Changes In the Pickup Ion Velocity Distribution Due to Solar Wind Compression and Interplanetary Shocks

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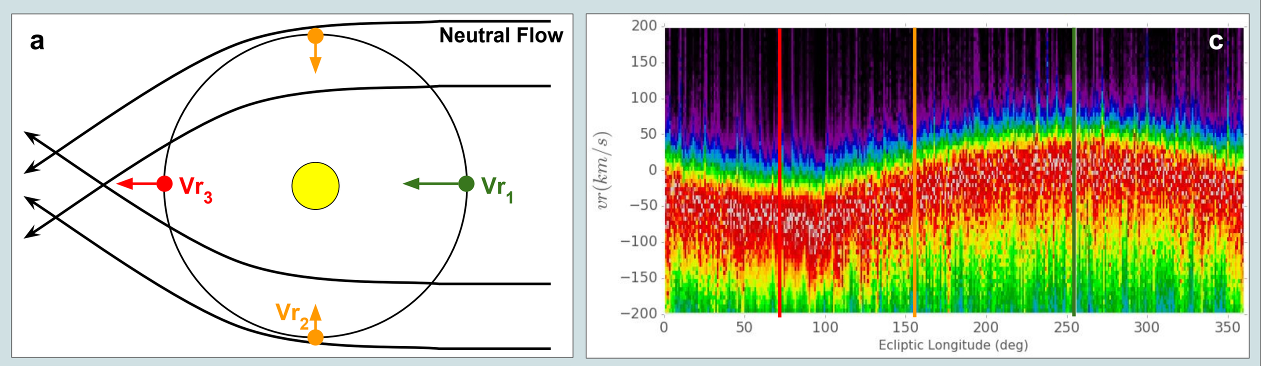
Introduction

IBEX measurements of the interstellar flow parameters yield a four dimensional parameter tube coupling the inflow longitude, latitude, speed and temperature (see Poster SH13-C2964). It has been shown by Moebius et al. (2015) that the pickup ion (PUI) cutoff shift variation in ecliptic longitude can be used as a potentially highly accurate method for measuring the inflow longitude of the ISM, in conjunction with the IBEX measurements, to reduce error for all inflow parameters. However, Saul et al. (2003) found that the PUI velocity distribution function can be modulated by rapid changes in the local solar wind. This study is motivated by the attempt to remove or correct for these effects on the determination of the inflow longitude. At the same time, this study will shed light on the physical mechanisms that lead to energy transfer between the SW and the embedded PUI population.

PUI Cutoff Variation



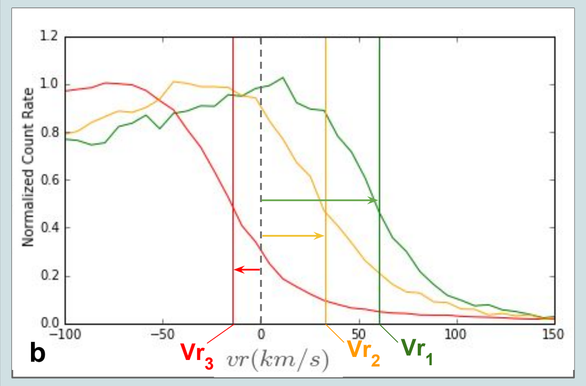


Figure 1: (a) Sample neutral particle trajectories under the influence of the Sun's gravitational pull, leading to a longitudinal dependence of the neutral particle radial speed. (c) Sample velocity distribution functions from three different ecliptic longitudes, with the largest shift in neutral radial speed exactly upwind. (b) He$^+$ VDFs arranged in ecliptic longitude, showing longitudinal dependence associated with the radial neutral injection speed.

