Interstellar helium pickup ion flux variations observed with SOHO/CELIAS

Lukas A. Saul
University of New Hampshire, Durham

Follow this and additional works at: https://scholars.unh.edu/dissertation

Recommended Citation

This Dissertation is brought to you for free and open access by the Student Scholarship at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Doctoral Dissertations by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact nicole.hentz@unh.edu.
Interstellar helium pickup ion flux variations observed with SOHO/CELIAS

Abstract
Interstellar pickup ions are formed when neutral atoms freely enter the heliosphere and are subsequently ionized. Once these particles are charged they become a component of the interplanetary plasma and are transported outward with the solar wind (SW). Measurements of these particles give information about the local interstellar gas in which our sun resides. However, fluxes of pickup ions in the solar wind are observed to vary substantially in both magnitude and energy spectrum.

Hypothized is that the main causes of these variations are transport phenomenon in the solar wind, determined by the solar wind and the interplanetary magnetic field. If so, solar wind conditions can be used to predict pickup ion fluxes, and pickup ion fluxes can be used to indicate solar wind transport conditions. To prove the feasibility of this hypothesis, in situ measurements of helium pickup ions from the CTOF instrument on the SOHO spacecraft are used to characterize transport parameters.

Results are presented which show the effect of solar wind structures on pickup ions. Compression regions are shown to strongly affect measured fluxes of pickup ions. Observations show that compression regions can also cause an adiabatic heating or a shift in the pickup ion velocity distribution.

Also investigated is the effect of interplanetary magnetic field fluctuations and waves on pickup ions. These fluctuations can scatter pickup ions, in both pitch angle and energy. Comparison with WIND/MFI magnetic field measurements show that the pitch angle scattering rate is correlated with the wave-power. A hemispheric model for the pickup ion distribution is used to determine pitch angle diffusion coefficients from observed spectra. We find that the observed scattering rate differs from the predictions of simple diffusion models, especially in low wave-powers. Energy diffusion or particle acceleration is also observed in the pickup ion velocity distribution, most notably in the passage of solar wind disturbances such as shocks but also during quiet times. However, suprathermal pickup ions are not found to be well correlated with resonant wave-power. Finally, measurements of SW parameters are used to de-trend the pickup ion data, reducing the variability of the dataset.

Keywords
Physics, Astronomy and Astrophysics, Physics, Fluid and Plasma

This dissertation is available at University of New Hampshire Scholars' Repository: https://scholars.unh.edu/dissertation/272
NOTE TO USERS

Page(s) not included in the original manuscript and are unavailable from the author or university. The manuscript was scanned as received.

4, 6, 9, 28, 40, 42, 49, 51, 55, 56, 63, 64, 67, 78-80, 86, 90-92, 107, 709-110, and 112

This reproduction is the best copy available.

UMI®

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
INTERSTELLAR HELIUM PICKUP ION FLUX VARIATIONS
OBSERVED WITH SOHO/CELIAS

BY

LUKAS A. SAUL
BS Yale University, 1997

Submitted to the University of New Hampshire
In Partial Fulfillment of
The Requirements for the Degree of

Doctor of Philosophy
In
Physics

May, 2005
This dissertation has been examined and approved.

Dr. Eberhard Möbius, Dissertation Director
Professor of Physics and Earth, Oceans, and Space

Dr. John F. Dawson, Professor of Physics

Dr. Philip A. Isenberg, Research Professor of Physics and Earth, Oceans, and Space

Dr. Martin A. Lee, Professor of Physics and Earth, Oceans, and Space

Dr. Charles W. Smith III, Research Professor of Physics and Earth, Oceans, and Space

4/22/2005
Date
DEDICATION

To Rachel
ACKNOWLEDGEMENTS

Graciously acknowledged is the support of National Aeronautics and Space Administration through the Graduate Student Research Program, Grant NGT5-50381, for three years. This work was also partially supported by NASA grants NAG5-10890 and NNG04GA24G.

The hospitality and instruction of Maciej Bzowski and Daniel Rucinski of the Space Research Centre of the Polish Academy of Sciences in Warsaw over the summer of 2000 are acknowledged, and were important for initiating this work.

The investigators of the SOHO spacecraft project, in particular the CELIAS instrument package, as well as investigators of WIND spacecraft and the MFI instrument, are acknowledged for their hard work obtaining the observations on which this dissertation is based.

The International Space Science Institute in Bern, and the Swiss National Foundation are acknowledged for their collaboration and support.

The tutelage of the Experimental Space Plasma Group at UNH, and the departments of Physics and of Earth, Oceans and Space at UNH, have greatly assisted this author and made this work possible.

Most importantly, the committee members, John Dawson, Phil Isenberg, Marty Lee, Chuck Smith, and especially Eberhard Möbius, are acknowledged for the ideas, advice, and expertise which have so improved this thesis and its author.
# TABLE OF CONTENTS

DEDICATION..................................................................................................... iii
ACKNOWLEDGEMENTS................................................................................ iv
LIST OF TABLES............................................................................................... viii
LIST OF FIGURES............................................................................................. ix
ABSTRACT................................................................................................... xi

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1. THE HELIOSPHERE IN THE LOCAL INTERSTELLAR MEDIUM</td>
<td>3</td>
</tr>
<tr>
<td>Stellar Winds and the Solar Wind</td>
<td>5</td>
</tr>
<tr>
<td>The Outer Heliosphere</td>
<td>7</td>
</tr>
<tr>
<td>Interstellar Neutrals in the Heliosphere</td>
<td>10</td>
</tr>
<tr>
<td>Ionization Interactions</td>
<td>12</td>
</tr>
<tr>
<td>Helium</td>
<td>14</td>
</tr>
<tr>
<td>2. PICK-UP ION TRANSPORT</td>
<td>16</td>
</tr>
<tr>
<td>Gyrotropy</td>
<td>16</td>
</tr>
<tr>
<td>Charged Particle Distributions</td>
<td>19</td>
</tr>
<tr>
<td>Convection and Cooling</td>
<td>22</td>
</tr>
<tr>
<td>The Diffusive Approximation</td>
<td>24</td>
</tr>
<tr>
<td>Transport Coefficients and Resonance</td>
<td>26</td>
</tr>
<tr>
<td>Timescales</td>
<td>29</td>
</tr>
</tbody>
</table>
3. INTERPLANETARY MAGNETIC FIELD FLUCTUATIONS ............... 30
   Power Spectrum Distribution in Frequency Space .................. 33
   Single Spacecraft Observations ......................................... 34
4. INSTRUMENTATION .............................................................. 36
   SOHO/CELIAS/CTOF .......................................................... 37
   WIND/MFI and Data Extrapolation ....................................... 39
   Computational Methodology, Data Preparation and Techniques ........... 42
5. COMPRESSION REGIONS AND SOLAR WIND BULK EFFECTS ... 46
   Co-rotating and Stream Interaction Regions ......................... 46
   Pickup Ion Variations – Statistical Analysis ......................... 47
   Interpretation ................................................................. 52
   Individual Compression Events ............................................. 53
   Cutoff Shift at Magnetic Discontinuities ............................... 57
   Upwind Cutoff Shift ....................................................... 61
   Detrending PUI Variations with SW Correlations .................. 64
   Conclusions .......................................................................... 70
6. PUI WAVE-PARTICLE INTERACTIONS ............................... 72
   Pitch Angle Scattering by Waves ......................................... 72
   Wave Parameters ............................................................. 73
   PUI Parameters ..................................................................... 74
   Observations ........................................................................ 76
   Superposed Epoch Analysis ................................................ 78
   Statistical Correlations ...................................................... 81
Preliminary Conclusions .....................................................................................84
Hemispheric Model of Pitch Angle Diffusion ...................................................85
Conclusions .........................................................................................................93
7. ENERGY SPACE DIFFUSION ..................................................................95
2nd Order Fermi Acceleration ......................................................................95
Observations of Accelerated PUIs.................................................................96
Individual Acceleration Events ..................................................................99
Acceleration by IMF Fluctuations and Waves ............................................106
Conclusions .......................................................................................................113
8. RESULTS AND CONCLUSIONS .............................................................115
Review of Results ...........................................................................................115
Open Questions for Further Research ..........................................................117
REFERENCES ...............................................................................................118
APPENDIX A .................................................................................................133
LIST OF TABLES

Table 2.1 Major Transport Processes for Helium PUIs.........................29
Table 6.1 Wave/PUI parameter correlation coefficients......................82
Table 7.1 Largest He⁺ acceleration events observed by SOHO/CTOF.....101
Table A.1 Ancillary Data Parameters.............................................135
LIST OF FIGURES

Figure 1.1 Working Map of LISM ...............................................................4
Figure 1.2 Parker Spiral and Interplanetary Magnetic Field .....................6
Figure 1.3 Heliosphere and LISM Interface with Voyager Spacecraft ....9
Figure 2.1 Ring Distribution in Velocity Space (Perpendicular Field) ...17
Figure 2.2 Ring Distribution in Velocity Space (Oblique Field) ..........18
Figure 2.3 Particle Trajectory and IMF Fluctuations Cartoon ............28
Figure 3.1 IMF Frequency Spectrum Example .......................................31
Figure 4.1 CTOF Sensor Diagram ...........................................................37
Figure 4.2 Data convection technique diagram ......................................40
Figure 4.2 WIND Orbit Plot (Earth Orbiting) .........................................41
Figure 4.3 WIND Orbit Plot (L1 Point) ..................................................42
Figure 5.1 CIR overview figure ...............................................................47
Figure 5.2 PUI energy spectra sorted by SW proton density .................49
Figure 5.3 Histogram of PUI cutoff flux vs. SW proton density ..........50
Figure 5.4 PUI energy spectra sorted by IMF magnitude ....................51
Figure 5.5 PUI energy spectra sorted by |B| in radial fields ..................52
Figure 5.6 Stream interaction observed on DOY 170 .........................55
Figure 5.7 Magnetic cloud interaction observed on DOY 149 .............56
Figure 5.8 Energy spectra illustrating cutoff shift on DOY 170 ..........58
Figure 5.9 Model predictions vs. observations for cutoff shift ..........60
Figure 5.10 Injected PUI distribution w/ upwind cutoff shift ............62
Figure 5.11 Example of upwind cutoff shift fitting procedure ............63
Figure 5.12 Upwind cutoff shift vs. Keplerian model..............................64
Figure 5.13 Example of real vs. corrected PUI flux data.........................67
Figure 5.14 Example of real vs. corrected PUI flux data incl. IMF............69
Figure 6.1 PUI spectra sorted by IMF orientation.................................76
Figure 6.2 Dynamic PUI spectra and SW data for DOY 82-84...............77
Figure 6.3 Distribution of observed wave-powers in IMF......................78
Figure 6.4 PUI spectra sorted by transverse wave-power, radial IMF...79
Figure 6.5 PUI spectra sorted by transverse wave-power, perp. IMF....75
Figure 6.6 Trend plot of PUI flux vs. wave-power (radial IMF)...........83
Figure 6.7 Trend plot of PUI flux vs. wave-power (perp. IMF).............83
Figure 6.8 Alfvén wave dispersion relations and resonance.................86
Figure 6.9 Hemispheric fit in radial IMF with high wave-power.........90
Figure 6.10 Hemispheric fit in radial IMF with low wave-power..........91
Figure 6.11 Hemispheric model: mean free path vs. wave-power..........92
Figure 7.1 PUI spectra with maximum acceleration spectrum.................97
Figure 7.2 PUI flux spectra showing the effect of shocks................98
Figure 7.3 PUI flux spectra without shocks.......................................99
Figure 7.4 PUI acceleration events on DOY 94.................................103
Figure 7.5 PUI acceleration events on DOY 99.................................104
Figure 7.6 PUI acceleration events on DOY 210...............................105
Figure 7.7 PUI spectra sorted by fluctuation index η.......................107
Figure 7.8 PUI spectra sorted by resonant transverse wave-power........109
Figure 7.9 PUI spectra sorted by resonant parallel wave-power..........110
Figure 7.10 PUI spectra sorted by pitch angle diffusion index..........112

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
ABSTRACT

INTERSTELLAR HELIUM PICKUP ION FLUX VARIATIONS

OBSERVED WITH SOHO/CELIAS

by

Lukas A. Saul

University of New Hampshire, May, 2005

Interstellar pickup ions are formed when neutral atoms freely enter the heliosphere and are subsequently ionized. Once these particles are charged they become a component of the interplanetary plasma and are transported outward with the solar wind (SW). Measurements of these particles give information about the local interstellar gas in which our sun resides. However, fluxes of pickup ions in the solar wind are observed to vary substantially in both magnitude and energy spectrum.

Hypothesized is that the main causes of these variations are transport phenomenon in the solar wind, determined by the solar wind and the interplanetary magnetic field. If so, solar wind conditions can be used to predict pickup ion fluxes, and pickup ion fluxes can be used to indicate solar wind transport conditions. To prove the feasibility of this hypothesis, in situ
measurements of helium pickup ions from the CTOF instrument on the SOHO spacecraft are used to characterize transport parameters.

Results are presented which show the effect of solar wind structures on pickup ions. Compression regions are shown to strongly affect measured fluxes of pickup ions. Observations show that compression regions can also cause an adiabatic heating or a shift in the pickup ion velocity distribution.

Also investigated is the effect of interplanetary magnetic field fluctuations and waves on pickup ions. These fluctuations can scatter pickup ions, in both pitch angle and energy. Comparison with WIND/MFI magnetic field measurements show that the pitch angle scattering rate is correlated with the wave-power. A hemispheric model for the pickup ion distribution is used to determine pitch angle diffusion coefficients from observed spectra. We find that the observed scattering rate differs from the predictions of simple diffusion models, especially in low wave-powers. Energy diffusion or particle acceleration is also observed in the pickup ion velocity distribution, most notably in the passage of solar wind disturbances such as shocks but also during quiet times. However, suprathermal pickup ions are not found to be well correlated with resonant wave-power.

Finally, measurements of SW parameters are used to de-trend the pickup ion data, reducing the variability of the dataset.
INTRODUCTION

Interstellar Pickup Ion Flux Variations

We live in the heliosphere. We are protected from much of the high energy radiation present throughout the heliosphere by the Earth’s atmosphere and magnetic field, but we cannot deny our place as residents of the extended Sun. In fact, almost all energy used on Earth comes from the Sun. Without it, not only would life on Earth be impossible, but Earth itself would not have formed. For these reasons, we must study the sun and its surroundings! Its variations, its travels through our galaxy, and its interaction with its surroundings, all give key evidence into our place in the universe, our past, and our future.

Our knowledge of the heliosphere has tremendously increased over the last 50 years, with the advent of the space age. We can now leave our protected sanctuary, and sample the heliosphere elsewhere, measuring its particle energies and composition and electromagnetic properties in amazing detail. Interstellar material measured in the solar wind acts as a messenger from outside the borders of the heliosphere, and as a tracer to heliospheric processes. These particles tell us of the conditions from where they come, i.e. the great voids and clouds of interstellar space. They also tell us of their journey through the heliosphere, where they become ionized, and what happens to them in the solar wind.
In this thesis this last aspect of the interstellar pickup ions is pursued in detail, in which interstellar pickup ions can act as tracers of solar wind particle transport. Large variations of pickup ion flux are classified based on ideas of solar wind transport, in the process explaining many of the variations. Interstellar pickup ions provide a valuable tool for studying space plasma physics, and only some of their potential is included here. It is my hope that this effort will be continued, using some of the basics included here, to use interstellar pickup ions to better understand space plasma, heliospheric physics, and our place in the universe.
CHAPTER 1

THE HELIOSPHERE IN THE LOCAL INTERSTELLAR MEDIUM

*In which the stage is set for the arrival of the interstellar pickup ion at our home, the heliosphere.*

Absorption lines in stellar spectra were a first clear indicator that the space between the stars is not empty and indeed contains a diffuse gas or plasma. As observations of interstellar matter improved, the importance of this material, the interstellar medium, became more clear. In fact, clouds of interstellar hydrogen form the seed and the growth conditions for stars such as our sun, and can shape the evolution of astrospheres and stellar systems such as our solar system. Interstellar material contains the building blocks of stars, planets, and even life [for review see Shklovskii, 1975].

