Kinetic Energy</td>
<td>0.499</td>
</tr>
<tr>
<td>$\langle J^2 \rangle$</td>
<td>422.45</td>
</tr>
</tbody>
</table>

**Figure 4.5:** Contour plot of z-component magnetic field.

to Fourier space, we obtain the original fields. The FFTW software package performs a procedure known as a the Fast Fourier Transform (FFT). FFT is a computationally faster approximation of a Fourier Transform.

There are two pictures of the magnetic field (Figure 4.5) in a plane and the electric current density normal to that plane (Figure 4.6). These images are contour plots where white indicates low levels of the pictured quantity transitioning through red into orange for high levels.
4.3.2 Calculation of Mean Square Current Density

Once the real fields were obtained, we used the real space magnetic field to calculate mean square current density by numerically taking the curl $\nabla \times \mathbf{B} = \mathbf{J}$. This was done using a central finite difference method using the two nearest neighbors to approximate the derivative:

$$j^i \approx \frac{B_{k+2}^j + 8B_{k+1}^j - 8B_{k-1}^j + B_{k-2}^j}{24\pi/N_i} - \frac{B_{j+2}^k + 8B_{j+1}^k - 8B_{j-1}^k + B_{j-2}^k}{24\pi/N_i}$$

where $N_x, N_y, N_z$ are the spatial dimensions of the data set. From this, the mean square current was obtained:

$$\langle J^2 \rangle = \sum_{i}^{N_xN_yN_z} (j_i^x)^2 + (j_i^y)^2 + (j_i^z)^2$$

(4.6)
Note that we do not get the same result for mean square current density in Fourier space as we do in real space. This is due to the inaccuracy of the finite difference method.

### 4.3.3 Simulating a Spacecraft Trajectory through the Box

The objective of this part is to simulate a spacecraft passing through the box at some angle, taking magnetic field measurements at discrete points and to make a power spectrum from that. Then, the power spectrum will be compared to the omnidirectional spectrum. The resolution of the trajectories is such that it takes 200 measurements across the simulation domain. This is roughly one measurement per grid cube. Table 4.3 contains a list of the start and end points used for this trajectory.

Linear interpolation was used to calculate the magnetic field for locations between grid points. To calculate the magnetic field inside a cube where the field is known at all the vertices, one must write a 1D linear interpolation function. Then, a 2D linear interpolation function is written, which calls the 1D function three times. Then a 3D linear interpolation function calls the 1D function four times, and the 2D function once, corresponding to the plane connecting the four points obtained by the four calls of the 1D function. From the trajectories, 25 time series magnetic field measurements were obtained, each containing 200 measurements. To obtain the power spectrum, the Blackman-Tukey method was used as in Matthaeus and Goldstein [1982a]. In the Blackman-Tukey method, the maximum lag typically cannot exceed 10% of the sample size. On the spectrum generated the maximum lag shown is 10 because a lag beyond that will exceed the Nyquist frequency. The 25 spectra have been averaged to obtain a cleaner spectrum. The averaged spectrum was normalized because each spectrum obtained has a different amplitude. By dividing each spectrum by its $k = 1$ value, they can be compared. After generating the spectrum it was compared to the
<table>
<thead>
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<th>Starting Point</th>
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<tr>
<td>(0,33,1)</td>
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<td>(0,57,25)</td>
<td>(128,121,89)</td>
</tr>
</tbody>
</table>

**Table 4.3:** Start and end points for the trajectories used.
omnidirectional spectrum using the formula

$$E_{od}(k) = 4\pi k^2 E(k)$$  \hspace{1cm} (4.7)$$

The slope of the omnidirectional spectrum is around $-1.2$, somewhat close to the expected value of $-5/3$.

### 4.3.4 Conclusions

This section has described the creation of initial conditions for a fluid simulation. Running the simulation for at least a nonlinear time, $L/U$ (where $L$ and $U$ are typical length and velocity scales of the system) will result in intermittent fields. One property of intermittent fields is non-Gaussianity. Figure 4.7 is a probability distribution of mean square current density in the system after the MHD simulation has been run. Randomized fields (blue) overlap a Gaussian distribution (red). The mean square current density after running the simulation is plotted in green and has wide non-Gaussian tails that occur in intermittent systems.
Chapter 5
EFFECT OF COHERENT STRUCTURES ON ENERGETIC PARTICLE INTENSITY