- The incoming neutral radial speed, and in turn the PUI injection velocity, changes with ecliptic longitude due to gravitational lensing.
- He$^+$ PUI observations are sampled from 2007-2014 with STEREO A PLASTIC
- To evaluate the interstellar gas flow it is most appropriate to use v_r, a quantity which reflects the radial component of the neutral velocity vector (v_n). *v_r is defined as:*

$v_r = (v_{ion})_r - v_{sw}$: where $(v_{ion})_r$ is the radial ion speed and (v_{sw}) is the solar wind speed

- The cutoff is determined through integrating the PUI distribution over time and finding the point of steepest descent in the Velocity Distribution Function (VDF).
  - Here v_r is identified by finding the location of ½ the peak height of the smoothed, interpolated VDF.
- Even for freshly injected PUIs, the speed can be additionally through heating processes, produced by Stream Interaction Regions (SIRs), Coronal Mass Ejections (CMEs) or turbulence.
- SIRs occur when fast solar wind rams into preceding slow solar wind, resulting in a heating of the intermittent plasma

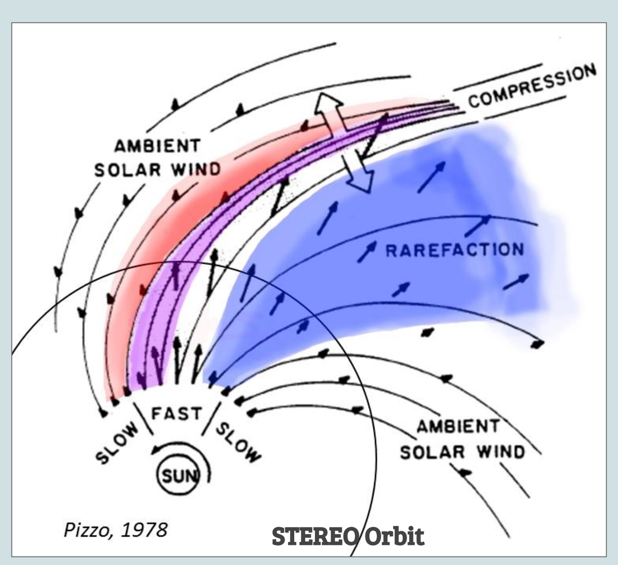


Figure 2: Schematic view of a SIR, showing general regions of compression and rarefaction (Red for the compressed slow wind, purple for the compressed fast wind, and blue for the rarefaction region)

- To isolate SW related effects, the longitudinal dependence is removed according to modeled cutoff shifts [Moebius et al. 2015, Lee et al., 2015] and normalized to the solar wind speed. He$^+$ PUIs are resolved using the parameter w^*. Defined as:

$$w^* = (v_r - v_{r\,calc})/v_{sw}$$

Here (v_r) is the measured radial cutoff speed and $(v_{r\,calc})$ is the expected radial cutoff speed

Goals

- Identify the evolution of the PUI VDF across SPE compression regions and shocks
- Identify possible correlations between compressive strength and PUI heating
- Find criteria to correct for or remove compression regions
- Gain understanding of physics behind the changing PUI VDF