However, the details and composition of interstellar matter are difficult to ascertain. No spacecraft has sampled the material directly, and it is not usually self-illuminating. Studies of absorption of light from background stars must model both the original spectrum of the light source and the geometry of the material along the line of sight. By measuring absorption lines in all areas of the spectrum, with telescopes both under and above the Earth’s atmosphere, much progress has been made in mapping the interstellar gas in the Milky Way and around the Sun [e.g. Trumpler, 1930]. The use of the fine structure radio emission line of Hydrogen at 21cm for finding interstellar H clouds was an
Once we know of the existence of this interstellar medium, the question arises of how the sun interacts with its environment, the LISM. A key aspect to this interaction is the unstable solar atmosphere or the solar wind.

**Stellar Winds and the Solar Wind**

One early clue that material streams away from the sun came from the correlation between observed sunspots and aurora on Earth, discovered in 1744 by Jean Jacque Dortous de Mairan. Further insight into this phenomenon came from its effect on comets, whose tails always stream away from the sun [Hoffmeister, 1943]. The comet tails showed that material was *always* coming from the sun, not only during flares or from sunspots. That the atmosphere of the sun could not be at equilibrium was pointed out by [Parker, 1960], who used magneto-hydrodynamic equations to model the plasma in the solar atmosphere and corona [for review see Hundhausen, 1968].

The advent of the space age enabled in situ measurements of the solar wind, confirming that a hot plasma is emitted from the sun and moves at supersonic (and super-Alfvénic) speeds through interplanetary space. The solar wind has been sampled from high and low heliospheric latitudes and as far as 80 AU from the sun. The solar wind is mostly protons, at densities on the order of 10 cm$^{-3}$ near Earth, and has a small percentage of fully ionized helium and an array of trace heavy elements, representing largely the composition of the solar atmosphere. It is not homogenous, and shows structures with a wide variety of spatial scales, compositions, densities and magnetic fields. Because of the ionized
\( \nabla \times (\vec{u} \times \vec{B}) = 0 \)  \hspace{1cm} (1.1)

When combined with the divergence free nature of magnetic fields (\( \nabla \cdot \vec{B} = 0 \)) and the boundary condition at the surface of the rotating sun, the components of the heliospheric magnetic field or Parker spiral can be written:

\[
B_r = B_0 \left( \frac{r_0}{r} \right)^2
\]

\[
B_\phi = \frac{u_\phi - r \omega \phi}{u_r} B_r
\] \hspace{1cm} (1.2)

The important features of this heliospheric magnetic field structure are that the azimuthal component is inversely proportional to the heliocentric distance, while the radial component is inversely proportional to the square of this distance. Hence, the field is primarily azimuthal in the outer heliosphere. The 27 day period of solar rotation and solar wind speed are such that this field is at nearly a 45 degree angle at 1AU.

**The Outer Heliosphere**

As the solar wind expands around the sun, it becomes cooler and less dense. Eventually, the wind reaches the outside pressure of the interstellar medium. Because of the supersonic and super-Alfvénic motion of the wind, a shock forms at the interface known as the termination shock. It is here that the solar wind becomes sub-sonic and enters the heliopause. Depending on the magnetic field in the LISM, a bow shock may form, analogous to the Earth’s bow shock. The position and properties of the heliosphere-LISM interface are very dependent on
the LISM parameters (such as density, magnetic field, and temperature), as well as the solar wind parameters in the outer heliosphere [see e.g. Baranov et al., 1981, Pauls et al., 1995; Izmondenov et al., 2003; Zank & Müller, 2003].

The positions of the boundaries of our heliosphere are believed to move with solar activity, as the solar wind pressure and field strength are altered. Unfortunately the material is too tenuous and not energetic enough to remotely sense the presence of these regions from Earth. However, as Voyager 1 moves closer to the termination shock (Figure 1.3) all eyes are on its measurements, which have indicated hints of heliosphere-LISM interaction [MacDonald et al., 2003; Krimigis et al., 2003]. Also, efforts are underway to build a dedicated neutral sensor in Earth orbit, the Interstellar Boundary Explorer (IBEX) which will detect interstellar neutral atoms and neutral products of the heliosphere-LISM interface [McComas et al., 2004].
Interstellar Neutrals in the Heliosphere

Before the neutrals are ionized to become pickup ions, they are already detectable and can also be used as probes of the interstellar medium. Detection can be done in situ with modern instrumentation [Witte et al., 1993], and remotely via resonant back scattering of solar UV radiation [e.g. Flynn et al, 1998; Paresce & Bowyer, 1973]. This detection is of great importance in constraining our knowledge of the very local interstellar medium. However, it is a later product of these neutrals, the more easily measurable population of pickup ions (PUIs) which this thesis is concerned with. We will find that PUIs are important not only in shaping the heliosphere and learning of its boundaries but also in diagnosing transport processes in the solar wind.

The LISM neutrals, immune to the effects of magnetic fields, are still affected by the gravitational field of the sun. Indeed, they follow hyperbolic Keplerian trajectories as they effectively enter the gravitational well of the sun from an infinite distance. They move only in the plane determined by their initial velocity vector and the position of the sun, and their distance from the sun can be solved as a function of the angle swept out by the particle $\theta - \theta'$:

$$r = \frac{a(1-e^2)}{1+e \cos(\theta - \theta')}$$

(1.3)

where $e$ (the eccentricity which is greater than one for interstellar neutrals on hyperbolic orbits), and $a$ are determined by the particles angular momentum and total energy which are conserved in the motion [e.g. Danby & Camm, 1957; Fahr, 1978; Wu & Judge, 1979].

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
One simple way to model the heliosphere – neutral LISM interaction is to assume the neutrals are a flowing gas without appreciable thermal motion of the interstellar neutrals, i.e. the cold model. The only forces on the neutrals as they approach the heliosphere are solar; the gravitational force and any radiation pressure due to solar photons. For the case of helium, the radiation pressure is negligible, while for hydrogen the strong Lyman alpha radiation pressure almost exactly cancels the gravitational pull \cite[e.g.][]{wu:1979}. For helium, the effect of the sun’s gravity on the inflowing gas acts to focus the gas on the downwind side forming the interstellar neutral focusing cone \cite[Fahr, 1991; Möbius et al., 1995; Bzowski et al., 1997]. In the cold model, there are two possible trajectories of interstellar neutrals at any point in the heliosphere, one coming from out of the heliosphere and going in (direct trajectory), and the other on a return voyage from the point of closest approach (indirect trajectory).

Despite the complication of the direct and indirect trajectories, the cold model is much simpler than a more complete hot or statistical approach. In the hot model, the interstellar neutrals take on a range of velocities, distributed about the mean velocity of the cold model with a Gaussian or Maxwellian distribution given by a characteristic temperature. The distribution function is given by:

$$f_{LISM}(\vec{v}) = n \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left[ -\frac{m|\vec{v} - \vec{u}|^2}{2kT} \right]$$

where $\vec{u}$ is the motion of the LISM with respect to the sun, $T$ is the temperature and $n$ the density of the LISM, $m$ is the mass of the neutral particle under consideration, and $k$ is Boltzmann’s constant. The addition of the thermal
velocity becomes important in the detail of the focusing cone on the downwind side [e.g. Bzowski et al., 1997].

**Ionization Interactions**

As the interstellar neutrals penetrate the heliosphere, they are subject to ionization processes. These can be identified as three main contributions [see e.g. Rucinski and Fahr, 1989; Rucinski et al., 1996]. The most important ionization process for interstellar helium is ionization by solar UV radiation. Any UV photon above the ionization potential of helium can eject an electron from an interstellar neutral. The intensity of this radiation is inversely proportional to the square of the heliospheric distance, and the intensity has recently been well measured by UV monitors on SOHO [McMullin et al., 2002].

Another important ionization mechanism is charge exchange. When two atoms are close enough, an electronic interaction can take place in which an electron is transferred from one to the other. Charge exchange interactions are important for ionizing hydrogen and other species with high charge exchange cross sections with solar wind particles. For these species, a knowledge of the SW flux is crucial to calculating the ionization rate, and variable SW speeds and densities make this calculation more difficult. For this reason, the interaction of interstellar hydrogen with the heliosphere is particularly complex, and a good model must take into account latitudinal asymmetries (e.g. faster solar wind in the polar regions) and time dependences. In the case of helium, a noble gas, charge...
exchange interaction are negligible, contributing to about four percent of the helium ionization rate [e.g. Rucinski et al., 1996].

A third ionization mechanism is direct electron impact ionization. A neutral particle bombarded with a solar wind electron can lose one of its own electrons, leaving behind an ion. The cross section for electron impact ionization is dependent on the velocity of the electrons, and so the electron temperature as well as electron density is important for determining the relative importance of electron impact ionization. For this reason electron impact ionization will be enhanced in interplanetary shocks [Isenberg & Feldman, 1995], due to the turbulent heating of electrons in these regions. Because the electrons are hotter close to the sun, the electron impact ionization rate does not diminish with heliocentric radius squared, as the UV ionization rate does. This means electron impact ionization takes on a higher relative role close to the sun. This effect has been invoked to describe measurements of the focusing cone near the sun by the UVCS imager on SOHO [Michels et al., 2002; Lallement et al., 2004], where hot electrons, especially during solar maximum, can erode the neutral population.

The distribution of neutrals given by (1.3) & (1.4) can be integrated over velocity space to yield the density of neutrals anywhere in the heliosphere. However, their loss due to ionization must be included. Remarkably, one of the velocity integrals can be solved analytically using Bessel’s functions (assuming the ionization rate is proportional to the inverse square of heliocentric radius), leaving only two dimensions to integrate numerically [see e.g. Wu & Judge, 1979].
Helium

The discussion thus far has been general, in that interstellar atoms of all species can be described. However, there are numerous differences in the details of the interaction that make pickup ions of different species behave differently. For a number of reasons, this work focuses on helium pickup ions despite the fact that hydrogen is the dominant species.

One reason to consider helium is that its high ionization potential (as a noble gas) allows the neutrals to penetrate deep into the heliosphere. Other species, such as the dominant hydrogen component, do not penetrate in sufficient number to be detected at 1AU, and much less data is available. Another potential advantage of helium is that it is more easily identified as a pickup ion component. Solar wind helium, coming from the hot corona, is almost all fully stripped or doubly charged, whereas interstellar pickup helium is singly charged.

One final reason to focus on measurements of helium PUIs is the minor role of charge exchange in their creation. Because the charge exchange rate depends on solar wind properties, the dynamic solar wind can have a complex effect on pickup ion distributions. The small charge exchange cross section for helium makes the heliosphere – LISM interaction far easier to model. Essentially, interstellar helium is unaffected by the heliospheric boundary, and therefore enables sampling of pristine interstellar conditions from 1 AU.
Once the neutral material is ionized and picked up by the solar wind, the evolution becomes much more complex, as magnetic and electric fields become the dominant forces acting on the particle, which change far more rapidly than the constant gravitational force that has been the main player in describing the physics in this chapter.
CHAPTER 2

PICK-UP ION TRANSPORT

*In which the newly picked up ions are pushed and prodded by the solar wind*

**Gyrotropy**

As soon as interstellar neutral atoms are ionized, they are affected by the magnetic field in the solar wind. This is due to the Lorentz force $\vec{F} = q(\vec{v} \times \vec{B})$, or the electric field seen because the new ions are at motion with respect to the rest frame of the plasma and its magnetic field. In the rest frame of the solar wind, the ion is moving at the solar wind speed $-\vec{v}_{sw}$ towards the sun or in the $x$ direction.

Thus, the velocity of a pickup ion takes the form (for the special case of a perpendicular magnetic field):

$$
\begin{align*}
    v_x &= v_{sw}\cos(\omega t) \\
    v_z &= -v_{sw}\sin(\omega t)
\end{align*}
$$

where $\omega$ is the gyrofrequency and here the magnetic field is taken in the $+y$ direction.

When viewed in the spacecraft frame or the heliospheric rest frame, the motion of the solar wind is simply added (the motion is non-relativistic):

$$
\begin{align*}
    v_x &= v_{sw}\cos(\omega t) + v_{sw} \\
    v_z &= -v_{sw}\sin(\omega t)
\end{align*}
$$

Here it can be seen that the radial velocity of a pickup ion $v_x$ varies from a minimum of zero to a maximum of twice the solar wind speed. This cycloidal motion is the same as that of a pebble embedded in a wheel of a moving vehicle –
whose instantaneous velocity is zero as it touches the ground but is twice the vehicle speed when it is on top of the wheel. The signature of this motion is important for detecting pickup ions in any plasma.

Fig 2.1. One half of the ring distribution of newly injected PUIs is seen as the thick shaded line in a velocity space diagram. The other half of the ring appears behind the sphere. The origin represents particles at rest in a heliospheric or spacecraft rest frame. The particles which can enter the CTOF instrument are shown with velocities between the dashed lines.

Because PUIs are created continuously from the source population of interstellar neutrals, the injected distribution forms a ring in velocity space, filled
by PUIs at all phases of the Larmor gyration. The resulting ring distribution for the case of a perpendicular IMF is shown in Figure 2.1.

In a collisionless plasma, charges are free to move and so the conductance is effectively infinite. In such a system, the electric field will vanish. However, magnetic fields remain and the Lorentz force is the dominant force acting on plasma evolution.
If the magnetic field is at an oblique angle, a similar ring distribution results, although without the symmetry present in Figure 2.1. Instead, the ring distribution will have a smaller radius and will be present on one side of the sphere, as shown in Figure 2.2.

Because the phase angle in a particle's rotation about the field is not important, one degree of freedom can be eliminated from the system. This aspect is known as gyrotropy, and a gyrotropic distribution is one which is equally distributed in cycloidal phase of Larmor gyration. The three dimensional velocity space is reduced to two dimensions, which are usually referred to as particle speed $v$ and pitch angle $\alpha$, where the pitch angle is the angle from the field vector to a particle's velocity vector.

**Charged Particle Distributions**

The solar wind is a nearly fully ionized gas, and the evolution of this gas and the pickup ions contained therein is properly described by the techniques of plasma physics. Treatment of every particle in a plasma, its motion and the forces on it due to all other particles, quickly becomes tedious or impossible. It behooves us to use a statistical interpretation, in a kinetic theory. In such a theory, the plasma's constituents are described with distribution functions, which keep track of the relative amounts of particles with different velocities and locations. Probabilistic distributions of the particles are considered, in both physical space.
(particle positions) and in velocity space (particle velocities). The total phase space density describes the relative amounts of particles at different velocities and at different positions in space at a given time. Each particle species $\alpha$ can be fully described by a seven dimensional distribution function $f_\alpha$ which gives the phase space density of particles at a given location, velocity, and time:

$$f_\alpha = f_\alpha (\vec{x}, \vec{v}; t)$$  

(2.1)

Kinetic theories have been enormously successful in describing systems with many constituents, including gases and plasmas [for reviews see Wu, 1966; Liboff, 1969]. The Liouville theorem, which states that the total phase space density is conserved in the absence of collisions, gives a starting point for the derivation of a system of kinetic equations to describe the evolution of a system under any external forces. For the case of a plasma where only electric and magnetic fields act on the constituent particles, these derivations lead to the Vlasov equation, which describes the evolution of a charged particle distribution:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i} v_i + \frac{\partial f}{\partial v_j} \frac{q}{m} (E_j + \epsilon_{ijk} v_k B_k) = 0$$  

(2.2)

Here $f$ is the distribution function of a constituent particle, $q$ and $m$ are the charge and mass of the particle, and $\vec{E}, \vec{B}$ are the electric and magnetic fields, functions of space and time alone. Repeated indices in (2.2) are to be summed over all their possible values, and $\epsilon_{ijk}$ is the fully anti-symmetric unit tensor which generates the cross product, and its usage in (2.2) is in the Lorentz force term. Equation (2.2) can be multiplied by powers and combinations of velocities
and integrated over velocity space to obtain the moment equations that form the heart of magneto-hydrodynamics (MHD). For a review of the power and utility of the Vlasov equation in plasma physics, see the texts [Chen, 1984; Ichimaru, 1992]. It is important to note that the right hand side of this equation is zero, whereas for a gas with frequent collisions between constituent particles there will be a collision term here. The solar wind is so diffuse that the mean free path to Coulomb collisions is on the order of the size of the heliosphere, and so the plasma is effectively collisionless. For the larger volumes of interstellar space, the collision terms will need to be taken into account, but for analyzing transport of an ion from its injection (ionization) inside of 1AU to a spacecraft near the Earth, this term can be safely neglected.