The observation, from simulation and solar wind data, that heating and dissipation are preferentially found in coherent structures inspires the search for the presence of energetic particles in and around coherent structures. The results of Dmitruk et al. [2004] and Ambrosiano et al. [1988] in which there is an association between PVI and energetic particles as well as observed dropouts motivate a search for similar results in the solar wind. This is done using conditional statistics, local averaging and sample events; we also implement the superposed epoch analysis method employed by Osman et al. [2012b]. It must be kept in mind the separate phenomena that we know are already present; flares and DSA. Additionally, it is important to untangle the effects of acceleration and transport. What we find is that in a superposed epoch analysis there is a higher average flux associated with the strongest discontinuities than with shocks and there is a local increase in energetic particle flux at non-shock discontinuities that falls off monotonically as one moves away from it. A caveat to this result is that one must be careful with how shocks are chosen and mitigate the effects of DSA. Additionally, there are instrumental issues to look out for. We start out by looking at statistics like the superposed epoch analysis, and proceed to look at sample events to confirm that what is seen in the statistics is reflected in the data finding that these statistical analyses are a composite of different types of events. For this reason, looking at sample events is essential. The results are explained further in Tessein et al. [2013] and Tessein et al. [2015] (hereafter referred to as T15).
5.1 Data and analysis procedures

The data are from the MAG, SWEPAM, and EPAM instruments. We use the energetic particle flux from EPAM (LEMS30 and LEMS120) in an unorthodox manner: for the statistical analysis, we sum over the 8 channels of the EPAM detector, weighted by the width of channel. For example, the $P1'$ channel of LEMS120 covers the energy range 47 keV to 68 keV resulting in a weighting factor of 21 keV. The ACE/SWEPAM instrument was used for the sample events and MAG for both sample events and magnetic field for PVI. We use the LEMS30 and LEMS120 detector heads on EPAM. These are nearly identical except for the orientations, 30° and 120° to the spin axis respectively. Since the spacecraft spin axis is within 20° of the Sun-Earth line, LEMS30 points mostly Sunward while LEMS120 points anti-Sunward. One problem with LEMS30 is the failure of the $P1$ channel during 2001 [Haggerty et al., 2006] and X-ray contamination [Marhavilas et al., 2015]. This resulted in an elevated noise floor and eventually the instrument had to be turned off. Since this may also affect statistics, we can stop the analysis using LEMS30 at day 150 of 2001. Since this may also affect statistics, we can stop the analysis using LEMS30 at day 150 of 2001. We performed statistics with both LEMS30 and LEMS120. Since both instruments produced qualitatively similar results we use LEMS120 since it has more usable data.

The data set we use for the statistical analysis merges magnetic field and energetic particle flux. Because energetic particle flux is on a different cadence from the magnetic field (5 minute and 64 seconds respectively) we merged them by reducing the magnetic field to 5 minute temporal resolution. This was done by taking each measurement of the EPAM energetic particle flux and averaging together all magnetic field measurements from the 5 minute period leading up to that measurement and attaching to it the same time tag as for the energetic particle flux. In all of the following analyses, the lag ($\tau$) used to compute PVI is 5 minutes.
Table 5.1: Summary of the data used. Time format is (year)-(day of year).

<table>
<thead>
<tr>
<th>ACE Instrument</th>
<th>Measurement</th>
<th>Energy Range</th>
<th>Cadence</th>
<th>Time Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEMS30</td>
<td>Ion Flux</td>
<td>0.046-4.7 MeV</td>
<td>5 min.</td>
<td>98-23 to 01-050</td>
</tr>
<tr>
<td>LEMS120</td>
<td>Ion Flux</td>
<td>0.047-4.78 MeV</td>
<td>5 min.</td>
<td>98-23 to 10-258</td>
</tr>
<tr>
<td>SWEPAM</td>
<td>Plasma Params.</td>
<td>0.26-36 keV</td>
<td>64 sec.</td>
<td>98-23 to 10-258</td>
</tr>
<tr>
<td>MAG</td>
<td>Mag. Field</td>
<td>N/A</td>
<td>64 sec.</td>
<td>98-23 to 10-258</td>
</tr>
<tr>
<td>MAG</td>
<td>Mag. Field</td>
<td>N/A</td>
<td>16 sec.</td>
<td>98-23 to 10-258</td>
</tr>
</tbody>
</table>

5.1.1 Search for Weak Shocks

It is possible that weak shocks, which do not appear in a shock list, can accelerate particles through DSA. For this reason, we deemed it necessary to make a superposed epoch analysis of average energetic particle intensity for weak shocks, strong shocks (from the lists) and non-shock discontinuities in order to determine the possible effects of DSA from weak shocks. This is shown in Figure 5.1. We identified weak shocks by taking a list of 279 PVI > 8 shocks and searching for shock-like characteristics by eye. This method returned 6 out of 279 events as possible weak shocks. Admittedly, only sampling PVI > 8 events is not a good way to identify shocks since they tend to have lower PVI values (see Figure 5.2), so there are inevitably many shocks that will not be identified using this method. This was intended to be a zeroth order solution to see what the result would look like in the superposed epoch analysis. The other 273 events cannot be forward or reverse shocks because the gradients in the data were not shock-like and there was not a clear transition from shocked to unchecked plasma. In addition, this method can also lead to false positives. Thus, the weak shocks identified by this analysis seem far less important. In this case, the PVI > 8 line is lower than the shock trace because these are the discontinuities 12 or more hours away from a shock, cases that have been shown to have much lower average energetic particle flux. For these reasons we choose to ignore the weak shocks. Henceforward, we will not consider PVI > 8 questionable shocks as a separate category because they do not seem to be associated with high energetic particle flux. Weak shocks are not efficient accelerators of energetic particles because the efficiency is correlated with ratio.
Figure 5.1: Superposed epoch analysis comparing strong shocks, weak shocks and non-shock PVI > 8 discontinuities. This justifies the assumption that weak shocks are not important as participants in DSA.