PUIs in a SPE Compression

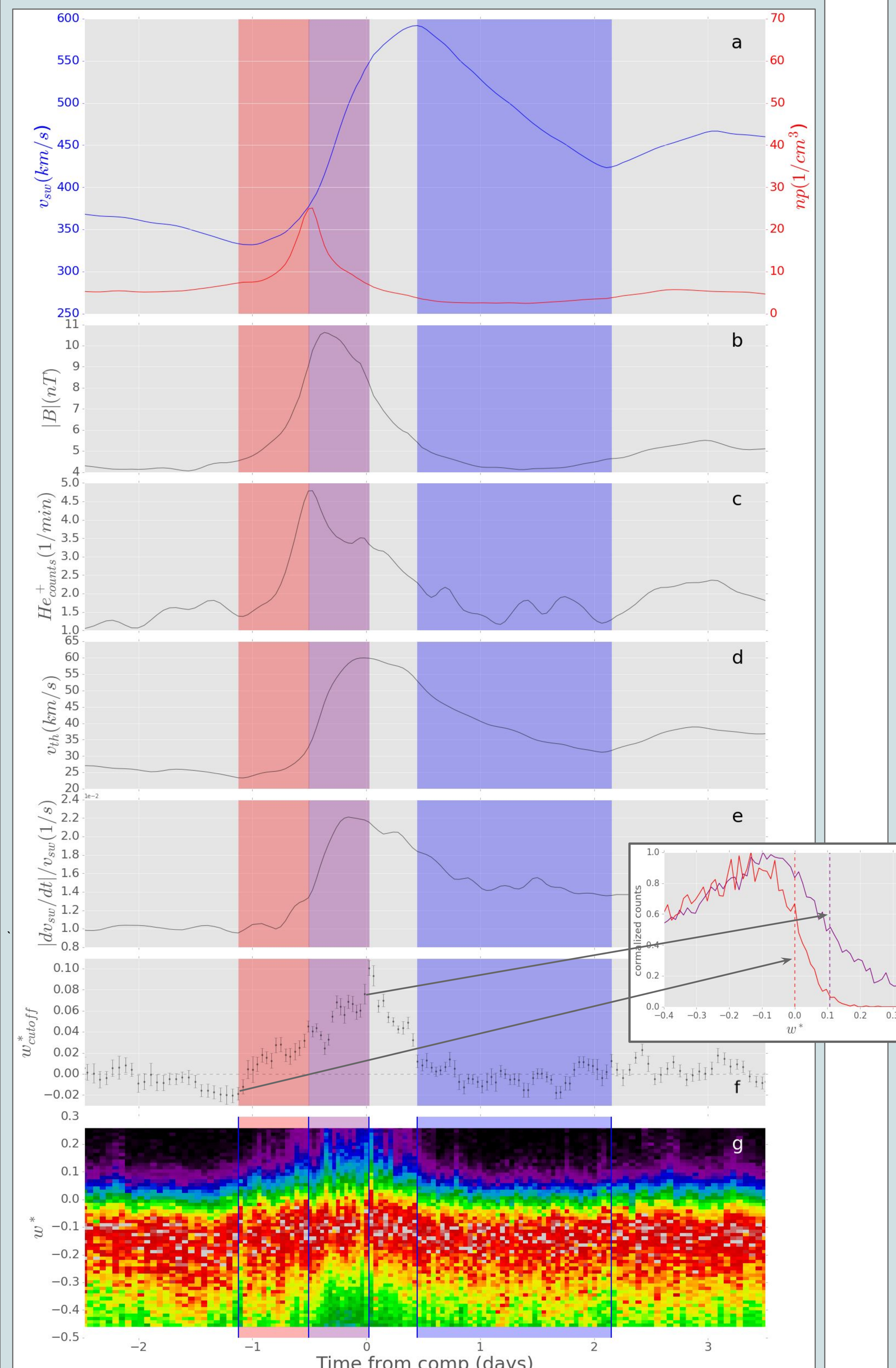


Figure 3: Average temporal evolution across the superposition of compression regions, shown here for, SW velocity (a, blue), density (a, red), magnetic field strength (b), PUI count rate (c), kinetic temperature (d), the magnitude of the fast local solar wind speed fluctuation (e), PUI cutoff (f) and PUI VDF. Shown is the result from an SPE analysis of 100 compression regions selected for large total increase in solar wind speed. Color coding follows Figure 2 (Indicating the compressed slow wind (red), compressed fast wind (purple) and rarefaction region (blue))

- A Superposed Epoch analysis (SPE) allows for the accumulation of PUI measurements under similar solar wind conditions, thus improving statistics. This technique enables the study of variations in compression parameters and their effects on the cutoff at short time scales.
- The compression region is characterized by increasing solar wind speed, which contains peaks in density and field strength, as well as high average PUI count rate and strong gradients in local solar wind speed.
- We see a large positive cutoff shifts that increase through the compression region and persist half a day into the rarefaction (where the solar wind is expanding and adiabatically cooling).
- Heating signatures in the rarefaction region imply the existence of substantial transport or non adiabatic heating processes.
  - Due to He$^+$ limited mobility, and the high fast local solar wind speed fluctuations, this heating is likely driven by turbulence.