The problem of PUI transport in the solar wind can be described as the application of the Vlasov equation to the PUI population, although in practice many assumptions must be made to proceed. This problem was addressed as early as the 1970s [Vasilyunas & Siscoe, 1976], before the first confirmation of the existence of this population [Möbius et al., 1985]. The problem of ion transport is also of great interest in other aspects of plasma and fluid dynamics, as various approximations of (2.2) such as MHD and diffusion models have limitations which make the evolution difficult to predict.

The first step in tracing the motion of the PUIs is the determination of the injection population, or the initial distribution from which the evolution is to be calculated. In the simplest model, the interstellar neutrals are ionized with zero velocity (in a heliocentric rest frame). Because the inflow velocities and thermal
velocities are small compared with the solar wind speed, this cold model approximation is justified, and more detailed models will include a thermal or even non-Maxwellian spread about this initial distribution.

**Convection and Cooling**

As the solar wind moves out in the heliosphere, the magnetic field changes. Some of these changes are due to the global heliospheric magnetic field, and some are due to waves or turbulence present in interplanetary space. It behooves us to consider these two portions of the IMF separately. The global or "bulk" field is described by the Parker spiral, and takes (on average) the form given in equation (1.2).

This change in the magnetic field strength is an electric field according to Faraday’s law, which slows the particles in their gyration. Such a process can be viewed as the conservation of an adiabatic invariant, and is therefore known as *adiabatic cooling*. A similar process occurs in the expansion of an ordinary gas, as the temperature is reduced when volume is expanded due to collisions with expanding walls of the container. For the solar wind plasma, there are no walls of the container to cool the plasma. The cooling is accomplished by the magnetic field which controls and contains the plasma.

The precise amount of cooling of the PUI distribution depends on the pitch angle distribution of the PUIs, as well as the heliospheric magnetic field. An adiabatic invariant for a single particle gyrating about a magnetic field is $\frac{v_{\perp}^2}{B}$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
This means that a particle moving with zero pitch angle (no perpendicular velocity) will not be affected by the changing magnetic field, as can be shown by noting that such a particle sees no Lorentz force and so is unaffected by the magnetic field of any magnitude. For a Parker spiral field with $|B| \sim 1/r$ this implies the perpendicular velocity will decrease as $r^{1/2}$.

If the particles are scattered in pitch angle quickly, specifically more quickly than the adiabatic expansion of the solar wind or the decrease of the magnetic field, then a spherical distribution is formed in place of the ring distribution. In effect, the magnetic field of the expanding solar wind acts as an opening piston does on a volume of gas, and the PUIs behave as an ideal gas in their cooling characteristics. The speed of a pickup ion (in the solar wind frame) at a position $r_0$ can then be written as

$$\frac{v}{v_{SW}} = \left(\frac{r_0}{r}\right)^{3/2}$$

(2.3)

where $r$ is the radius at which the PUI was injected and $v_{SW}$ is the solar wind speed [e.g. Vasilyunas & Siscoe, 1976; Möbius et al., 1995]. This relation enables the PUI velocity spectrum to be interpreted as a radial injection spectrum, where a given velocity maps to a given injection radius.

However, neither the spherical distribution nor the ring distribution describes the cooling process precisely. This issue will be returned to when the effects of magnetic discontinuities on the PUI distribution are discussed in Chapter 5. To proceed in the case of less efficient pitch angle scattering we must consider the
entire distribution of pickup ions, and how many of these ions are at different pitch angles, calculating the cooling for each pitch angle from the adiabatic invariant. To do so requires treatment of magnetic field fluctuations which can scatter particles to different pitch angles, or cause pitch angle diffusion.

The Diffusive Approximation

The lack of collisions due to the low density of the SW plasma and the lack of electric fields due to its high conductance suggest that the system described by (2.2) should be easy to solve, describing the subsequent motion of the PUls. However, this is not the case as the magnetic field is not known everywhere in the heliosphere, and fluctuates over a variety of timescales. Such behavior in theory makes the system intractable. However, there is a way to proceed, as the fluctuations of the magnetic field can be treated statistically as effectively random, allowing these effects to be treated as a Markov process or a “random walk”. A similar effect occurs in a normal gas, when collisions happen often enough to be effectively random in time and space, forcing concentrations to diffuse away from the area of concentration. This is known as the diffusive approximation.

To proceed from (2.2), the total magnetic field is written as the sum of a bulk term $\bar{B}_i$, which is stationary or constant in time, and a fluctuating term $\delta B_i$, which is composed of MHD waves and turbulence present in the solar wind:

\[
\begin{align*}
E_i & \rightarrow \bar{E}_i + \delta E_i \\
B_i & \rightarrow \bar{B}_i + \delta B_i
\end{align*}
\]
The Vlasov system now can be written as a Boltzmann equation [see e.g. Ichimaru, 1992]:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i} v_i + \frac{\partial f}{\partial v_i} m (\epsilon_{ijk} v_j B_k) = \hat{S}f$$

(2.4)

where the scattering operator contains the action of the fluctuating fields on the distribution, and in the diffusive approximation can be written:

$$\hat{S}f = \frac{\partial}{\partial \mu} \left( D_{\mu\nu} \frac{\partial f}{\partial \mu} \right) + \frac{\partial}{\partial \mu} \left( D_{\mu\nu} \frac{\partial f}{\partial v} \right) + \frac{1}{v^2} \frac{\partial}{\partial v} \left( v^2 D_{\mu\nu} \frac{\partial f}{\partial \mu} \right) + \frac{1}{v^2} \frac{\partial}{\partial v} \left( v^2 D_{\nu\lambda} \frac{\partial f}{\partial \lambda} \right)$$

(2.5)

Here the diffusion coefficients are taken to be gyrotropic, and written in terms of the particle speed $v$ and the cosine of the pitch angle $\mu$, as well as being position and possibly time dependent.

The basic idea behind (2.5) is that the essentially random collisions which make up the scattering operator will act to push the distribution toward isotropy. We say that the physical process of scattering is a Markov process, similar to a random walk. The rate at which the distribution diffuses is proportional to the gradient of the distribution, or the anisotropy. The constants of proportionality are the components of the diffusion tensor, which are written in terms of pitch angle and energy space in (2.5). These terms represent the amount by which a gradient of the distribution in pitch angle space will affect the energy space evolution, and in which a gradient of the distribution in energy space will affect the pitch angle space evolution. In general they can be calculated in terms of the power in fluctuations of the IMF [see e.g. Bogdan et al., 1991].
PUIs are subject to pitch angle scattering processes after their initial injection, such as magnetic field fluctuations which will be considered in more detail Chapter 3. The scattering due to a pure magnetic fluctuation does not change the energy of the particles (as only an electric field can do that), but spreads their distribution out onto the spherical shell visible in Figure 2.1.

Such a system of only pitch angle scattering can be described to evolve as:

\[
\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i} v_i + \frac{\partial f}{\partial v_i} q \left( e_{ijk} v_j \bar{B}_k \right) = \frac{\partial}{\partial \mu} \left( D_{\mu\nu} \frac{\partial f}{\partial \mu} \right)
\]

(2.6)

The scattering agents which underlie the diffusion coefficients are contained in the magnetic and electric fields found in the third term of Equation 2.2.

As the solar wind travels outward, the magnetic field decreases and the wind cools adiabatically, as described above. The PUIs see the decreasing magnetic field as an electric field and are thus decelerated, cooling with the solar wind. This adiabatic cooling is described by the convection terms of the Vlasov equation. The gyrophase averaged form of this equation has been expressed in [Isenberg, 1987; see also Skilling, 1971].

**Transport Coefficients and Resonance**

Much work has gone into determination of the transport coefficients of (2.5) from the types of magnetic fluctuations that exist [see e.g. Jokipii, 1972 & 1974; Bogdan et al., 1992; Schlickeiser, 1998, Isenberg et al., 2003]. We will not review the quasi-linear methods here, as that is beyond the scope of this thesis.
However, we must review that the major contribution to the pitch angle diffusion term is usually taken to be resonance with MHD waves.

When a particle gyrates about the magnetic field with such a frequency that its phase is precisely matched by that of a magnetic field wave, we say the particle is in resonance with the wave. This condition can be expressed mathematically (in the non-relativistic limit) by writing the frequency of the wave, Doppler shifted to the particle’s center of motion:

\[ \omega - k_i v_i = -n\Omega \]  

(2.7)

Here \( \omega \) is the frequency of the wave, \( k_i \) is the component of the wave vector parallel to the magnetic field, and \( v_i \) and \( \Omega \) are the velocity parallel to the magnetic field and the gyro-frequency (respectively) of the particle. The integer \( n \) is the degree of harmonic of the resonance, with lower harmonics usually representing a stronger coupling between particle and wave motion. In the solar wind, a spectrum of MHD waves is present, representing a range of frequencies and wave numbers, such that waves are moving both in many different directions and with different frequencies. However, the conditions at 1 AU and closer are such that most of the sources for these waves are sunward, i.e. the waves propagate anti-sunward. The presence of Alfvén waves and other turbulent disturbances in the solar wind is well established by in situ measurements.
Timescales

Although our discussion of pickup ion transport in the solar wind is in some ways just beginning, it behooves us to review the major processes involved to help as a guide with comparison to observations and more detailed modeling later in this thesis. One natural way to order the transport processes is by their timescale, i.e. the rate at which they effect the pickup ion distribution. These processes and their associated timescales are listed below in Table 2.1.

<table>
<thead>
<tr>
<th>Process Name</th>
<th>Description</th>
<th>Relevant Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lorentz Force</td>
<td>Leads to gyration about magnetic field.</td>
<td>~10 sec. - 30 sec.</td>
</tr>
<tr>
<td>Pitch angle Diffusion</td>
<td>Forms isotropic distribution (due to magnetic fluctuations).</td>
<td>~10 hrs. - 100 hrs.</td>
</tr>
<tr>
<td>Adiabatic Cooling</td>
<td>Expanding solar wind and decreasing IMF cools pickup ions.</td>
<td>~100 hrs.</td>
</tr>
<tr>
<td>Energy Diffusion</td>
<td>Statistical acceleration by waves will scale with Alfvén speed over solar wind speed, squared.</td>
<td>~1000 hrs.</td>
</tr>
<tr>
<td>Coulomb scattering</td>
<td>SW density decreases as r^2; mean free path becomes on order of size of the heliosphere.</td>
<td>~5000 hrs.</td>
</tr>
</tbody>
</table>

Further details of pitch angle scattering and energy diffusion will be discussed later in this thesis, in Chapters 6 & 7 respectively, where models of these processes are used to compare transport theory with in situ observations of pickup ion velocity distributions. This table orders the transport processes for average solar wind conditions, however extenuating circumstances discussed in later chapters can change the timescales given significantly. It is important to note that the time scales associated with pitch angle diffusion and with adiabatic cooling can be similar. This makes transport modeling difficult as time ordering approximations fail.
CHAPTER 3

INTERPLANETARY MAGNETIC FIELD FLUCTUATIONS

In which our pickup ions are jostled and scattered by oscillations of the IMF

The Parker spiral and the IMF configuration described in Chapter 1 are an idealized solution. In reality, there are large fluctuations from this field over a variety of time and length scales. Measurements of the IMF have been taken in situ to very high time resolution and in many different locations in the heliosphere. For example, Ulysses took a near polar orbit via a Jupiter swing-by, Helios I & II took an elliptical orbit in the inner heliosphere, and Voyager executed a grand tour of the planets finally leaving Neptune on an escape trajectory. Although the details are very different, fluctuations in the solar magnetic field are observed in all locations of the solar wind. Many changes can be ascribed to “global” heliospheric changes, for example movement of the current sheet or superstructures on the sun.

In addition to global heliospheric IMF changes, which combine to create the switch in polarity over the eleven year solar cycle, there are rapid fluctuations which come more under the category of waves or turbulence. To discuss in detail the causes and effects of these fluctuations it is useful to Fourier analyze the fields, or to refer to the power of the oscillations in frequency space. An example of the resultant fluctuation spectra as observed by the WIND spacecraft is shown in Figure 3.1.
The frequency (x-axis) spectrum of IMF fluctuations is shown for one half hour interval (DOY 99.43-99.45) as an example. The frequency in Hertz is on the x axis, while the power is on the y axis. The frequency spectrum of the X, Y, and Z components of the field, as well as the frequency spectrum of the magnitude and trace of spectral tensor are shown. Spacecraft spin harmonics can be seen as spikes in the higher frequency portion of the spectrum, and power law fits are shown for comparison. [plot from Charles W. Smith and WIND/MFI team]

The discovery of waves and fluctuations in the IMF was not a surprise. The physical forces which appear in a plasma, including the magnetic field and the kinetic pressure of individual particle populations, act as restoring forces and enable a variety of wave modes to propagate in the plasma from any disturbances. The details of the zoo of plasma wave modes and their interplay are beyond the scope of this thesis. However, it will be important for us to recognize the differences between modes that can be observed via spacecraft measurements, and that are likely to affect ion distributions.

Alfvén waves are named for Hannes Alfvén who first hypothesized their existence, solving for linear propagation modes coupling particle motion and magnetic fields. They result from disturbances in which the field fluctuates perpendicular to the mean field. These disturbances are analogous to waves on strings, where in this case the field lines are represented as strings, resistant to
change in direction. Alfvénic fluctuations in the solar wind were detected by the Helios spacecraft [Belcher & Davis, 1971; Neubauer et al., 1977].

Magnetosonic waves are analogous to sound waves, except that the magnetic field pressure gives an additional boost to the restoring force for the wave. There are two main types of magnetosonic waves, the fast and slow modes, named for the relation of their phase speeds. For derivations and dispersion relations related to these waves (and other wave modes) see texts e.g. [Ichimaru, 1992; Chen, 1984; Kallenrode, 1998]. It is expected that the effects of these wave modes will change the evolution of the pickup ion distribution [e.g. Ragot & Schlickeiser, 1998; Michalek et al., 1999], however because more energy is in Alfvén mode oscillations those are expected to have stronger effects on the PUI distribution.

The character of IMF fluctuations from the point of view of an experimentalist is somewhat different from that of a theoretical physicist analyzing behavior of single wave modes. When measuring the magnetic field on a spacecraft, a three dimensional field vector is determined for each measurement, via a fluxgate magnetometer or other magnetic field vector measurement. The fluctuating portion of these measurements is determined by choosing a time scale to average over, for which the average field or mean field becomes the background to any fluctuations. After subtracting this background, the fluctuating component is left, and spectral analysis can begin.
Power Spectrum Distribution in Frequency Space

The fluctuations of each vector component are important, as are fluctuations in combinations of the components. When analyzing these fluctuations it is important to use a coordinate system sympathetic to the mean field direction. The z axis is usually chosen parallel to the mean field, and the solar wind velocity vector is used to choose the x and y axes [e.g., Belcher & Davis, 1971]. Once the fluctuating field components have been expressed in mean field coordinates, Fourier or spectral analysis can begin.

For example, the Fourier transform of a magnetic field component $B_i(t)$ in frequency space is given by $\tilde{B}_i(\omega) = \int_{-\infty}^{\infty} B_i(t)e^{-i\omega t}dt$. In practice, the field strength components are measured as a time series, and so a discrete Fourier transform is used (see Chapter 6 for more details).