Figure 5.2: Histogram of PVI values for shocks from the augmented shock list used in T15. The shock PVI was obtained by taking the largest of the five PVI values nearest each shock.
5.1.2 Upstream Events

The look direction of LEMS120 can subject it to upstream events when it is magnetically connected to the bow shock [Haggerty et al., 1999, Dwyer et al., 2000, Haggerty et al., 2000]. An example of this effect is shown in Figure 5.3, with the three lowest energy channels of LEMS30 and LEMS120 from the same time period in 1999, with LEMS120 on top, LEMS30 in the middle and PVI time series on the bottom. Spikes in the data appear in LEMS120 but not LEMS30 due to upstream events caused by ACE being magnetically connected to Earth’s bow shock at this time. Many of these cases have been observed and we can avoid upstream events in the data by using LEMS30 instead, thus avoiding contamination to our statistics.

5.1.3 Shock List

Our shocks come from the ACE shock list, however, this list cannot include all shocks. Figure 1.3 shows an example of an ACE shock not appearing in the ACE list. It is important to get all the shocks into the list for this study so avoid effects of DSA in the statistics. The three panels are time series of PVI (top), energetic particle flux from LEMS120 (middle) and magnetic field (bottom). The location of the shock is obvious; it is the location where energetic particle flux increases with simultaneous transition from unshocked to shocked plasma. The energetic particle profile is exactly what we would expect for DSA; the ramp leading up to the shock and a slow drop off behind. Obviously, this is a big shock and should be classified as such in the database.

5.1.4 Shock PVI

A histogram of PVI values at shocks from our augmented list is shown in Figure 5.2. The PVI value for each of 498 shocks was obtained by taking the 5 nearest temporal PVI data points to the shock (closest measurement plus two on either side) and taking the maximum value of those five measurements. While the distribution has a long tail extending up to large PVI values, it is peaked at relatively small (< 3)
Figure 5.3: The three lowest energy channels of LEMS30 and LEMS120 from the same time period in 1999, with LEMS120 on top, LEMS30 in the middle and PVI time series on the bottom. Spikes in the data appear in LEMS120 but not LEMS30 due to upstream events caused by ACE being magnetically connected to Earth’s bow shock at this time. Many of these cases have been observed and we can avoid upstream events in the data by using LEMS30 instead, thus avoiding contamination to our statistics.
Figure 5.4: PVI threshold scattered against average energetic particle flux for the LEMS120 detector. The energetic particle flux has been averaged for each particular PVI threshold. The different lines correspond to differing amounts of data removal around the shock. Thus the line labeled as “6 hours” has 6 hours of data removed on each side of the shock and the line labeled 0 hours has no data removed. The 6 hours line has had a total of 7% of the total data removed and the intermediate lines have monotonically reduced percentages until zero is reached. These values provide the interesting information that looking for high PVI values is, in general, not a good way to identify shocks.

5.2 Statistical Analysis

Figure 5.4 scatters PVI threshold against average energetic particle flux for the LEMS120 detector. The energetic particle flux has been averaged for each particular PVI threshold. The different lines correspond to differing amounts of data removal around the shock. Thus the line labeled as “6 hours” has 6 hours of data removed on each side of the shock and the line labeled 0 hours has no data removed. The 6 hour line has had a total of 7% of the total data removed and the intermediate lines have monotonically reduced percentages until zero is reached. There are two interesting
things to note here. The first is that the more data we remove around the shock, the lower the energetic particle flux becomes. This confirms that shocks are strongly associated with elevated energetic particle flux. This is evidence for DSA. The second thing to note is the increase of energetic particle flux as we increase PVI threshold even when data around shocks are removed. Discontinuities away from shocks appear to be associated with elevated energetic particle flux and the effect becomes more pronounced as the discontinuity becomes more intense. This result can be unpacked further by looking at a superposed epoch analysis.