PUIs in SPE Shocks

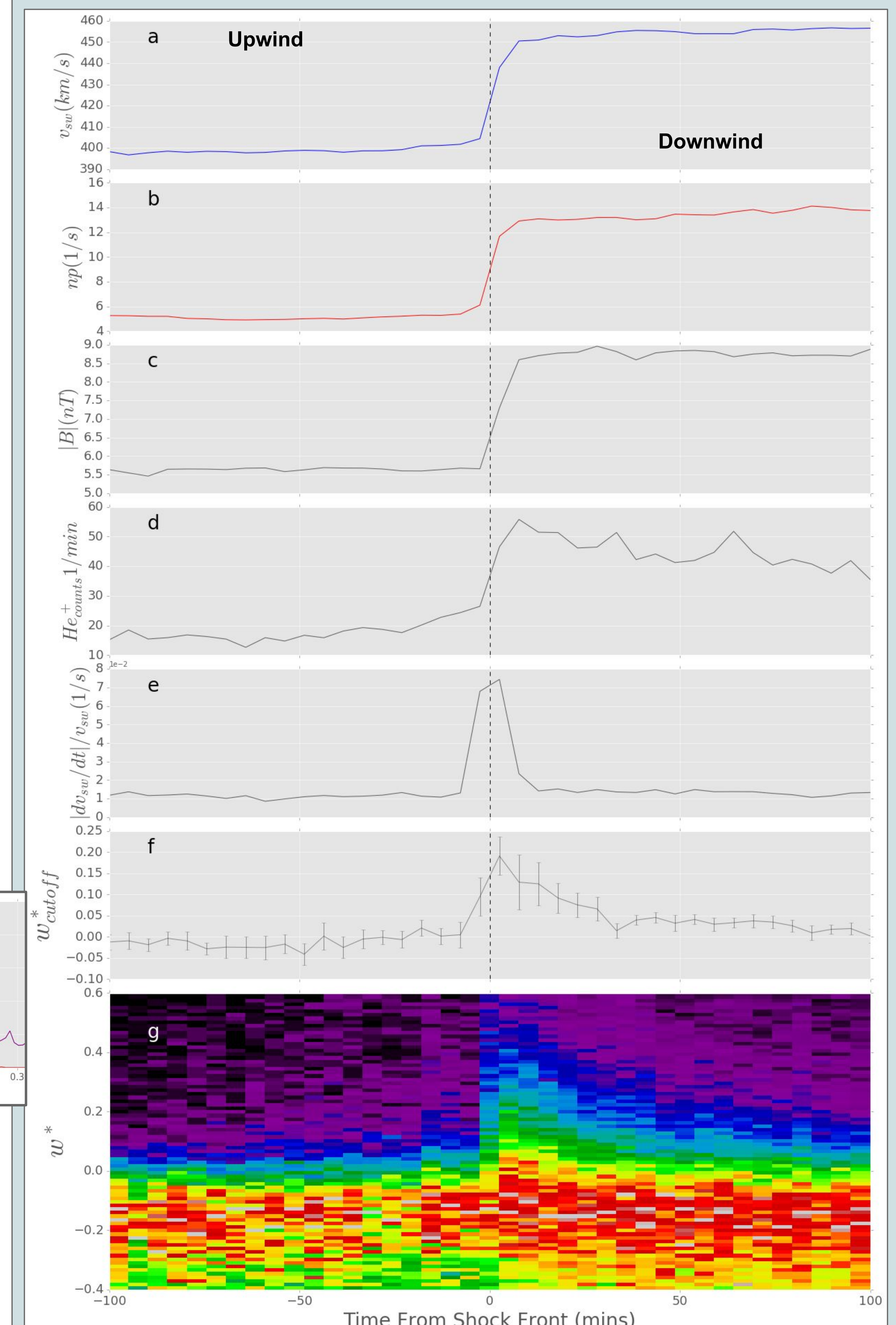


Figure 4: Average temporal evolution across the superposition of fast interplanetary shocks, shown here for, SW velocity (a), density (b), magnetic field strength (c), PUI count rate (d), the magnitude of the fast local solar wind velocity gradient (e), PUI cutoff (f) and PUI VDF (g). Measurements are accumulated in the shock frame.