The power distribution of the IMF fluctuations can be taken from any combination of components, such as a single component, the magnitude of the magnetic field vector, or more complicated quantities. In general, all the quadratic quantities which can be analyzed form the spectral matrix $P_\omega$, whose components are defined as

$$P_\omega(\omega) = \left[ \begin{array}{ccc} \tilde{B}_x \tilde{B}_y & \tilde{B}_y \tilde{B}_x & \tilde{B}_z \tilde{B}_x \\ \tilde{B}_y \tilde{B}_y & \tilde{B}_y \tilde{B}_x & \tilde{B}_y \tilde{B}_z \\ \tilde{B}_x \tilde{B}_x & \tilde{B}_x \tilde{B}_y & \tilde{B}_x \tilde{B}_z \end{array} \right]$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
where the tilde indicates a Fourier transform of the quantity below it. From this matrix one can construct the trace, giving the power in the magnitude squared of the field vector. Of immediate interest are the diagonal components of the spectral matrix. \( P_x \) is the power in the magnitude of fluctuations parallel to the mean field, and the transverse components \( P_{xx} \) and \( P_{yy} \) give power in fluctuations perpendicular to the mean field. The cross terms are also important, e.g. for measurements of helicity [Smith, 2003], but they will not be used in the analysis of pickup ion – wave power correlations that is presented in this thesis.

**Single Spacecraft Observations**

Although the IMF measurements and spectral analysis techniques are powerful, they are limited in that they represent a time-series obtained from a single spacecraft, from only a single point in space at any one time. Any spatial variations of the magnetic field other than the radial motion of the plasma past the spacecraft are not observable. In fact, if the spacecraft moves so quickly with respect to the bulk plasma, the time series measurements taken by a spacecraft magnetometer can be seen as a spatial distribution of magnetic field vectors, and the measured spectrum and its components can be interpreted as a wave-number \((k)\) spectrum:

\[
P_k(\omega) \approx P_y(\vec{k} \cdot \vec{V}_{sw})
\]

where \( \vec{k} \) is the wave number and \( \vec{V}_{sw} \) is the plasma flow velocity past the spacecraft.

The determination of wave power in all four dimensions (three of wave number and one of frequency) cannot be made with single spacecraft observations.
To compensate for this techniques are available that use time series of particle measurements as well, and that rely on estimates of spatial gradients using e.g. the frozen in condition [see e.g. Matthaeus & Smith, 1981; Smith, 2003]. For the purpose of comparing wave power to the pickup ion distribution observed in the solar wind, we use Fourier time series of magnetic field data alone, using the frequencies near gyro-resonance as a proxy for waves satisfying the resonance condition.
CHAPTER 4

INSTRUMENTATION

_In which the solar wind speaks to us directly, via in situ particle and field measurements._

The remarkable advances over the last century in technology are paralleled by modern space measurement instruments. For this research we rely on two basic groups of instruments, particle spectrometers and magnetic field sensors, each on board spacecraft outside of the Earth's magnetosphere, in the solar wind. The primary particle instrument used for the data in this thesis is the SOHO/CELIAS/CTOF time of flight spectrometer. The fluxgate magnetometers on board WIND served as magnetic field measurements for this survey [Lepping et al., 1995], as SOHO did not have a magnetometer. The procedure used to determine field conditions at SOHO via these WIND wave measurements, as well as a brief discussion of the instruments, are included in this chapter.

A full review of the many techniques that have been used to measure the particles in the solar wind is well beyond the scope of this thesis. However, because the bulk of our material comes from a specific instrument on board SOHO, capable of identifying helium PUIs and measuring their energy and flux density, we give some background into this instrument here. The bulk solar wind measurements (i.e. proton density and temperature) are also used in this thesis, and these are provided from SOHO by the proton monitor MTOF/PM [Ipavich et al., 1998].
SOHO/CELIAS/CTOF

The CTOF instrument, in the CELIAS package on board SOHO, produced 150 days of data in the upwind region of the interstellar flow. The large geometric factor of the instrument makes high time resolution observations of PUI velocity spectra possible [Hovestadt et al., 1995]. Furthermore, its location at the Lagrangian point and 3-axis stabilized platform gives continuous sampling of the solar wind near 1AU. This makes the dataset interesting for studying short term variations in both total flux and velocity distribution of interstellar He⁺ PUIs as caused by interplanetary disturbances.

![Figure 4.1](image)

**Figure 4.1** Schematic of the Charge Time of Flight (CTOF) sensor in the CELIAS package on board SOHO. Diagram from [Aellig & Bochsler, 1998].

The instrument (see Figure 4.1) consists of an entrance collimator (which faces sunward), an electrostatic analyzer (hemispherical analyzer), a time of flight (TOF)
spectrometer, and a solid state detector (SSD) that can measure the final energy of a particle. These three components enable measurement respectively of the energy per charge of the particle \( E/Q \), the TOF across a known distance, and the final energy \( E_{SSD} \). The hemispherical analyzer, along with the quadrupole focus and the entrance to the instrument, only allows an ion with a certain range of energy per charge to continue to the TOF portion of the instrument (Figure 4.1).

The TOF system then uses an acceleration system with a negative voltage of typically 23 kV. After the post-acceleration the ions pass through a thin carbon foil. Electrons emitted as the ion passes through the foil trigger a multi-channel plate detector (MCP), providing a start signal. When the ion passes through the TOF section and enters the solid state detector, additional electrons are produced that trigger the MCPs, providing a stop signal. Fast electronics determines a digital value for the time of flight.

This allows determination of the mass per charge of the particle:

\[
m/q = 2(T/d)^2 (U_{acc} + E/q) \cdot \beta
\]

Here \( d \) is the distance traveled by the particle between start and stop signals in the applied potential \( U_{acc} \), and \( T \) is the time of flight. \( E/q \) is determined by the electrostatic analyzer, and \( \beta \) is a number between zero and one due to loss in the carbon foil and depends on the energy and species.

The SSD then provides the energy \( E_{SSD} \), as well as a third timing signal for triple coincidence. This allows determination of the mass:

\[
m = 2(T/d)^2 E_{SSD} \cdot \mu
\]

Here \( \mu \) is greater than one and due to energy loss in SSD. The energy losses in the foil and the SSD are significant and energy dependent, and the instrument
must be carefully calibrated accordingly to determine the form of $\beta$ and $\mu$

[Aellig & Bochsler, 1998; Hefti, 1997].

The electrostatic analyzer selects ions based on their energy per charge, and
this energy per charge is stepped logarithmically to allow sequential measurement
of ions over the energy range of the instrument, from 0.1 to 55 keV per charge.
The ions enter through a 50 degree opening centered in the sunward direction, i.e.
antisunward particles enter the instrument.

Further details of instrument calibration and operation procedures can be found
in the CELIAS Dataphase Manual [Wurz et al., 1997].

**WIND/MFI and Data Extrapolation**

SOHO was unfortunately not equipped with a magnetometer, so interplanetary
magnetic field (IMF) measurements from the fluxgate magnetometers from the
Magnetic Field Investigation (MFI) on the WIND spacecraft were used [Lepping
et al., 1995]. These IMF measurements were used both to determine the
orientation and magnitude of the magnetic field and to determine the level of
fluctuations or turbulence present in the solar wind.

During the time period considered (DOY 80-230, 1996) WIND passed through
the Earth’s magnetosphere 3 times, and was always within 250$R_E$ of SOHO. The
position of the spacecraft is shown in Figures 4.3 and 4.4. We ignored data from
well before to well after the magnetosphere crossings to avoid terrestrial effects
(DOY 86-89, 109-111, 130-133). The IMF measurements were shifted in time to
correspond to SOHO’s location, using the measured solar wind speed and IMF
The amount of ancillary data was also large, including not only the average magnetic field vectors from WIND/MFI and proton parameters from SOHO/MTOF/PM but also three second magnetic field vectors from which SW turbulence levels could be determined. The software used and the libraries created in this work are catalogued in Appendix A.

While the software details will not be discussed in detail here, there are two components of the analysis that merit discussion in this context, as much of the results relied on these aspects, and they are relatively unique to pickup ion data analysis techniques. The first is the normalization of spectra by the solar wind speed, and the second is the use of energy flux density as the unit of choice over the flux density or the distribution function that are more closely related to the measurement and commonly discussed in particle measurements.

The measured energy spectra of pickup ions need to be normalized to the solar wind speed if they are to be compared during times of different solar wind speeds. Due to the nature of the pickup process as described in Chapter 1 & 2, a cutoff velocity is expected at twice the solar wind speed. This cutoff will not be clear if the spectra are averaged over times of different solar wind speed, unless a proper normalization procedure is carried out when forming a spectrum or energy histogram.

To create a normalized spectrum, a histogram is created in \( v/V_{SW} \). An individual helium event, which has a possible range of velocities, is translated to a range in \( v/V_{SW} \) using the MTOF/PM data from the same time period. The individual helium event is not put wholly into the most applicable bin in \( v/V_{SW} \), rather it is treated as a fraction of an event in the \( v/V_{SW} \) bins straddled by the
velocity range determined by the instrument. This avoids the so-called "fencepost
effect", in which certain $v/V_{SW}$ bins collect more counts by virtue of their
placement in the original spacecraft energy bins. This also enables a final
normalized histogram with a different number of bins than the energy bins of the
instrument.

The energy flux density is tabulated in this histogram, by multiplying the
calibrated number fluxes $J_i$ from the count rates by the midpoint energy in the
energy bin:

$$EFlux_i = J_i E_i$$

(4.3)

where the subscript $i$ indicates the $i$th energy bin and $E_i$ is the energy of particles
in that bin. The number flux is determined from the count rate with the
instrument geometric factor and calibrated energy efficiency [see Aellig &
Bochsler, 1998; Hefti, 1997]. In terms of the PUI distribution function $f$, the
number flux can be written as:

$$J(E, \Omega, \bar{r}) = \frac{\gamma^2}{m} f(\bar{r}, \bar{v})$$

(4.4)

where the instrument then integrates this over the solid angle $\Omega$ and energy range
$\Delta E$ dictated by the aperture and electrostatic analyzer [e.g. Kallenrode, 1998].
The energy flux density is used here because this quantity is predicted to be
independent of the solar wind speed, in contrast with other quantities which could
be used [Mobius et al., 1995]. This can be seen by examining the form of $f(\bar{r}, \bar{v})$
for an isotropic model [e.g. Vasilyunas & Siscoe, 1976]. This PUI distribution
has as its source the interstellar neutral distribution multiplied by the ionization
rate, neither of which depends on the solar wind speed. However, a parcel of
solar wind which spends more time in the inner heliosphere (lower SW speed) has
more time to accumulate PUIs. This implies an inverse dependence of the pickup
ion density on the SW speed. Also, in the solar wind frame the ions are injected at the solar wind speed. Assuming that they fill a sphere in velocity space isotropically implies this volume of phase space is $\sim V_{SW}^3$, and so the distribution function contains an additional factor of $V_{SW}^{-3}$. This means that the phase space density $f(\vec{r}, \vec{v})$ is inversely proportional to fourth power of the solar wind speed.

From the definition of the energy flux density in terms of the velocity distribution, using (4.4):

$$EFlux = J \ast E = \frac{v^4}{2} f(v, r) \sim \frac{(wV_{SW})^4}{2} \frac{1}{V_{SW}^4}.$$  \hspace{1cm} (4.5)

Here the EFlux is expressed in terms of the normalized velocity, $w = v / V_{SW}$, and the distribution function $f(w)$. The solar wind velocity dependence of (4.5) cancels.

In a fast solar wind, the PUIs are swept out quickly and do not accumulate to as high a density, hence their density is inversely proportional to the SW speed. The number flux of PUIs also exhibits this inverse dependence. However, the energy flux, which includes the speed of the ions as they move with the solar wind, does not include a term proportional to the solar wind speed, for simple models of pickup ion generation and transport. For this reason, energy flux density, as measured in cm$^{-2}$s$^{-1}$sr$^{-1}$ is appropriate when comparing pickup ion spectra from different solar wind conditions. In actuality some dependence on the solar wind speed may still be observed, as PUI transport parameters vary with different SW conditions, and the distribution is not always isotropic.
CHAPTER 5

COMPRESSION REGIONS AND SOLAR WIND BULK EFFECTS

In which the solar wind pushes itself and its constituents, causing variations in magnetic fields, solar wind bulk parameters, and pickup ions.

Co-rotating and Stream Interaction Regions

It is a necessary consequence of a variable speed solar wind that compression regions will form. Convection of a faster flow into a region of slower flow compresses the fluid ahead. Because such compression also affects the SW magnetic field, the pickup ions in the SW are also affected. Indeed, many of the features in the dynamic pickup velocity spectrum can be explained as results of SW compression or rarefaction [Schwadron et al., 1996; Klecker et al., 2001].

Presented in this chapter are results that concentrate on the effects of SW compressions on PUI fluxes.

When such a fast wind flows from a coronal hole, the structure appears from Earth to repeat, with the frequency of the solar rotation. This is called a co-rotating interaction region (CIR), and is depicted in a cartoon in Figure 5.1. As the fast wind continues to push the slow wind ahead, very high densities can form, and due to the supersonic and super-Alfvénic flow speeds involved, a shock can form. Often such a region will have a forward and reverse shock on either side of the compression region. Such a shock often does not form until the region moves further out in the heliosphere (2 or more AU), where the pressure has had more time to build up in the interaction region and the magnetic field lines become more perpendicular to the fluid flow enabling further compression.
Such a compression region can be formed in other circumstances as well. A fast moving CME will have a compression region ahead of it, which may or may not steepen to form a shock. Smaller changes in the solar wind, or those more variable or transitory than a full solar rotation, are also common and have earned the moniker “transient interaction region”, or TIRs. Such structures were also found to have strong effects on PUI distributions.

![Figure 5.1. A co-rotating or stream interaction region. The Parker spiral is shown in magnetic field lines, and the solar wind velocity is depicted with arrows. A high speed stream emission is represented by the dark shaded region, with a compression region ahead of it and rarefaction region behind it. A possible shock front is indicated with dashed line. Figure taken from Forsyth, 2002.](image)

**Figure 5.1.** A co-rotating or stream interaction region. The Parker spiral is shown in magnetic field lines, and the solar wind velocity is depicted with arrows. A high speed stream emission is represented by the dark shaded region, with a compression region ahead of it and rarefaction region behind it. A possible shock front is indicated with dashed line. Figure taken from [Forsyth, 2002].

**Pickup Ion Variations – Statistical Analysis**

That compression regions play a role in PUI dynamics is not a surprise. ULYSSES measurements [Gloeckler et al., 1994] showed that enhancements in pickup helium were mirrored by pickup hydrogen, a result consistent with solar wind transport processes playing a role. Strongly accelerated PUIs were also found to coincide with CIRs and interplanetary shocks from ACE SEPICA
measurements [Möbius et al., 2002; Kucharek et al., 2003], and at lower energies from SOHO STOF measurements [Klecker et al., 2001]. We concentrate here on the effect of compression regions on the bulk PUI population, as pitch angle and energy diffusion by compressions and shocks will be discussed later.

One goal of this work is to determine the causes of the large variations in PUI fluxes. To do so we examine individual events of pickup ion variations, and we perform a statistical analysis searching for correlations between various solar wind parameters and the PUI fluxes. While individual event analysis is compelling, the statistical results are unambiguous in their determination of compression region effects on PUI distributions and so are presented first. By combining time periods of similar solar wind density in a superposed epoch analysis, PUI spectra were made for different ranges of SW parameters. Spectra were combined with respect to the normalized velocity, as described in Chapter 4. Pickup ion spectra were obtained by accumulating different ranges of the parameters which included IMF as well as proton density, velocity, and temperature (see Appendix A for complete list of parameters considered).

A strong trend emerged when this technique was employed with proton density as measured by MTOF/PM, to produce e.g. Figure 5.2.
magnetic moment decreases the pitch angle of particles, enabling them to escape more quickly from a compression region.

Because the PUI fluxes showed correlations with both IMF strength and proton density, we then looked in more detail at individual times of solar wind compression, which have both enhanced IMF and proton density. The unique nature of each compression region (due to different conditions at its formation) will be washed out in the statistical analysis, but should be clear from looking at individual events.

**Individual Compression Events**

SOHO saw several solar wind compression events during 1996. Some CIRs and transient stream interaction regions have also been observed over this time period with other instruments on SOHO [Klecker et al., 2001]. Two events are shown in detail here; the interested reader is directed to the catalog of events that was produced along with this dissertation research and described in Appendix A.