Figure 5.5 is a superposed epoch analysis showing average energetic particle flux conditioned on temporal distance from shocks (red line) and non-shock discontinuities (all other lines) where $\Delta t = 0$ corresponds to the location of the coherent structure. Data are from the LEMS30 spacecraft for 1998 through 2010. The trace corresponding to shocks shows a signature of DSA; a ramp up to the shock and a slow decrease in energetic particle flux after. The measurements on the x-axis are temporal offset from the event in the spacecraft frame. The right y-axis axis shows how many events have gone into each trace. There is also a local effect analogous to what has been observed by Osman et al. [2012b]; an increasing of average energetic particle intensity as we increase the intensity of the coherent structure, as has already been shown in Figure 5.4. Note that the peak in energetic particle flux for non-shock discontinuities occurs just to the left of $\Delta t = 0$, corresponding to about 30 minutes. This is due to the shear generated by the shocks, resulting in the formation of discontinuities. A visualization of this is shown in Figure 5.6 in which most of the strong discontinuities occur immediately after a shock. Because of the evidence for DSA in this figure it is of interest to remove shocks to observe what effect they have. In these analyses shocks (which are a type of discontinuity) are not included as non-shock discontinuities and vice versa. Figure 5.7 is analogous to Figure 5.5 but with data within 6 hours of a shock removed. As expected, there is a drop in energetic particle flux because of the strong association between energetic particle flux and shocks. However, the local increase in flux at the discontinuity remains and is centered now since this offset was due to shocks. Given the issues mentioned above with the shock list, mainly the results of T13, it is of interest to correct these results. One piece of low hanging fruit seems to be the matter of the shock list. Since shock acceleration is a feature of the solar wind energetic particle landscape, we must properly account for the presence of shocks in the analysis as shocks are coherent structures that will be identified by the PVI statistic. The ACE shock list misses some strong shocks with nominal DSA time intensity profiles; thus, the list cannot include “weak shocks” [Vorotnikov et al., 2008]. By weak shocks, we mean shocks with a smaller density or magnetic field jump across them. For this reason we used the WIND shock list, compiled by the Harvard Smithsonian Center for Astrophysics. Since late in 2004 WIND has been at L1 with
Figure 5.5: Superposed epoch analysis showing average energetic particle flux conditioned on spatial/temporal distance (through the Taylor Hypothesis) from shocks (red line) and non-shock discontinuities (all other lines) and $\Delta t = 0$ corresponds to the location of the coherent structure. Data are from the LEMS30 spacecraft from 1998 through 2010. Again we see evidence for DSA by looking at the profile for 322 shocks. This is exactly what one would expect for a composite of hundreds of shocks; a ramp up to the shock and a slow decrease in energetic particle flux after. The measurements on the x-axis are time increments as measured on the spacecraft. So a position 5 points in the negative direction corresponds to what the spacecraft observed 25 minutes before the observation of the coherent structure.
Figure 5.6: Superposed epoch analysis, with the shocks from the augmented shock list plotted against probability of finding a discontinuity subsetted for PVI threshold. PVI events are very likely to occur within two hours after a shock has passed.
Figure 5.7: Analogous to Figure 5.5 but with data within 6 hours of a shock removed. As expected, there is a drop in energetic particle flux because of the strong association between energetic particle flux and shock. However, the local increase in flux at the discontinuity remains and is centered now. There is a strong signal linking energetic particle flux to discontinuities, that seems to be more than just DSA.
ACE and they should be able to observe the same shocks. Prior to that time WIND was occasionally within the same path as ACE. For example, from 1999 through 2002 WIND executed petal orbits which took it in and out of Earth’s magnetosphere. The procedure for using the WIND shock list to augment the ACE shock list is as follows:

1. Find shocks that are in the WIND list but not in the ACE list
2. Check that WIND is at L1 during this time period
3. Calculate the time at which the shock should appear in the ACE data
4. Check the ACE data at this time for the corresponding shock. If it is there, the shock can be added to the list.

This allowed us to obtain an “augmented” shock list made up of 519 shocks. We can now repeat the analysis with the augmented shock list, more confident that shocks haven’t leaked into what are supposed to be non-shock analyses. Figure 5.8 is that analysis. The local peak is still present but with energetic particle flux further reduced. Again, this is not surprising, given the well known association between shocks and energetic particle.

Figure 1.3 is an example of a shock that is not in the ACE list but is clearly an accelerator of particles. There is a concern that more shocks like this can populate our list.

Figure 5.9 is a superposed epoch analysis similar to Figure 5.4 but for electrons from ACE/EPAM in the 38-315 keV energy range. The result for electrons is comparable to that of ions.

5.2.1 Waiting Times

Figure 5.10 is a histogram of waiting times for non-shock PVI > 8 events, of which there are 451. These events are more than 12 hours away from an ACE shock. Included are average waiting times for various cutoffs. For example, a cutoff of 100 minutes means that we are averaging over all waiting times that are less than 100 minutes. The reason for doing this is due to the long tail of the histogram in which the average waiting time over the entire data set is 2.72 days. Note that if we include
**Figure 5.8:** Analogous to Figure 5.7 but using the augmented shock list. The energetic particle flux has decreased due to the large number of shocks taken out. However, the temporal peak in energetic particle flux remains except for the highest PVI threshold.

**Figure 5.9:** PVI threshold scattered against average energetic particle flux for electrons from ACE/EPAM in the 38-315 keV energy range. As with ions, there is also a correlation between PVI and average energetic particle flux for electrons. Diamonds correspond to energetic particle flux (left axis) and the solid line corresponds to the number of events in the sample (right axis).
the smallest 52% of the waiting times, the average is only 30 minutes. The bins have a constant size of 5 minutes.