These two figures (5.6 & 5.7) are shown as examples of compression regions in the solar wind and the resulting disturbances in the PUIs in three energy ranges. They show the data from three instruments, SOHO/MTOF/PM in the top three plots (proton data), WIND/MFI in the next two plots (IMF), and SOHO/CTOF in the lower three plots (Helium PUIs).

We observed a strong transient stream interaction on DOY 170 (Figure 5.6), with a clear jump in the solar wind speed driving the compression. The proton density jumped to the highest level in the dataset, approaching 50 cm$^3$. A
simultaneous compression of pickup ions was also observed during this time (lower three panels of Figure 5.6), though their larger gyro-radii and more diffuse density made the width of the PUI compression region wider than the narrow proton peak. The PUIs in the range $1.8 < \frac{v}{V_{SW}} < 2.0$ (second PUI panel) are seen to be enhanced for four times longer than the protons.

Acceleration of the PUIs is also visible in the higher energy ranges in the bottom two panels of Figure 5.6, which will be discussed later in Chapter 7. In particular, note the apparent strong enhancement of the high energy PUIs (with speeds greater than the cutoff velocity) in a single data point coincident with the largest magnetic field discontinuity. It will be shown later that this is not true acceleration but is indicative of an adiabatic shift of the PUI distribution.

A magnetic cloud CME around DOY 149 (Figure 5.7) was also observed. This cloud displayed compression of the solar wind and He$^+$ before and after its passage, with stronger compression trailing the region. As the cloud arrived, a strong jump in magnetic field magnitude was observed, and a smaller spike in proton density and in the PUI density. Again, the close correlation of the PUIs to the SW conditions can be observed despite the collisionless and diffuse nature of the interaction. It can also be seen from this compression region that the PUIs are most affected in the range of $1.8 < V_{SW} < 2.0$, near the injection or cutoff velocity. This corresponds to the statistical observations (Figures 5.2 - 5.5) and lends credence to the explanation that compression regions are behind this effect. It could be that these recently injected particles are more susceptible to compression due to their more anisotropic distribution or to their larger gyroradii; however the exact reasons for the preferred enhancement near the cutoff velocity are not known at this time.
Cutoff Shift at Magnetic Discontinuities

To determine how the pickup ion distribution changed during these events, we plotted one hour spectra and overlaid them to see the change, as in Figure 5.8. In some cases, the PUI spectra showed a shift in the cutoff velocity right at the onset of compression regions. This shift can be seen in the velocity spectra shown in Figure 5.8., where the PUI spectra at the discontinuity looks just like the normal PUI spectra shifted in normalized velocity space. The data are taken from the time period shown in detail in Figure 5.6., where the cutoff shift appears as the strongest peak in the lowest panel showing supra-thermal PUIs. In Figure 5.6 it can be seen that this peak in higher energy PUIs coincides with the jump in IMF magnitude (4th panel). Although these PUIs do have energies exceeding the nominal cutoff (2V/V_{SW}), they are not actually a supra-thermal tail, as can be seen by the velocity distribution in Figure 5.8. A supra-thermal distribution would show an extended tail, or a hard spectrum, whereas the observed spectral characteristics show only a shift in energy space. The cutoff shift is most clearly visible around a magnetic field discontinuity in the compression region on DOY 170, and the spectra just before, during, and just after the magnetic field jump are shown in Figure 5.8.
Figure 5.8. Logarithmic PUI differential energy flux spectra corresponding to three one hour time periods right at the magnetic discontinuity visible in Figure 5.4. The spectrum shifts to the right and returns to its original position in velocity space. The downward arrows show expected cutoff position before and after magnetic discontinuity using an isotropic model of the PUI distribution (see text).

We hypothesized that this phenomenon was due to conservation of the adiabatic moment \( \frac{v^2}{|B|} \) as the PUI distribution entered a compression region with enhanced IMF. Consistent with this explanation, such a short term shift was only observed close to a jump in magnetic field magnitude.

We consider two models of this effect based on the hypothesis, one for a ring distribution of pickup ions (e.g. the injected population, unmodified), and one for a distribution isotropic in pitch angle (e.g. assuming efficient pitch angle scattering). The ring distribution is the simpler model. If the shift is due to...
conservation of the adiabatic moment it will only affect perpendicular velocity. Therefore, the maximum PUI velocity shift is predicted for a ring distribution, for which the shift is: 

\[ v_2 = v_1 \sqrt{\frac{B_2}{B_1}}. \]

To find the shift for an isotropic distribution we can integrate the velocity shift over all pitch angles, where the shift in velocity magnitude for pitch angle \( \alpha \) is given by:

\[ v_2 = v_1 \frac{\sqrt{B_2}}{B_1} \sin^2(\alpha) + \cos^2(\alpha). \]  

(5.1)

The average shift for the isotropic distribution is thus:

\[ v_2 = v_1 \frac{\pi}{2} \int_0^\frac{\pi}{2} \frac{B_2}{B_1} \sin^2(\alpha) + \cos^2(\alpha) \sin \alpha \, d\alpha \]  

(5.2)

This can be approximated numerically as 

\[ v_2 = v_1 \left( B_2 / B_1 \right)^{0.4}. \]

The injection speed (in the SW frame) is taken as the solar wind speed [e.g. Vasilyunas & Siscoe, 1976]. The isotropic approximation of adiabatic cooling from that paper, as described in Equation (2.3), describes the change of PUI speed as a function of radius. Here we have described the velocity change as a function of magnetic field magnitude. The isotropic adiabatic cooling rate due to the expanding volume of the solar wind is recovered from the above analysis only if the IMF magnitude has inverse cubed or slower dependence on the distance from the sun. This is a lower power of radius than is expected from the Parker spiral model of the IMF, however we note that the model described here treats only the change of PUI velocity due to changing field, and does not include effects due to the expanding volume of the solar wind or other forces that isotropize the distribution.
The model described above for heating by magnetic discontinuity of an isotropic distribution predicts the relative variation between the initial and compressed (final) cutoff velocities based on the change in field magnitude. The determination of the initial cutoff velocity reflects the non-zero injection speed of the PUIs due to the LISM flow, which will be discussed in the next subsection, while the determination of the final cutoff velocity is taken to be that which exhibits the same decrease in flux as the initial distribution did at its cutoff.

![Graph](image)

**Figure 5.9.** Predicted velocity shift ratios for isotropic (dashed line) and ring distributions (solid line) are shown vs. the corresponding magnetic field compression ratio observed at four compression events (crosses). The magnetic field data is from WIND/MFI and the PUI cutoff shift is observed with SOHO/CELIAS/CTOF. The estimated shifts in 4 observed distributions are shown.

To further test the interpretation the cutoff shift phenomenon at IMF discontinuities the ratio $v_2/v_1$ was estimated for four observed magnetic field
discontinuities and PUI distribution shifts using the inflection points of polynomial fits to the spectra (in linear representation). The results are shown for four compression events (Figure 5.9), including the one shown here at DOY 170, the trailing edge of the event at DOY 149, and two smaller compressions on DOY 99. The results suggest the isotropic distribution model is more accurate than the ring distribution, i.e. the distributions are mostly isotropized before the passage of the discontinuity.

When measuring small shifts in velocity space of the interstellar PUI distribution, one effect arises that must be taken into account, especially when comparing data over time scales approaching a year. There can be a PUI distribution shift due to non-zero injection velocity of the interstellar neutrals.

**Upwind Cutoff Shift**

The neutral interstellar atoms that are the seed for the pickup ion population are moving much slower than the solar wind speed. For this reason most simple models take the injection speed of PUIs to be zero relative to the sun (see Chapters 1 and 2). However, the non-zero injection velocity of PUIs can be observable, notably in the upwind portion of the heliosphere. The interstellar neutral velocity is also enhanced by the gain in speed as the neutral particles fall into the gravitational potential well of the sun; the resulting speed of a cold interstellar neutral at 1AU is near 50km/s. This changes the injected ring distribution of PUIs by making it a larger ring, extending it slightly in the sunward direction and slightly past the nominal cutoff of $V/V_{sw}=2.0$, as shown in Figure 5.10. As viewed from the solar wind frame and on the upwind side of the LISM flow, the incoming neutrals have a slightly higher speed than the solar wind...
speed, therefore the initial ring distribution is wider and goes above the nominal cutoff.

Figure 5.10. The injected ring distribution of pickup ions is shown for a small but nonzero injection velocity corresponding to the interstellar flow speed. PUIs are present at speeds greater than twice the solar wind speed due to the shift in the distribution.

Despite the small ratio of interstellar neutral velocity to solar wind velocity, the resulting shift in the pickup ion distribution is visible in in-situ measurements with SOHO/CTOF especially when the solar wind speed is low [see Möbius et al., 1999]. Here we extend the analysis by [Möbius et al., 1999] to the entire data set. To measure the cutoff shift, we compared PUI distributions during time periods of near perpendicular field to an isotropic model of the pickup ion distribution. Despite many variations due to changing magnetic field strengths, compression
precision measurements of heliospheric and interstellar parameters. This chapter has emphasized the importance of solar wind compression regions in creating PUI flux variations. Here our knowledge of compression regions is used to attempt a detrending of the PUI dataset. While the outcome is far from our goal of an invariant energy flux dataset, the procedure does reduce variability. A simple model was used to give a first order measurement of the efficacy of PUI smoothing based on statistical correlations with solar wind data, and this was extended to include field orientation and wave power.

We used the solar wind proton density as measured onboard SOHO as a proxy for the overall compression of the plasma, and compared this to the energy flux of singly charged helium near the cutoff of the velocity distribution. The scatter is quite large, but a trend is clearly visible, that higher PUI fluxes are observed during times of higher proton density. This correlation was described in more detail earlier in this chapter (see Figure 5.3).

The data points consisting of energy flux in the range range \(1.8V_{SW} < V_{PUI} < 2V_{SW}\) were binned, counting the total number of points in each range of proton density. The mean in each bin was taken to emphasize the trend to produce Figure 5.3. The points in this figure were fit to a linear model with the least squares method.

Each energy flux measurement, taken in the reference range \(1.8V_{SW} < V_{PUI} < 2V_{SW}\) was then detrended according to the formula:

\[
F^*(t) = F(t) + a(N_p - N_p(t))
\]

(5.3)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Here $a$ is the slope of the linear fit, $F^*$ is the modified or detrended flux, and $\bar{N}_p$ is the mean proton density in the dataset. This procedure ensures that the mean flux will remain the same, while lowering the value during times of high proton density and raising it during times of lower density.

The detrending of the helium integral energy flux according to a linear fit of the SW density reduced the total variance by only 7%, bringing the standard deviation of the 15 minute averages from 52,300 to 48,800 (the average value of both real and smoothed integral energy flux was 76,721 (cm$^3$sr$^{-1}$s$^{-1}$)). An example of the original and detrended data is shown in Figure 5.13. Here it can be seen that the detrended data is more constant, until a spike in the proton density brings the corrected dataset into negative values. Figure 5.13 illustrates one problem inherent in such compensation schemes, that correcting for variations in the proton density will not always make the pickup ion data more constant but can make it more variable during some time periods.
distribution is effectively isotropized in the GSE \( x \) direction (sunward – anti-

sunward) by Larmor gyration, and the wave-power or pitch angle scattering rates

will not affect CTOF fluxes. For these reasons we consider a detrended PUI flux
defined as:

\[
F^*(t) = F(t) + a(\bar{N}_p - N_p(t)) + b \cos(\theta(t)) \cdot (\log(\bar{P_{tr}}) - \log(P_{tr}(t))) \tag{5.4}
\]

Here the coefficient \( b \) is determined analogous to the determination of \( a \) as just
described. Equation (5.4) corrects a given time series of PUI flux data assuming
linear relationships to proton density and the log of the wave-power.

Including the wave-power dependence reduced the variance of the dataset still

further. The standard deviation dropped to 37,000 cm\(^{-1}\)sr\(^{-1}\)s\(^{-1}\), \(-30\%\) lower than

the deviation of the original dataset. A sample of the detrended data is shown in
Figure 5.14, which is taken from a particularly fluctuating time period previously

seen in Figure 5.7. It can be seen from this figure that the addition of IMF
orientation and wave-power to the correcting procedure (Equation 5.4)

significantly reduces the variance of the He\(^+\) flux data. However, there are still

substantial variations in pickup ion fluxes even after correcting the dataset using
proton density, wave-power, and IMF orientation.
Conclusions

The CTOF measurements of He\(^+\) pickup ions show strong correlations with solar wind parameters, especially the proton density. This is perhaps not a surprise; one would expect conditions that compress the bulk solar wind to compress the PUIs contained in the wind. The observed correlation with IMF magnitude was similar in character to that of the proton density, pointing to a similar cause for these two correlations. This could also explain Ulysses observations which show correlations between helium and hydrogen PUIs despite the differing ionization processes involved in injecting the two species in the solar wind [Gloeckler et al., 1994], although for the time periods considered in that paper correlations were not found with bulk SW parameters. The observations here are consistent with the hypothesis that compression regions are responsible for many of the PUI flux variations, with IMF orientation and velocity distribution anisotropies also playing a role.

The compressions not only enhance the overall flux, but change the shape of the distribution, most notably in an enhancement near the injection velocity in compressed regions. The observations are consistent with the compression compensating for some of the adiabatic cooling of the PUIs, thus keeping their speeds close to \(V_{SW}\) in the solar wind frame (\(2V_{SW}\) in the spacecraft frame). The observed velocity shift due to magnetic discontinuities can be explained with adiabatic effects. Further work is needed to model this effect more fully and interpret its influence on different distributions or in different solar wind conditions. However, strong shocks are known to affect PUI distributions in other

70

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
ways, including heated electrons increasing the ionization. It could be that something similar takes place in compression regions, contributing to the still unexplained enhancement near the cutoff.

We also find PUI flux variations due to the location of the spacecraft in the heliosphere, even outside the focusing cone. The upwind cutoff shift is due the non-zero injection velocity of the interstellar neutrals, and this effect can be used to estimate the LISM motion.

Finally, although we have found that many of the pickup ion flux variations can be explained with compression regions and bulk effects, a number of PUI flux variations, visible in both individual events and in statistical analyses, do not conform to the simple models of solar wind compression. Even when the now explained PUI flux variations are compensated for, substantial variations are visible that still await an explanation.
CHAPTER 6

PUI WAVE-PARTICLE INTERACTIONS

In which our pickup ions are jostled and scattered by oscillations of the IMF, leading to observations of phase space scattering and diffusion in both pitch angle and energy.

In Chapter 5 the power in fluctuations of the IMF was used to correct PUI flux data and reduce the variance. Here the relationship between the PUI distribution and magnetic field wavepower is studied in more detail.

Pitch Angle Scattering by Waves

Magnetohydrodynamic waves play an important role in energetic particle and pickup ion transport. Alfvénic (transverse) fluctuations can act as pitch angle scatterers in the wave frame, which is important for particle transport processes such as the modulation of cosmic rays. It has been assumed that diffusive transport and diffusive shock acceleration are dominated by magnetic field fluctuations [e.g. Skilling 1971, Lee & Völk 1975]. Quasi-linear theory uses the assumptions of small fluctuations and resonance to calculate pitch angle diffusion coefficients due to different types of waves in the solar wind (SW) [e.g. Jokipii, 1972 & 1974; Schlickeiser 1998]. While theoretical descriptions of such wave-particle interactions abound, until now there had been no direct experimental verification of a correlation between the power in the fluctuations and the strength of observed transport effects. Because of their well defined initial distribution, pickup ions provide a tracer for such transport.
Interstellar neutral helium enters the heliosphere and is ionized predominantly by solar ultraviolet radiation. The resulting PUIs are then convected outwards through the heliosphere with the SW, subject to such wave-particle interactions. Long before the first in situ detection of interstellar PUIs [Mobius et al., 1985], a number of wave-particle effects had been suggested which could influence such ions [e.g. Jokipii 1972]. The treatment of PUI evolution in the solar wind by [Vasyliunas & Siscoe, 1976] is based on the assumptions of complete isotropization of the distribution. Detailed models of the evolution of this population have been devised [Isenberg, 1997, Schwadron 1998, Zank & Pauls 1997] which assume pitch angle diffusion by SW magnetic turbulence. The helium is injected (picked up) at a speed slow compared to the solar wind speed, and is created from the presumably constant interstellar neutral density, creating a ring distribution in velocity space. This well known initially anisotropic distribution of injected interstellar PUIs allows the study of their isotropization by pitch angle scattering, where other less well known or more isotropic initial populations (e.g. cosmic rays) would not permit such quantitative analysis. As part of the research in this dissertation, we compared in situ PUI velocity distributions with concurrent measurements of IMF wave power.