Figure 5.11 is like Figure 5.10 but is a probability density function. The bins are constant statistical weight with 25 points per bin for a total of 18 bins.

5.3 Sample Events

In solar wind observations it is important to look at sample events in addition to statistics, as the statistics can sometimes produce spurious results from averaging together different types of events. There are three possible reasons to explain why
**Figure 5.11:** Like Figure 5.10 but is a probability density function. The bins are constant statistical weight with 25 points per bin for a total of 18 bins.
the PVI has higher associated energetic particle flux for coherent structures than for shocks.

1. Shocks appearing not on the list
2. Extended Diffusive Shock Acceleration Tails
3. Edge Events

The first item should be resolved by the augmentation of the ACE shock list from the WIND list. Item two is related to extended (in time) DSA tails. When DSA occurs the energetic particle flux tends to peak at the shock unless there is a complex time-intensity profile (see, e.g., Giacalone [2012]). The slow decay of energetic particle intensity can last for days. In the interest of not throwing away too much data, we removed up to 30 hours of data (15 hours before, 15 hours after) for each shock neighborhood. In cases of these DSA “tails” discontinuities more than 15 hours away from a shock will be counted as non-shock discontinuities even though they are clearly related. An example of this is shown in Figure 5.12 in which two shocks are shown, both with DSA occurring. The DSA tail from the first shock extends into the second shock, making this entire interval DSA influenced. The shocks are likely from CMEs sourced at the same active region. Between the shocks, in the region of stirred up plasma from the first shock, is a cluster of high PVI events. Using 15 hours of shock removal, PVI events like these will not be classified as shock influenced, even though they clearly are. However, since we are looking for effects that will lead to peaks in energetic particle flux, adding up plateaus will likely not produce a peak. Thus, we can continue with the analysis mindful of these “plateau” type events that can elevate the average energetic particle flux away from shocks.

Figures 5.13 and 5.14 are so-called “edge type” events in which the energetic particle flux is changing in the presence of a discontinuity. This could be interpreted as local acceleration or a flux tube boundary in which the spacecraft is passing between filled and empty flux tubes. In each example there is a local peak in the energetic particle intensity; the PVI peak near this energetic particle enhancement could be due to local acceleration.
Figure 5.12: In this event particles are accelerated by a shock on day 252. Before the energized particles completely decay, a second shock hits on day 254, re-accelerating them. PVI events are more than 12 hours away from both shocks and can be erroneously classified as non-shock events.

Figures 5.15 and 5.16 are possible flux tubes. The PVI event represents the discontinuity at the flux tube boundary. Well lined up with the magnetic discontinuity are discontinuities in some or all of the plasma data time series. The plasma discontinuities are not shock-like and may be due to compression in one of the flux tubes as a result of collision. These tubes may act as pipes for energetic particle transport. A flux tube that is not magnetically connected to an active region may be adjacent to one that is, leading to the energetic particle changes at discontinuities shown above. In a case like this, one could also look for a rotation in the magnetic field as one would expect adjacent flux tubes to have different magnetic field orientation. This is the phenomenon of Mazur et al. [2000]. It should be noted that the flux tubes invoked here need not be space filling or connected to the photosphere as implied by the schematics of Borovsky [2008].

In Figure 5.15 there is a discontinuous increase in the magnetic field, and a discontinuous decrease in density near $t = 62.39$. The peak in density occurs near the
Figure 5.13: Examples of “edge type” events in which the energetic particle is changing near a PVI peak. The panels depict time series measurements of 5 minute PVI (top), 5 minute LEMS120 intensity (middle) and 16 second magnetic field (bottom). The high PVI values are associated with a gradient in the energetic particle intensity.
Figure 5.14: Examples of “edge type” events in which the energetic particle is changing near a PVI peak. The panels depict time series measurements of 5 minute PVI (top), 5 minute LEMS120 intensity (middle) and 16 second magnetic field (bottom). The high PVI values are associated with a gradient in the energetic particle intensity.
boundary and is likely due to compression. There is a small discontinuity in solar wind speed. This is a current sheet rather than a shock; none of these changes are shock-like and there is no clear transition from shocked to unshocked plasma or vice versa.

In Figure 5.16 a possible flux tube boundary has been identified at $t = 179.19$. Again, there is a spike in density at the interface, indicative of compression. This tube is also a current sheet rather than a shock for reasons stated above.

5.4 Further Statistics

With the possible scenarios that we have obtained, we can create a lagged cross correlation to test these scenarios keeping in mind that doing statistics will admit many
Figure 5.16: Time series of PVI, LEMS120 intensity, magnetic field, density, temperature and proton flow speed. There is a possible flux tube boundary near $t = 179.19$. The presence of two PVI peaks indicates two possible flux tube boundary crossings.
different type of events and averaging them together may be misleading. The lagged cross correlation is defined by

\[ I'(t) = I(t) - \langle I \rangle \] (5.1)
\[ \bar{F}'(t) = \bar{F}(t) - \langle \bar{F} \rangle \] (5.2)

where \( \langle \ldots \rangle \) denotes time average over the entire data set, and \( I \) and \( \bar{F} \) are the energetic particle and PVI time series respectively. Thus, we are correlating the fluctuating part of these quantities.

Figure 5.17: Lagged cross correlation between fluctuating PVI and energetic particle flux for various PVI thresholds. In this case fluctuating PVI is the lagged quantity. The correlation is maximized for zero time shift.

Figure 5.17 is the cross correlation subset for various PVI thresholds. This plot includes only data with shock neighborhoods removed 15 hours on either side as in the figure shown above. The correlation peaks at zero lag, meaning that the quantities are likely to be changing together. This is consistent with simulation results showing a correlation between energetic particles with coherent structures [Greco et al., 2012, Servidio et al., 2012, Karimabadi et al., 2013, Dalena et al., 2014].
We have repeated this analysis with the alternative formulation

\[ C(I', \delta') = \frac{\langle I'(t)\delta'(t + \tau) \rangle - \langle I' \rangle \langle \delta' \rangle}{\sqrt{\sigma_I \sigma_\delta}} \]  

(5.3)

which is the same as Equation 5.2 with an added term in the numerator. The second term carries the assumption that the means of \( I' \) and \( \delta' \) are not zero, which may be the case given the burstiness of the signal and the removal of data due to shocks. However, we found that the second term is near zero, so the result will be the same.

![PDFs of the signed percent difference in energetic particle flux across discontinuities for PVI > 3, 4 or 5 and PVI < 4 with varying lag with a Gaussian distribution (dotted curve) shown for reference.](image)

**Figure 5.18:** PDFs of the signed percent difference in energetic particle flux across discontinuities for PVI > 3, 4 or 5 and PVI < 4 with varying lag with a Gaussian distribution (dotted curve) shown for reference.
Figure 5.18 depicts Probability Density Functions (PDFs) of the signed percent difference

\[ 100 \times \frac{x_{i+L} - x_{i-L}}{\left(\frac{x_{i+L} + x_{i-L}}{2}\right)} \]  

in energetic particle flux across discontinuities, where in this case the lag \( L \) is equal to one hour lag and \( x \) is energetic particle flux times series. This procedure has been applied for PVI > 3, 4 or 5 and PVI < 4 with varying lag and a Gaussian is shown for reference. Like many increment-type statistics in the solar wind, the distributions of energetic particle flux increments are non-Gaussian. In addition, for the stronger discontinuities the PDF is more non-Gaussian than for weak coherent structures and statistics with longer lag are more non-Gaussian than those with shorter lag. The tails becoming stronger with higher PVI values can be seen as a statistical manifestation of many small changes in energetic particle intensity, supporting our guess that the edge type events are common.

5.5 Flux Tube Boundaries

Flux tubes are regions with distinct magnetic and plasma properties that are not necessarily space filling and/or connected back to the sun as described by Borovsky [2008]. The boundaries between them go a long way toward explaining the results shown above. Many of the commonly observed edge events shown above, in which the energetic particle flux is changing at a discontinuity, are likely to be flux tube boundaries [Neugebauer and Giacalone, 2015, Tessein et al., 2015]. When crossing a flux tube boundary the change in the magnitude and/or direction of the magnetic field will trigger a PVI peak in the magnetic field. If the flux tube is acting as a pipe for transporting energetic particles, passing between filled and empty flux tubes explains the change in energetic particle flux across the boundary. This could be an observational manifestation of “empty” field lines diffusing into a “core” of energetic particles or vice versa and is related to the dropouts described by Mazur et al. [2000]. The particles may also become entrained within flux tubes as shown in the simulations of
Matsumoto et al. [2015]. In this case, flux tubes could facilitate both local acceleration and transport. There could be an added complication of reconnecting current sheets at flux tube boundaries. In this case, it may be difficult to distinguish between energization associated with the reconnection and flux tube transport.

5.6 Local Acceleration Downstream of Shocks

When a shock passes the spacecraft, it leaves in its wake a turbulent downstream region, in which most of the discontinuities identified by the PVI statistic are located.

Figure 5.6 is a PDF showing the probability of finding a discontinuity relative to a shock. This is a superposed epoch analysis using the augmented shock list. Most of the discontinuities in shock neighborhoods occur within several hours after the shock has passed, especially for higher PVI thresholds. If there is modulation of the energetic particle flux in discontinuities, be it by acceleration, transport, or some combination of the two, one might expect it to be occurring in the downstream of the shock. There is evidence for this from observations and simulation. Figure 5.19, from T13 is an example of a complex time intensity profile where energetic particle intensity can reach equal or higher values immediately downstream of the shock rather than at the shock itself. An example of energetic particle trapping downstream of a shock is shown in Particle-in-Cell simulations done by Matsumoto et al. [2015] in which there are energetic particles trapped in secondary magnetic islands downstream of a shock.