Wave Parameters

We used Fourier analysis in mean field coordinates to determine components of the power spectrum distribution of IMF variations as observed by WIND/MFI. The frequency range considered is from 0.002 Hz. to 0.16 Hz (the Nyquist frequency for the 3s public MFI data). It is not possible to uniquely identify frequency and wavevectors with only a single spacecraft, so this range of frequencies is used as an indicator of resonant wave power. The typical He$^+$
gyrofrequency in the SW is 0.015 Hz (2 nT) to 0.15 Hz (20 nT). For other details in spectral decomposition of IMF vector measurements, see Chapter 3.

The power spectrum was computed for each contiguous 15 minute period in the dataset, and each component was fit to a power law with the least squares method. A sliding principal axis coordinate system was used to determine each power spectrum distribution. The principal axes for each 3s field vector were calculated using a 15 minute sliding mean field direction $\hat{B}$. The z component is chosen along the mean field, $x$ along $\hat{B} \times \hat{r}$, and $y$ along $\hat{B} \times (\hat{B} \times \hat{r})$ [Belcher & Davis, 1971]. We consider here two components of the spectral matrix, the power in the z direction $P_z$, and the transverse power $P_{TR} = P(\sqrt{x^2 + y^2})$. $P_z$ is the power in parallel (or compressive) fluctuations and $P_{TR}$ is the power in perpendicular (or transverse) fluctuations [Matthaeus & Smith, 1981]. The quantities $P_z$ and $P_{TR}$ are taken from the power law fit, and are thus affected by wave power over the entire frequency range considered. The numerical value used for comparison is the value of the power law fit of the spectral component evaluated at 0.1 Hz.

**PUI Parameters**

Helium PUIs are injected with a speed much less than the SW speed; they are traditionally expected to scatter into a sphere in velocity space quickly, generating a distribution with a sharp cutoff at $V=2V_{SW}$ in the spacecraft frame [e.g. Vasyliunas & Siscoe, 1976]. However, slower pitch angle scattering rates produce distributions that differ from this expectation, in particular during times of near radial IMF. The PUIs are initially injected into the sunward hemisphere in
velocity space. If the IMF is near radial, injected PUIs must be pitch angle scattered to enter the anti-sunward hemisphere (in the solar wind frame). This leads to reduced PUI fluxes in this hemisphere during times of radial IMF, as has been reported by [Gloeckler et al. 1995] and [Mobius et al. 1998].

PUIs ionized at smaller heliospheric radii have more time to be scattered, but are also adiabatically cooled in the expanding solar wind and so will be observed at a lower energy. The PUI velocity distribution is thus different for cases of near radial and near perpendicular field, the perpendicular case exhibiting a much sharper cutoff, with the two distributions approaching each other for lower velocities in the solar wind frame. Therefore, a good proxy for the strength of PUI pitch angle scattering during times of near radial IMF is the integral energy flux in the range near the cutoff velocity $1.8 < V/V_{SW} < 2.0$ (in the spacecraft frame), which we call here for simplicity He$^+_{c}$.

The CTOF aperture points sunward, with an opening angle of 50°, thus sampling is done in the anti-sunward hemisphere of the PUI velocity distribution in the spacecraft frame. This should allow sampling of all interstellar PUIs which in the SW frame have speeds between $-V_{SW}$ and $V_{SW}$. However, the collecting power of electrostatic analyzers scales strongly with the ion energy, which reduces the detection efficiency of PUIs at the low energy end. In addition, it is difficult to separate PUIs from the solar wind at energies near that of the bulk SW. In practice we consider here only PUIs with $V_{\|} > V_{SW}$ in the spacecraft frame, or $V_{\|} > 0$ in the SW frame, which translates to preferential detection of PUIs in the antisunward hemisphere in the SW frame. This selection results in the observed reduction of flux during times of radial IMF [Gloeckler et al. 1995, Mobius et al., 1998], as the PUIs start in the sunward hemisphere, and must be pitch angle
time periods of near perpendicular field corresponding with high PUI flux (He$^+$) as expected [e.g. Moebius et al., 1998]. However, the transverse wave power (3rd panel) is also changing by over an order of magnitude, and could also be correlated with He$^+$. It is difficult to see in this figure the separate effects of a dynamic IMF orientation and a dynamic wave power on the PUI distribution. To distinguish between these effects, we pursue a statistical approach.

Figure 6.2. Dynamic PUI energy flux spectra from SOHO/CTOF (bottom panel) and related SW data for day of year 82.2 – 84.2 in 1996. 1st panel: proton density from SOHO/MTOF/PM. 2nd panel: IMF angle to radial. 3rd panel: log$_{10}$ of transverse wave power ($B^2$). 4th panel: He$^+$ integral energy flux density near cutoff velocity (see text). The normalized velocity is on the vertical axis, with the expected cutoff at $V/V_{SW}$=2 shown with a dashed line.
Statistical Correlations

To see whether there is a quantitative correlation between the wave power and the PUI distribution, we use Pearson's correlation coefficient [e.g. Richardson & Paularena, 2001] to correlate the PUI and wave parameters. For two variables $X_i$ and $Y_i$, with $n$ values that change over time with the $i$ index, and have averages $\bar{X}$ and $\bar{Y}$, the correlation coefficient is defined:

$$r = \frac{\sum_{i=0}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=0}^{n} (X_i - \bar{X})^2 \cdot \sum_{j=0}^{n} (Y_j - \bar{Y})^2}} \quad (6.1)$$

This coefficient can vary from -1 to 1, for perfectly anti-correlated variables to perfectly correlated variables. We also want to determine the uncertainty for a calculation of this coefficient. The correlation is not normally distributed, however its normally distributed transform ("Fisher's z") is within 1% of the correlation $r$ for $r < 0.3$. For such correlations we take a statistical uncertainty equal to the standard deviation of that function [e.g. Freund, 1962]:

$$\Delta r \equiv \sqrt{1/(n-3)} \quad (6.2)$$

Statistical correlations of PUI fluxes and wave power are shown in Table 6.1. As in Figs. 6.3 & 6.4, only events during which the SW proton density was $< 15$ cm$^{-3}$ were included. The strongest correlation is observed between the energy flux of He$^+$ near the cutoff (He$^+_C$) and the transverse power in IMF fluctuations ($P_{TR}$). The range of He$^+_C$ is from $1.8 < V/V_{SW} < 2.1$. The correlation is calculated using data from all IMF orientations in Column 1. This correlation coefficient
increases when only periods of near radial field are considered (Column 3), and decreases in near perpendicular IMF (Column 2). The important result is the significant difference between the correlation coefficients in the radial and perpendicular cases. The correlation even disappears in perpendicular fields, for the case of parallel wave-power. This is again consistent with pitch angle scattering by IMF waves isotropizing the distribution in radial IMF. However, the

<table>
<thead>
<tr>
<th>(r)</th>
<th>He⁺ C</th>
<th>He⁺ C − (Perp.)</th>
<th>He⁺ C − (Par.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_TR</td>
<td>0.19 ± 0.01</td>
<td>0.12 ± 0.03</td>
<td>0.21 ± 0.06</td>
</tr>
<tr>
<td>P_Z</td>
<td>0.14 ± 0.01</td>
<td>0.00 ± 0.03</td>
<td>0.19 ± 0.06</td>
</tr>
</tbody>
</table>

Second column includes only IMF within 80° - 90° from radial; the last column within 0° - 10° from radial.

This statistical correlation can also be made visible in a plot of helium fluxes versus wave power. Observed fluxes near the cutoff velocity (from 1.8 to 2.1 times the solar wind speed in the spacecraft frame) are shown for radial and perpendicular IMF respectively in Figs. 6.6 & 6.7. Fifteen-minute flux averages were taken of this quantity He⁺ C (y axis), and binned in the mean value of the transverse wave power or P_TR (x axis) during those times. The error bars represent the statistical variation of the mean energy flux for each transverse wave power bin, i.e. the statistical error in determination of the mean from the samples in the histogram. The visible trend of increasing flux near the cutoff with increasing resonant wave power is consistent with a decreased anisotropy due to pitch angle scattering by resonant waves.
Figure 6.6 Average helium PUI energy fluxes during times of IMF in near radial or parallel to $V_{SW}$ are shown binned in different powers transverse resonant wave power. Only flux near the cutoff velocity ($1.9 < V/V_{SW} < 2.1$) is included. The trend of more PUIs present near the cutoff velocity for greater transverse wave-power is visible.

Figure 6.7 Average helium PUI energy fluxes during times of IMF near perpendicular to $V_{SW}$ are shown binned in different powers transverse resonant wave power. Only flux near the cutoff velocity ($1.9 < V/V_{SW} < 2.1$) is included. The flux near cutoff is mostly flat over two orders of magnitude in wave-power, consistent with isotropic injection and no dependence on pitch angle scattering for perpendicular fields.

The last two data points in Figure 6.7 show an increase in PUI flux for the highest transverse wave-powers, even in perpendicular IMF. The reason for this
increase is not known at this time, although it could be that in compression regions both PUI fluxes and wave-powers are higher.

**Preliminary Conclusions**

The observed correlations of PUI fluxes at the cutoff and IMF wave power as presented so far provide compelling evidence for pitch angle scattering due to wave–particle interactions. While this scattering has a strong theoretical framework, the observational evidence had so far had been limited. These studies give both qualitative and quantitative evidence of PUI isotropization by transverse IMF waves.

However, these studies do not provide direct evidence of the scattering mechanism. In particular, the wave vectors have not been identified, and so counter-propagation, resonant and/or non-resonant scattering, or other effects could be involved. The data is also limited in time, being taken during solar minimum in slow SW. It is possible that the observed correlation will change in SW with different flow and turbulent properties. The observed correlations with wave power at speeds closer to the bulk of the PUI velocity distribution (i.e. $1.6 < V/V_{SW} < 1.8$) could be due to the correlations between PUI fluxes and proton density or field strength, as wave power is statistically correlated with these parameters as well.

To study further the pitch angle scattering due to wave-particle interactions, we must model more completely the diffusive process – including not only a finite diffusion coefficient but a diffusion coefficient that is not constant but a function of pitch angle.
Hemispheric Model of Pitch Angle Diffusion

We consider here an anisotropic model of pitch angle scattering, in which pickup ions are expected to scatter quickly in either hemisphere of velocity space but scatter diffusively across the perpendicular (90 degree pitch angle), following [Isenberg, 1997]. The idea behind this model is that a particle at 90 degree pitch angle cannot be in resonance with transverse parallel propagating waves. This is referred to as the “resonance gap”, and particles are only scattered through this barrier by changes in mean field or non-resonant interactions.

The condition that a wave is in resonance with a proton is (Eq. 2.7): \( \omega - k_{||}v_{||} = -\Omega_{cp} \) (for parallel propagation we need only consider the first harmonic). A particle at 90 degree pitch angle \( (v_{||} = 0) \) is therefore in resonance only with waves whose frequency \( \omega = -\Omega_{cp} \), where no wave power is present due to ion-cyclotron damping.

In fact, a resonance gap can exist for more complex cases including other modes of wave propagation and some kinds of turbulence [e.g. Ng & Reames, 1995; Schlickeiser, 1998; Isenberg et al., 2003]. The details of this interaction for the case of helium depend on the dispersion relation of the waves in question, where the power is present in \( \omega \) and \( k \) space, and where the dispersion relation intersects the helium resonance condition: \( \omega - k_{||}v_{||} = -\Omega_{cHe} \) [see e.g. Dusenbury & Hollweg, 1981]. If we consider parallel propagating Alfvén waves at frequencies including the proton gyrofrequency (ion-cyclotron waves) [e.g. Stix, 1992] the dispersion relation can be written as:
From Figure 6.8 it can be seen that any helium ion (any parallel velocity) can be in resonance with a finite wave-number \( k \), provided that power is present in all four quadrants. This is not the case for proton resonance, for which the lines would intercept the vertical axis at \(-\Omega_{cp}\) creating a resonance gap at \( v_\parallel = 0 \).

However, it can also be seen that a parallel velocity exists for which helium can no longer be in resonance with outgoing waves. Because more power exists in outward modes at 1AU, a particle reaching such a parallel velocity will have a lower chance of begin scattered. This parallel velocity will be on the order of the Alfvén speed.

Because \( V_{sw} \gg V_A \), and the pickup ion is injected in the plasma rest frame with velocity \( V_{sw} \), it’s speed \( |v| \) is also much greater than the Alfvén speed. From this it can be seen that the pitch angle as the particle leaves resonance with outward propagating waves is near 90 degrees, as \( \mu = \frac{v_\parallel}{v} \approx \frac{v_A}{V_{sw}} \ll 1 \). For this reason we assume the first order anisotropies of pickup helium can still be described with a hemispheric model.

The Fokker-Planck pitch angle diffusion coefficient is in general a function of pitch angle, and for the case of resonant wave-particle interactions with parallel propagating waves, this coefficient tends toward zero for pitch angle \( \alpha = 0 \), or \( \mu = \cos(\alpha) = 1 \) [see also Jokipii, 1972 & 1974]. The precise dependence of pitch angle scattering rates (and all Fokker-Planck diffusion coefficients) on the magnetic field fluctuation spectrum has been the subject of much theoretical work, mostly in terms of the application of quasi-linear theory [see e.g. Hasselmann &
Wibberenz, 1968; Jokipii, 1972; Schlickeiser, 1994; Ragot, 1999; Isenberg et al., 2003]. The form of the dependence depends on the type of fluctuations which cause the scattering, and many authors choose different combination of wave-modes or correlation scales when calculating diffusion coefficients. However, a simple model predicts a linear dependence of pitch angle diffusion on the wave-power [Fisk et al., 1974]. These authors arrive at an expression for the pitch angle diffusion coefficient:

\[
D_{\mu \nu} = \frac{\langle (\Delta \mu)^2 \rangle}{\Delta t} = \frac{2 \pi (1 - \mu^2) \eta^2 \varepsilon^2 \nu}{\lambda_c^{\perp} |\mu|} P_1(k = 1/\mu r_g)
\]  

(6.4)

where \( P_1 \) is the transverse wave-power, \( \nu \) is the particle speed, \( \varepsilon = \lambda_c / r_g \) is the ratio of the correlation length of the field fluctuations to the particle gyroradius, and \( \eta \) is the ratio of the mean square field strength to the mean field strength squared. Although many problems with the derivation of Equation 6.4 are addressed in [Fisk et al., 1974], the linear dependence on wave-power can be used as a starting point for the predictions of quasi-linear theory [e.g. Jokipii, 1972].