Figure 5.20 is a possible scenario like this in the solar wind. The highest peak in energetic particle intensity occurs downstream of the shock and changes in the intensity may be modulated by discontinuities, represented by the PVI time series. Even if the energetic particle peaks and discontinuities do not directly overlap, it has been shown in simulations and observations that the peak dissipation in reconnection can occur away from the reconnection site [Cassak and Shay, 2007, Sundkvist et al., 2007, Zhdankin et al., 2013, Wan et al., 2014].
Figure 5.19: Example of a shock with a complex time-intensity profile in which the energetic particle intensity peaks away from the shock. This may be due to local acceleration associated with trapping in the magnetic structures stirred up by the passage of the shock.
Figure 5.20: Example of a shock with a complex time-intensity profile in which the energetic particle intensity peaks away from the shock. Changes in energetic particle intensity throughout the downstream region may be modulated by transport and/or local acceleration.
5.7 Discussion

The results above show a clear connection between energetic particle intensity and coherent magnetic structures. In ascribing to these results a physical mechanism it is important to consider how all acceleration and transport effects will manifest themselves and if they are consistent with observations. The question we must answer is: What are the relative roles of transport and acceleration in these observations?

Local acceleration may be due to DSA, magnetic reconnection and the betatron mechanism. DSA operates through the Fermi mechanism in which particles are energized through multiple reflections across a shock, thereby gaining energy from the shock. Since collisionless shocks are themselves coherent structures, this would produce a peak in energetic particle intensity at shocks. However, shocks often have low PVI values and a significant amount of time was spent in this work confining the analysis to regions away from shock neighborhoods in which DSA dominates the energetic particle profile. Acceleration at magnetic reconnection sites may operate through the island merging mechanism [Drake et al., 2009, Zank et al., 2014, Le Roux et al., 2015]. This mechanism is compatible with the observations as reconnection sites are coherent structures that have a strong association with PVI [Osman et al., 2014] and are ubiquitous in turbulent simulations [Servidio et al., 2011]. Dalena et al. [2014] has shown that test particles of a certain energy range can be confined to current sheets. This mechanism is betatron-like, in which particles resonate with electric field “kicks”, and will act strongly in current sheets. In these simulations, energetic particles within filamentary coherent structures could produce results like those shown above.

Magnetic reconnection can also accelerate particles in flares near the sun. The particles will then be transported by the magnetic field to 1 AU. In this case observed changes in energetic particle flux may be related to observed dropouts in which filled and empty flux tubes are advected past the spacecraft. This is related to field line meandering because a flux tube not connected to an active region may end up within the “core” of an SEP event at 1 AU. However, this assumes that flux tubes are space filling and/or connect back to the photosphere (see e.g. Borovsky [2008]) which may
not be true. Additionally, acceleration from any of the mechanisms above may be happening at remote locations and the particles observed will have been the result of transport mechanisms like diffusion or field line diffusion. Another possibility that will complicate observations of impulsive events is that of flare-associated particles being re-accelerated by a shock.

The relative role of transport and acceleration is an open topic that remains unsolved. For example, it is one of the science goals of the Solar Probe Plus mission, which will shed light on this matter by going close to the sun where much of the acceleration is happening [McComas et al., 2014]. The work shown here partially answers these questions; it has been shown that there is acceleration happening in addition to DSA preferentially in and around coherent structures.

Fisk and Gloeckler [2006] ascribe much of the energetic particles to acceleration by compressive turbulence and Khabarova et al. [2015] claim observation of acceleration of trapped particles through reconnection at the HCS. Due to the limitations of space instrumentation and the myriad of processes available to accelerate particles one should proceed with caution in this matter.

Desai et al. [2015] point out the two principal theories behind SEPs: continuous acceleration in the interplanetary medium and remnant material from transients like CIRs and flares. Composition measurements of $^3$He and heavy elements tend to vary with solar cycle and can be a powerful tool in understanding the relative effects of transport and acceleration. Roelof [2015] shows the possibility that particles becoming trapped in “reservoirs” associated with the leading edge of CMEs can accelerate SEPs.

An improved understanding of pitch angle distributions may help elucidate this matter. For example, Dalena et al. [2014] found in test particle simulations that particles trapped within filamentary structures in the smaller simulation domain have a different pitch angle distribution from those more evenly distributed in the larger simulation domain. This indicates different physics at work for different distributions. Pitch angles tend to be scattered to isotropy at a shock whereas in betatron acceleration one would expect a pitch angle in which velocity and magnetic field are perpendicular.
Figure 5.21: Cartoon showing a flux tube collision scenario that could give rise to our results. The collision can warp the tubes and change the pressure in one or both of them. It is not possible to rule out the possibility that some of the particles are associated with flux tube boundaries or accelerated at or near these locations.