The motivations and the transport equations for a hemispheric distribution were presented by [Isenberg, 1997]. The pitch angle diffusion coefficient is treated as an inverse delta function in pitch angle space, being infinite everywhere except at \( \mu = 0 \) where it is a constant. This effectively reduces the problem to a first order anisotropic treatment, dividing the PUI distribution function into two hemispheres in velocity space, where fast scattering leads to isotropy in each hemisphere. We follow the procedure outlined therein which arrives at expressions for the normalized pickup ion distribution functions in the anti-sunward and sunward hemispheres. The model is modified when appropriate for our consideration of singly charged interstellar helium PUIs, assuming that a
resonance gap or a decrease in scattering rate occurs near $\mu = 0$. Remarkably, an analytic solution exists which can be expressed as an integral of Bessel functions, for the case of radial magnetic field. The distribution in the anti-sunward hemisphere takes the form:

$$f(w,r) = \frac{3\beta_0 r_0^2}{8\pi U^4} \frac{D + 1}{r w^{3/2}} \exp(-\alpha D) \int_0^{2\pi} \int_{-\infty}^{\infty} N[r w^{3/2} \exp(z - a)] J_0(\Phi) dz$$

(6.5)

Here $\beta_0$ is the ionization rate at $r_0$, $D$ is a dimensionless scattering parameter representing the cross-hemispheric diffusion rate, $w$ is the normalized velocity $v/v_{sw}$, $r$ is the heliocentric distance, $a = 3(1 - w)/4$, and the argument $\Phi = [z(2a - z)(1 - D^2)]^{1/2}$. The inflowing neutral particle density $N[r]$ considered in [Isenberg, 1997] was that of hydrogen, for which the radiation pressure nearly balances the gravitational force. We use here the appropriate numbers for consideration of upstream interstellar helium, the ionization rate at

$1$AU $\beta_0 = 3.0 \times 10^{-8}$ s$^{-1}$, and the cold model for the neutral density:

$$N[r] = N_0 \exp(-\frac{\beta_0 r_0^2}{GM_\odot} \sqrt{v^2 + 2GM_\odot/r})$$

(6.6)

Here we have assumed that radiation pressure does not influence the trajectory of the incoming neutral helium atoms. It is important to note that this model includes not only the effects of pitch angle scattering between the two hemispheres, but also convection terms including adiabatic focusing due to the diverging magnetic field. This focusing can act to bring particles from one hemisphere to the other even in the absence of waves [Isenberg, 1997].

The hemispheric model was compared to PUI data from SOHO/CTOF taken during times of near radial IMF, and for several different ranges of resonant
observed in the best fit to data hemispheric diffusion coefficient in Figure 6.11. The quasi-linear pitch angle diffusion coefficient is clearly of a different character than that of the hemispheric model. However, their comparison could shed light on the differences of the theories and help interpret observations of pickup ion pitch angle transport. Because it is not clear which wave modes are responsible for the bulk of cross-hemispheric diffusion, or which wave vectors have been observed with a single spacecraft, it is difficult to compare these results with quasi-linear theory.

The large mean free path for cross-hemisphere scattering derived from the observations is not unreasonable. PUI anisotropies observed at 1 AU [Mobius et al., 1998] and further out in the heliosphere [Gloeckler et al., 1995] suggest pitch angle scattering mean free paths on the order of an astronomical unit. This analysis shows (hemispheric) pitch angle scattering mean free paths that do not average below two tenths of an AU even at the highest wave-powers. We also find mean free paths as large as six AU for the case of the lowest wave-power.

Conclusions

The comparison of SOHO/CTOF pickup ion data and convected WIND IMF fluctuation data with the hemispheric model gives compelling qualitative and quantitative evidence that the hemispheric model and wave-particle scattering provide a good picture of PUI transport in the inner heliosphere. Application of the model allows a measurement of the functional dependence of pitch angle diffusion coefficients on wave power. However, many questions are left to be answered. In particular, the exact form of the relation of the scattering parameter or mean free path to the wave-power as observed in Figure 6.11 remains

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
unexplained. The nature of interactions that scatter pickup ions across the resonant gap is not specified, though the reliance of such an interaction on IMF fluctuations is clear. The applicability of the hemispheric model to other IMF orientations has also not been demonstrated here. There is much room for further work in the arena of PUI pitch angle scattering models which extend this result to more general transport regimes.
In which our pickup ions are accelerated, by the geometry and oscillations of the IMF

In Chapter 6 measured PUI distributions were compared to a transport model based on Equation (2.3), and considering only the pitch angle diffusion term. We now consider diffusion in energy space as well.

2nd Order Fermi Acceleration

It has been suggested [e.g. Fisk, 1976] that energy diffusion of ion velocity distributions is enhanced by the presence of magnetic field fluctuations. Although the details vary, and such phenomenon are described by a number of names (e.g. transit time damping, 2nd order Fermi acceleration, statistical acceleration), the basic concept is similar. Particles can gain or lose energy in a scattering process in which there is an electric field parallel to the particles motion. While the bulk of these particles will gain and lose energy equally, some individual particles will continue to gain energy and become part of the high energy particle population.

A variety of theoretical work has been done on the problem of pickup ion transport and related acceleration by waves and the details of scattering mechanisms [e.g. Isenberg, 1987, Bogdan et al. 1991], but the experimental record in the solar wind remains thin, especially in comparison to the evidence of shock acceleration. Nonetheless, the observation of suprathermal tails in PUI populations even in quiet solar wind suggests that a 2nd order Fermi or stochastic
acceleration mechanism is at work [Gloeckler, 2002], while numeric simulation has shown that such mechanisms could explain these observed tails [e.g. Chalov & Fahr, 1998 & 2002]. Further studies of PUIs near CIRs with Ulysses observed enhanced supra-thermal tail during times of strong IMF fluctuations, again suggesting a statistical acceleration mechanism [Gloeckler et al., 1994; Schwadron et al., 1996].

Observations of Accelerated PUIs

The CTOF dataset shows clear evidence of acceleration or energy space diffusion of the PUIs after their injection into the solar wind. For example, logarithmic energy flux density spectra are shown in Figure 7.1. In this figure the CTOF average is compared to a time period from the dataset with the most prominent acceleration beyond the PUI cutoff velocity. During that time period the spectrum is nearly flat across the instrument energy range, and the expected cutoff at twice the solar wind speed is not visible. This period showed the largest flux of PUIs at speeds above the cutoff velocity observed, and was related to the passage of an interplanetary shock discussed later in this chapter.

In addition, even in the time averaged spectra there is clear acceleration visible in the form of a supra-thermal tail. This tail is clearly observed up to three times the solar wind speed, suggesting that acceleration mechanisms are at work, as this is far above the cutoff including the bulk flow and the thermal velocity of interstellar neutrals.
To work towards identifying the origin of this tail, we used further statistical analysis of the dataset. The first step was to remove the times during which shock acceleration was clearly playing a role in generating the higher energy PUIs. By using a list of interplanetary shocks published by the WIND spacecraft team [see Lin et al., 1995], and maintained by the Berkeley Space Physics Research Group, we removed all time periods around these shocks, and compared this to the spectra obtained by only including shocked solar wind (or time periods near an interplanetary shock). The results are striking as the differences in the suprathermal tail span almost two orders of magnitude, as seen in Figure 7.2. From this figure the efficiency of acceleration by shocks is clear, as predicted by generally accepted models of shock acceleration, or 1st order Fermi acceleration. Shocks are responsible for most of the energetic particle populations, and in this process particles with initial speeds greater than the bulk solar wind speed are preferentially injected [Blanford & Ostriker, 1978; Lee, 1984; Zank et al., 2001].

Figure 7.1. Pickup ion velocity spectrum and suprathermal tail. The energy flux density during the strongest acceleration region (squares) and for the whole dataset (circles) are shown logarithmically versus normalized velocity.
Figure 7.2. Pickup ion velocity spectrum and suprathermal tails are shown for three different sets of solar wind conditions. Times within one hour of a shock (from the WIND shock list) are shown as diamonds, times within six hours of a shock are shown as squares, and times that are not within twelve hours of a shock are shown as circles.

In addition to shocks, strong 1st order Fermi acceleration is predicted to occur in compression regions [Giacalone et al., 2002]. There were some strong acceleration regions visible in the PUI data that did not correspond to WIND shock list events. This can be seen in Figure 7.3, where after removing time periods of known shocks the spectrum becomes softer. Removing other time periods of pronounced PUI acceleration makes the spectrum still softer. The difference in the overall averaged spectra produced by these non-shock events is not large, but is significant, and is consistent with the theory that 1st order Fermi acceleration does occur in compression regions that have not steepened to form shocks.
SOHO/CTOF) are not always associated with the strongest compression ratios ($r$) of shocks or compressions.

Two criteria, the maximum intensity $I_{\text{MAX}}$, defined as the largest flux at speeds above the nominal cut-off over a 15 minute time period, and the total supra-thermal energy flux $E_{\text{TOT}}$, defined here as total energy from PUIs at speeds above the cutoff over the entire event, are listed for each event in Table 7.1. In the table it can also be seen that most PUI acceleration events were observed offset in time from the arrival of a change in proton density. Many other parameters are not listed in the table, for example the steadiness of the acceleration and the IMF properties.
Table 7.1. The Largest Helium PUI acceleration events observed by SOHO/CTOF.

<table>
<thead>
<tr>
<th>DOY (1996)</th>
<th>WIND shocklist</th>
<th>Duration (hrs)</th>
<th>Offset (hrs)</th>
<th>$E_{\text{TOT}}$</th>
<th>$I_{\text{MAX}}$</th>
<th>r(Np)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>93.42</td>
<td>Yes</td>
<td>1.8</td>
<td>-1.2</td>
<td>6007</td>
<td>3280</td>
<td>1.7</td>
<td>SIR</td>
</tr>
<tr>
<td>94.38</td>
<td>Yes</td>
<td>4.1</td>
<td>-0.5</td>
<td>246473</td>
<td>59874</td>
<td>1.4</td>
<td>See Figure 6.9</td>
</tr>
<tr>
<td>99.08</td>
<td>Yes</td>
<td>3.1</td>
<td>-0.4</td>
<td>974735</td>
<td>318462</td>
<td>2.0</td>
<td>See Figure 6.10</td>
</tr>
<tr>
<td>99.53</td>
<td>No</td>
<td>5.8</td>
<td>0.4</td>
<td>250422</td>
<td>94602</td>
<td>2.3</td>
<td>See Figure 6.10</td>
</tr>
<tr>
<td>150.47</td>
<td>No</td>
<td>7.9</td>
<td>n.a.</td>
<td>428077</td>
<td>76953</td>
<td>n.a.</td>
<td>No shock</td>
</tr>
<tr>
<td>170.95</td>
<td>Yes</td>
<td>6.0</td>
<td>4.8</td>
<td>574493</td>
<td>76484</td>
<td>4.2</td>
<td>Magnetic Cloud</td>
</tr>
<tr>
<td>174.50</td>
<td>No</td>
<td>4.3</td>
<td>n.a.</td>
<td>133883</td>
<td>37043</td>
<td>2.0</td>
<td>No shock</td>
</tr>
<tr>
<td>183.55</td>
<td>Yes</td>
<td>10.1</td>
<td>-3.4</td>
<td>846962</td>
<td>55421</td>
<td>1.7</td>
<td>Magnetic Rotation</td>
</tr>
<tr>
<td>185.76</td>
<td>No</td>
<td>0.3</td>
<td>0.0</td>
<td>74872</td>
<td>74872</td>
<td>0</td>
<td>Normalization relic-see text</td>
</tr>
<tr>
<td>198.15</td>
<td>No</td>
<td>9.6</td>
<td>-4.8</td>
<td>331685</td>
<td>59822</td>
<td>2.5</td>
<td>Compressions before &amp; after</td>
</tr>
<tr>
<td>210.49</td>
<td>Yes</td>
<td>7.4</td>
<td>-1.2</td>
<td>1099514</td>
<td>213598</td>
<td>2.2</td>
<td>See Figure 6.11</td>
</tr>
<tr>
<td>212.72</td>
<td>No</td>
<td>7.4</td>
<td>-3.7</td>
<td>1684996</td>
<td>113210</td>
<td>0.8</td>
<td>Radial field. Possible SIR</td>
</tr>
<tr>
<td>225.88</td>
<td>No</td>
<td>9.4</td>
<td>-2.4</td>
<td>813849</td>
<td>78559</td>
<td>3.0</td>
<td>Radial field. SIR</td>
</tr>
</tbody>
</table>

1° column: day of year 1996 of the shock or compression as observed in SW proton data.
2° column: event listed on the WIND interplanetary shock list?
3° column: duration of observed accelerated PUIs.
4° column: the offset in time from the center of PUI acceleration to the SW disturbance (n.a. if exact disturbance time unclear).
5° column: total energy flux for $V_{\text{HE}} > 2.2V_{\text{SW}}$ (keV cm$^{-2}$ sr$^{-1}$) during event.
6° column: peak 15 min. average $V_{\text{HE}} > 2.2V_{\text{SW}}$ energy flux density during event (keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$).
7° column: compression ratio for proton density.

To see the details of the solar wind conditions that underlie a PUI acceleration event, it is necessary to show more parameters than are visible in Table 7.1, and to see the time evolution of the event as observed with SOHO and WIND in bulk SW data as well as PUI spectra. For example, the parameters $E_{\text{TOT}}$ and $I_{\text{MAX}}$ indicate not only the acceleration rate but also the number of PUIs available to be accelerated. Although some effort was made to normalize these parameters to the bulk PUI flux, the large variations of bulk flux observed around acceleration regions made the normalization less useful.
Three strong acceleration regions are included here as Figures 7.4, 7.5, and 7.6, in which the relation of the bulk PUI fluxes to high energy fluxes can be compared. The PUIs observed by SOHO/CTOF are in the bottom panel of these figures and are shown as grayscale energy spectra with normalized velocity on the y axis. Other acceleration times are not included in this thesis but interested readers can find them in the PUI catalog produced as part of this dissertation work, currently available at:


In Figure 7.4, a shock can be seen in the SW speed (top panel) and the proton density (second panel). The helium pickup ion spectrum shows acceleration around the shock, but is not centered around the shock but rather exists predominantly before the passage of the shock. Additional PUI acceleration is seen four hours before the shock arrived at the spacecraft.

The most intense acceleration in the dataset $I_{\text{MAX}}$, defined here as the largest flux at speeds above the nominal cut-off over a 15 minute time period, was observed around an interplanetary shock at DOY 99.08. The duration of that acceleration was only 3.1 hours, and the color-coded spectrum is shown as a function of time in Figure 7.5. The strongest total supra-thermal flux $E_{\text{TOT}}$, defined here as total energy from PUIs at speeds above the cutoff over the entire event, was observed around a compression at DOY 212.72 (Figure 7.6), although the maximum intensity of that event was a factor of three smaller than the DOY 99.08 event.
Figure 7.4. An interplanetary shock as observed by MTOF/PM (solar wind proton data), WIND-MFI (magnetic field), and CTOF (helium PUIs). From the top, the panels show: SW speed, proton density, proton thermal velocity, IMF magnitude and radial component, IMF wave power transverse and parallel to the mean field. The velocity spectrum of He⁺ is shown in grayscale on the bottom panel, with a horizontal dashed line at the nominal cut-off velocity. Accelerated PUIs are observed before the arrival of the first shock (dashed line).
Figure 7.5. Two interplanetary shocks observed on April 8, 1996. For panel descriptions see Figure 7.4. The first shock corresponds to the most intense (see text) tail EFIux in the dataset, which appears before the compression of the bulk PUls visible in the bottom panel.
Figure 7.6. A SIR, shock, and associated strong PUI acceleration as observed on July 28, 1996. For panel descriptions see Figure 7.4.

Figures 7.4-7.6 and Table 7.1 show that PUI acceleration does not behave in an easily predictable manner, and depends on effects not usually included in
simple shock acceleration models. More work is necessary to determine shock geometries and histories that determine such acceleration in order to more accurately predict energetic particle populations around interplanetary disturbances. However we have attempted a statistical evaluation to determine whether the tails, after a subtraction of the known acceleration events, correlate with wave activity.

**Acceleration by IMF Fluctuations and Waves**

To determine the extent that 2\textsuperscript{nd} order Fermi processes are effective on the accelerated PUI population observed by CTOF, we first duplicated the analysis for 1AU that had been performed in CIRs with Ulysses [Schwadron et al., 1996]. We used 15 minute magnetic field averages to determine the relative level of fluctuations of the magnitude of the IMF, comparing them to the sliding 12 hour mean field. We follow [Schwadron et al., 1996] and call the level of fluctuations determined in this way \( \eta \):

\[
\eta = \frac{|B - \bar{B}|}{|\bar{B}|}
\]  

(7.1)

We then binned helium energy flux spectra in different ranges of this parameter to see what the effects of relative fluctuations are on the supra-thermal tails. The results are shown in Figure 7.7.
require. To examine the specific effects of resonant wave power we pursued a separate analysis designed to specifically capture resonant wave power.

We examined logarithmic PUI flux spectra obtained by combining times of similar background wave-powers as determined with three second data from WIND in a superposed epoch analysis. The determination of the wave spectra by minimum variance analysis was identical to the analysis described in Chapter 6 as related to determination of pitch angle scattering. Times within 12 hours of a shock (as determined by the published WIND shock list) were excluded from the spectra, in order to isolate the effects of resonant wave-particle interactions from those of shock acceleration. The results are shown in Figure 7.8, where three spectra are shown for different ranges of resonant transverse wave-power.
index of the diffusion coefficient in attempts to observe a correlation with PUI supra-thermal tails. The index used was calculated as:

\[ D_{yv}^* \frac{[B]}{P_{TR}} = \alpha D_{yv} \]  

where the star indicates that this is not an actual calculation of the momentum diffusion coefficient but merely a proxy, differing from the actual value by an undetermined factor \( \alpha \) which could be a function of pitch angle as well as other quantities involved.

While the wave-power is the active mechanism for scattering the particles (in energy space), other parameters affect the diffusion coefficient as it is calculated in the literature [Wibberenz et al., 1969, see also Möbius et al., 1982; Chalov & Fahr, 1998], such as the magnetic field strength and the proton density. We repeated the superposed epoch analysis, removing shocks from the WIND shock list as before, using this proxy instead of just the transverse resonant wave-power \( P_{TR} \). The results, which are shown in Figure 7.10., still did not show different PUI spectral characteristics for different ranges of the momentum diffusion index.
The solar wind speed itself is also a potential indicator of 2\textsuperscript{nd} order Fermi acceleration by IMF waves, as in slower solar wind the PUIs have more time to diffuse in energy space. Thus, one might expect stronger supra-thermal tails to be observed during times of slower solar wind speed. To look for this effect, a superposed epoch analysis was performed on the PUI normalized velocity spectrum. The resulting spectra again showed a null result, in that the PUI spectra for different ranges of $V_{\text{SW}}$ showed almost identical shape.

**Conclusions**

Strong acceleration of interstellar pickup ions was observed on numerous occasions by SOHO/CTOF, the strongest of which were tabulated in Table 7.1. Almost all of these time periods corresponded with the passage of an interplanetary shock. However, the characteristics of the shocks (such as compression ratio) were poor predictors of the PUI acceleration characteristics. This suggests that the simple planar and time independent models of interstellar shocks are not accurate enough for predicting detailed time profiles and energy characteristics of high energy particle populations. Acceleration was also observed during compression regions which had not steepened to form a shock, confirming the idea of 1\textsuperscript{st} order Fermi acceleration by compressions presented in [Giacalone et al., 2002].

The presence of supra-thermal tails during quiet interplanetary conditions was also observed, though at greatly reduced levels. Initial analysis suggested that IMF fluctuations were correlated with these tails. However, PUI spectra obtained through two and a half orders of magnitude in resonant wave-power showed similar high energy tails. Other analyses of the Alfvén speed to solar wind speed
ratio and the solar wind speed itself showed only small changes in the He$^+$ velocity distribution. We conclude that mechanisms other than 2$^\text{nd}$ order Fermi scattering by resonant waves are required to explain quiet-time supra-thermal tails on the PUI distributions.
CHAPTER 8

RESULTS AND CONCLUSIONS

Review of Results

The main motivation behind this work has been a better understanding of the physical processes that cause observed PUI flux variations. To this end we have worked with the hypothesis that the variations are caused by transport effects induced by the solar wind. The hypothesis has been quite successful, with co-measured solar wind parameters showing strong correlations to PUI fluxes observed with SOHO/CTOF. For example, the existence of compression regions in the solar wind was found to greatly influence PUI distributions. Strong correlations were found between PUI energy flux density and both solar wind proton density and magnetic field strength. In addition, the onset of a compression region with a magnetic field discontinuity was found to affect the PUI distribution adiabatically via a shift in the cutoff velocity.

An observation of similar character to the aforementioned cutoff shift is the change to the PUI distribution produced by a non-zero injection velocity of interstellar neutrals. This effect enables another estimate of the LISM velocity [Möbius et al., 1999]. Further study of PUI distributions merited compensating for this effect when constructing superposed epoch spectra.
An important process in shaping PUI velocity distributions is pitch angle scattering, as the ions are injected into the solar wind with an anisotropic distribution. Although the CTOF instrument did not record the angular distribution of PUI fluxes, information about pitch angle isotropy was obtained in this work from the energy spectra. In particular, data taken during radial magnetic field showed that pitch angle anisotropy was reduced at times of higher IMF wave-power. This observation confirms the hypothesis that pitch angle scattering of PUIs can be caused by Alfvénic fluctuations [Saul et al., 2004]. Diffusion coefficients and mean free paths for pitch angle scattering were calculated using a hemispheric model of pitch angle diffusion. The observations showed a deviation from simple quasi-linear wave-power dependencies for low wave-power.

PUIs are also efficiently accelerated as they move out through the heliosphere. Strong acceleration was found to occur near shocks and compression regions, confirming theories of shock acceleration and also 1st order Fermi acceleration by compression regions [Giacalone et al., 2002]. However, the amount of acceleration during such events was not easily predictable from solar wind parameters. This observation points to complex dynamics of shocks and solar wind structures.

In addition to acceleration by shocks and solar wind disturbances, we observed a supra-thermal tail present even in quite times, consistent with other measurements [e.g. Gloeckler, 2002]. However, we did not find the strength of this tail to correlate with resonant IMF wave-power in the solar wind, contrary to
Open Questions for Further Research

Despite the success of the hypothesis that solar wind transport causes PUI flux variations, many unexplained variations exist. It remains difficult to predict PUI fluxes, using only co-located solar wind and magnetic field measurements. A simple attempt to smooth the PUI energy flux data based on a linear dependence to solar wind proton density and to IMF orientation and wave-power reduced the deviation by only 30%. However, some of the remaining variations are still without any explanation at this time.

While this research was successful in observing the role played by IMF waves in pitch-angle scattering, the details of the interaction leave much room for further work. With improved measurements of PUI velocity distributions, for example with multiple sectors giving angular information about incoming ions, much more detailed analysis will be possible. In addition, a more detailed knowledge of the IMF waves would be valuable, for example in determination of the contribution of various wave-modes or wave-vectors to pitch angle diffusion coefficients. There is also much room for improvement in the modeling of PUI distributions. For simplicity we considered here static models of the global IMF, for example assuming that a measured radial field implies that the field was radial throughout the path of a PUI. More realistic models would include the twists and turns of the IMF as it makes its way from the inner heliosphere [see e.g. Isenberg & Lee, 1998].
REFERENCES


Mohr, E., Y. Litvinenko, H. Grünwaldt, M. R. Aellig, A. T. Bogdanov, F. M.
Ippich, P. Bochsler, M. Hilchenbach, D. L. Judge, B. Klecker, M. A. Lee and H.
Ogawa (1999). "Direct evidence of the interstellar gas flow velocity in the pickup
ion cut-off as observed with SOHO CELIAS CTOF." Geophysical Research
Letters 26(20): 3181.

parameters of the very local interstellar medium as derived from the distribution

interstellar pickup ion distributions in the solar wind with SOHO and Cluster." 
Annales Geophysicae 14: 492-496.

antisunward flux of interstellar pickup He+ associated with radial interplanetary

helium and heavy ion spectra in 3He-rich solar flares with model calculations
based on stochastic Fermi acceleration in Alfvén turbulence." Astrophysical
Journal 259: 397-410.

results from the Helios-1 search-coil magnetometer experiment." Zeitschrift fuer
Geophysik 42(61: 599-614.


distribution of interstellar pickup ions: Direct observation," Geophysical Research
Letters 29(12): 1612.

Sokolov and G. Toth (2003). "Probing the edge of the solar system: formation of

Owens, M. J. and P. J. Cargill (2002). "Correlation of magnetic field intensities
and solar wind speeds of events observed by ACE." Journal of Geophysical
Research 107(A5): SSH 1-1.

Paresce, F. and S. Bowyer (1973). "Resonance Scattering from Interstellar and


with the local interstellar medium." Journal of Geophysical Research 100(A11):
21595-21604.


APPENDIX A

Documented here are software packages and data products used during this thesis work. Further details on the implementation of these packages are included with the software itself, including documentation on both the source code and the data used, currently available at:

ftp://www-ssq.sr.unh.edu/pub/lsaul/.

The material is divided into two main packages described below.

CTOFGui

This package contains most of the utilities used to analyze the helium events observed by SOHO/CTOF. The routines that calculate the flux based on instrument geometry are here, as well as the routines that create superposed epoch histograms in bins of normalized velocity. The raw data from the telemetry is converted to binary format for enhanced speed of analysis and to save storage space. A graphical user interface (GUI) is built in the main class, CTOFGui, while the calculations are carried out in the separate class CTOFHistogrammer. Various data readers are used to read binary files with the SW parameters. This GUI was of great use in speeding up data analysis, for the many different filtering criteria needed. Other classes here are used to read data from various ancillary datasets, to modify the superposed epoch analyses. The data products read and analyzed by this program are listed in Table A1. Output from this class is mostly text based, although some routines for generating spectra, both line and color plots, are included. These utilities are built using the Scientific Graphics Toolkit
This package contains routines written to model interstellar PUI distributions. Neutral distributions are calculated based on the hot model (see Chapter 2), and the class Hemispheric which models hemispheric pitch angle transport resides here (see Chapter 6). No GUI class exists for this package. The package PICKSIM, including routines created by E. Möbius, A. Bogdanov, D. Rucinski, M. Bzowski, and others, was also used to model PUI distributions for this dissertation.

Solar Wind Parameters

In analyzing the PUI flux data, many separate ancillary data products were used for comparison with He⁺ measurements and to build superposed epoch spectra. These parameters are listed here with some explanation on their origin and purpose, in Table A1. The reference numbers used in coding were chosen to reflect the primary data source. All listed parameters are available as a time series.
<table>
<thead>
<tr>
<th>Name</th>
<th>Ref.</th>
<th>Sources</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLAR</td>
<td>1</td>
<td>WIND/MFI</td>
<td>Polar angle of IMF in GSE cords.</td>
</tr>
<tr>
<td>AZIMUTH</td>
<td>2</td>
<td>WIND/MFI</td>
<td>Azimuthal angle of IMF in GSE coords.</td>
</tr>
<tr>
<td>MAGNITUDE</td>
<td>3</td>
<td>WIND/MFI</td>
<td>IMF magnitude in (nT).</td>
</tr>
<tr>
<td>ALFVEN</td>
<td>4</td>
<td>WIND/MFI + MTOF/PM</td>
<td>Alfvén speed</td>
</tr>
<tr>
<td>ALFVEN_RATIO</td>
<td>5</td>
<td>WIND/MFI + MTOF/PM</td>
<td>Alfvén to solar wind speed ratio</td>
</tr>
<tr>
<td>ANGLE_TO_RADIAL</td>
<td>6</td>
<td>WIND/MFI</td>
<td>IMF angle to radial (0-90 degrees)</td>
</tr>
<tr>
<td>B_RADIAL_COMPONENT</td>
<td>7</td>
<td>WIND/MFI</td>
<td>Component of IMF in ecliptic</td>
</tr>
<tr>
<td>DELTA_B</td>
<td>8</td>
<td>WIND/MFI</td>
<td>Fluctuation of</td>
</tr>
<tr>
<td>AV_MAG</td>
<td>9</td>
<td>WIND/MFI</td>
<td>12 hour sliding average</td>
</tr>
<tr>
<td>AV_DENSITY</td>
<td>10</td>
<td>WIND/MFI</td>
<td>Solar wind velocity (km/s)</td>
</tr>
<tr>
<td>VELOCITY</td>
<td>101</td>
<td>MTOF/PM</td>
<td>Proton Density (cm⁻³)</td>
</tr>
<tr>
<td>DENSITY</td>
<td>102</td>
<td>MTOF/PM</td>
<td>Proton Density (cm⁻³)</td>
</tr>
<tr>
<td>THERMAL_VELOCITY</td>
<td>103</td>
<td>MTOF/PM</td>
<td>SW proton thermal speed (km/s)</td>
</tr>
<tr>
<td>VELOCITY_WIND</td>
<td>104</td>
<td>WIND/SWE</td>
<td>SW velocity measured by WIND (km/s)</td>
</tr>
<tr>
<td>DENSITY_WIND</td>
<td>105</td>
<td>WIND/SWE</td>
<td>Proton density measured by WIND (cm⁻³)</td>
</tr>
<tr>
<td>THERMAL_VELOCITY</td>
<td>106</td>
<td>WIND/SWE</td>
<td>SW proton thermal speed at WIND (km/s)</td>
</tr>
<tr>
<td>FLUX</td>
<td>201</td>
<td>SOHO/CTOF</td>
<td>Flux of He⁺ (cm⁻³s⁻¹sr⁻¹keV⁻¹)</td>
</tr>
<tr>
<td>TAIL</td>
<td>202</td>
<td>SOHO/CTOF</td>
<td>Integral EFlux above a specified cutoff velocity</td>
</tr>
<tr>
<td>EFLUX</td>
<td>203</td>
<td>SOHO/CTOF</td>
<td>EFlux of He⁺ (cm⁻³s⁻¹sr⁻¹)</td>
</tr>
<tr>
<td>INTEGRAL_FLUX</td>
<td>204</td>
<td>SOHO/CTOF</td>
<td>EFlux over specified velocity range</td>
</tr>
<tr>
<td>CUTOFF</td>
<td>205</td>
<td>SOHO/CTOF</td>
<td>EFlux over specified velocity range near cutoff</td>
</tr>
<tr>
<td>ADIABATIC_INDEX</td>
<td>206</td>
<td>SOHO/CTOF</td>
<td>Fit of spectra to model of adiabatic cooling</td>
</tr>
<tr>
<td>TAIL_PARAM</td>
<td>207</td>
<td>SOHO/CTOF</td>
<td>Tail flux divided by bulk PUI flux</td>
</tr>
<tr>
<td>TAIL_POWER</td>
<td>208</td>
<td>SOHO/CTOF</td>
<td>Power law fit to high energy tail</td>
</tr>
<tr>
<td>CUTOFF_FIT</td>
<td>209</td>
<td>SOHO/CTOF</td>
<td>Least square fit to step function</td>
</tr>
<tr>
<td>FLUX_SMOOTHED_1</td>
<td>210</td>
<td>SOHO/CTOF + MTOF/PM</td>
<td>PUI EFlux detrended with linear dependence on proton density</td>
</tr>
<tr>
<td>FLUX_SMOOTHED_2</td>
<td>211</td>
<td>SOHO/CTOF + MTOF/PM + WIND/MFI</td>
<td>PUI EFlux detrended with linear dependence on proton density, IMF orientation, and wave-power</td>
</tr>
<tr>
<td>DOY</td>
<td>301</td>
<td></td>
<td>Day of year</td>
</tr>
<tr>
<td>PAR_INTERCEPT</td>
<td>403</td>
<td>WIND/MFI</td>
<td>Wave-power in parallel fluctuations from spectral fit</td>
</tr>
<tr>
<td>PAR_INDEX</td>
<td>404</td>
<td>WIND/MFI</td>
<td>Power index of wave-power in parallel fluctuations.</td>
</tr>
<tr>
<td>TR_INTERCEPT</td>
<td>405</td>
<td>WIND/MFI</td>
<td>Wave-power in transverse fluctuations from spectral fit</td>
</tr>
<tr>
<td>TR_INDEX</td>
<td>406</td>
<td>WIND/MFI</td>
<td>Power index of wave-power in transverse fluctuations.</td>
</tr>
<tr>
<td>TR/PAR_INTERCEPT</td>
<td>407</td>
<td>WIND/MFI</td>
<td>Ratio of wave-power in parallel fluctuations to transverse fluctuations.</td>
</tr>
<tr>
<td>D_VV_INDEX</td>
<td>408</td>
<td>WIND/MFI + MTOF/PM</td>
<td>Parameter to approximate energy diffusion coefficient from simple theory (see text)</td>
</tr>
<tr>
<td>ELECTRON_PARAM</td>
<td>501</td>
<td>WIND/3DP</td>
<td>Electron impact ionization rate</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.