5.8 Conclusions

We have performed a superposed epoch analysis in order to look at the average temporal energetic profile around coherent structures, identified using the PVI statistics and shocks. We find that the average energetic particle intensity near coherent structures is higher than that for shocks and the peak remains when shock neighborhoods are removed albeit with reduced energetic particle intensity. The analysis has been repeated using a different energetic particle instrument, ACE/SEPICA, with qualitatively similar results. This is a robust result with errors-of-the-mean smaller than the plot symbols. We have shown evidence that the peak in energetic particle flux shown in the superposed epoch analysis can be attributed to (1) extended plateaus of energetic particle intensity directly attributable to DSA and (2) energetic particle edges where the intensity is increasing or decreasing at or near a peak in PVI. In the
latter case, it is difficult to distinguish between local acceleration and entrainment. In fact, the acceleration may be due to entrainment, as in the island merging mechanisms of Matthaeus et al. [1984] and Drake et al. [2006], flux tube collision or betatron acceleration [Swann, 1933, Dalena et al., 2014]. Interestingly, this entrainment effect may be due to Fermi acceleration, exactly the same mechanism behind DSA. The sample flux tube event shown in Figure 5.15 has a peak in density near the boundary, indicative of the compression one would expect in flux tube collision. This summarized by the cartoon in Figure 5.21 depicting the possible deformation of flux tubes during collision, where the concentric circles represent magnetic o-points.

Though it is difficult to identify direct evidence for local acceleration in current sheets, evidence from simulation and theory [Karimabadi et al., 2013, Zank et al., 2014, Le Roux et al., 2015, Matsumoto et al., 2015, Zank et al., 2015] lead us to not rule it out here. At the same time there is the competing view that these correlations are entirely attributable to flux tube transport Neugebauer and Giacalone [2015].

Figure 5.18 shows probability distributions of percent difference in energetic particle flux across discontinuities conditioned on PVI threshold and lag. They are non-Gaussian, which is not surprising, however the heavy tails for increasing PVI is interesting. This could be due to the averaging over thousands of current sheets with changes in energetic particle flux, supporting our conclusion from item (2) above. Further, the peak at zero lag in Figure 5.17 shows evidence that energetic particle intensity and PVI are likely to be changing together, consistent with results from simulations [Greco et al., 2012, Servidio et al., 2012, Karimabadi et al., 2013, Dalena et al., 2014].

It should be noted here that we are not discounting DSA. The result of Tessein et al. [2013] and Tessein et al. [2015] show clear signatures of DSA, and further, any local acceleration mechanism is happening in concert with, and may even require the presence of DSA. We have gone to considerable effort to remove the effect of DSA but the signal remains in the statistics. Unraveling the relative role of transport and acceleration continues to be an open research topic. With improved computational ability and space instrumentation like Solar Probe Plus and Solar Orbiter we can expect further
progress in this area over the next decade.
Appendix A

PVI AVERAGING

One feature of PVI statistics is its dependence on its surroundings. Thus, the interval of averaging used in the denominator affects the observed values of PVI. An example of this effect is shown in Figure 3.2. Here we show the same period of time in 2003 using three different intervals of averaging: 1 day, 10 days and 200 days. The time around day 149.8 of 2003 was a time in which there were a lot of strong coherent structures. Thus, using the one day averaging interval for the PVI calculation, we are looking at mostly strong coherent structures throughout the entire 24 hour period, thus the PVI values reach a maximum of around 4. However, using the 10 day average, there are less coherent structures, so the strong event around day 150 will be much stronger in comparison, elevating the PVI above 10. Similarly, using the 200 day average, the effect is amplified further, increasing PVI to above 15.
Appendix B

PERMISSION FROM PRACHANDA SUBEDI FOR FIGURE 4.7

I, Pranchanda Subedi, authorize Jeffrey Tessein to use my figure in his dissertation.

Sincerely,
Pranchanda Subedi
Appendix C
ACRONYMS AND ABBREVIATIONS

- **ACE** - Advanced Composition Explorer
- **CIR** - Corotating Interaction Region
- **CME** - Coronal Mass Ejection
- **DSA** - Diffusive Shock Acceleration
- **ENA** - Energetic Neutral Atom
- **EPAM** - Electron, Proton, and Alpha Monitor (ACE)
- **GCR** - Galactic Cosmic Ray
- **HCS** - Heliospheric Current Sheet
- **HD** - Hydrodynamics
- **IMF** - Interplanetary Magnetic Field
- **K41** - Kolmogorov et al., Dokl. Akad. Nauk. SSSR, 1941
- **LEFS** - Low Energy Foil Spectrometers (ACE/EPAM)
- **LEMS** - Low Energy Magnetic Spectrometers (ACE/EPAM)
- **MAG** - ACE magnetic fields experiment
- **MHD** - Magnetohydrodynamics
- **PIC** - Particle-in-Cell
- **PDF** - Probability Density Function
- **PVI** - Partial Variance of Increments
- **SDK** - Scale Dependent Kurtosis
- **SEP** - Solar Energetic Particle
• **SWEPAM** - Solar Wind Electron Proton Alpha Monitor (ACE)
Appendix D

PUBLICATIONS


Bibliography


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