- Fast collisionless shocks lead to some of the most substantial acceleration processes that are observed in the solar wind.
- The vast majority of interplanetary shocks are the result of compressive interactions driven by stream interaction regions or coronal mass ejections
- Shocks are characterized directionally, where forward shocks are propagating into the slow wind and reverse shocks into the fast wind.
  - Forward shocks are most frequent because they also occur in front of CMEs
- Forward and reverse shocks are accumulated in an SPE analysis in the shock frame, with the shock crossing as the epoch.
  - Shock list provided by STEREO team
    - 154 forward, 41 reverse shocks
- Solar wind parameters show strong discontinuities at the shock crossing where there is strong adiabatic heating and turbulence.
- PUI heating is most substantial at the shock crossing, but is observable up to one hour into the downstream region.

SPE Parameter Relations

SPE Compression Region Results

- To identify the cutoff dependence on compression strength, PUIs are accumulated according to the average solar wind speed gradient in each region (compressed slow,compressed fast, rarefaction).

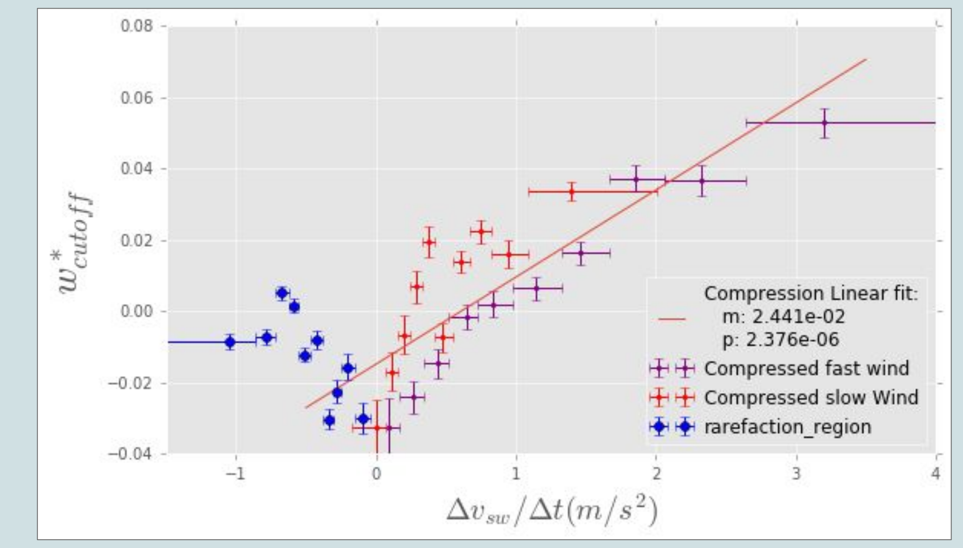


Figure 5: Variation of the PUI cutoff shift as a function of the speed of the compression v_{sw} increase in the compressed slow (red) and fast wind (purple), and the steepness of v_{sw} in the rarefaction region (blue).

- The PUI cutoff shift is correlated with the strength of the solar wind speed increase across the compression.
  - Both compressed slow and fast wind show a similar dependence on the gradient.
- In the rarefaction region, one would expect to see cooling of the PUI VDF, instead heating is observed for the first ⅓ of the rarefaction.

SPE Shock Results

- Shock parameter dependence is investigated using the speed jump across the shock and the onset time (~10min) which is equivalent to the compression strength above

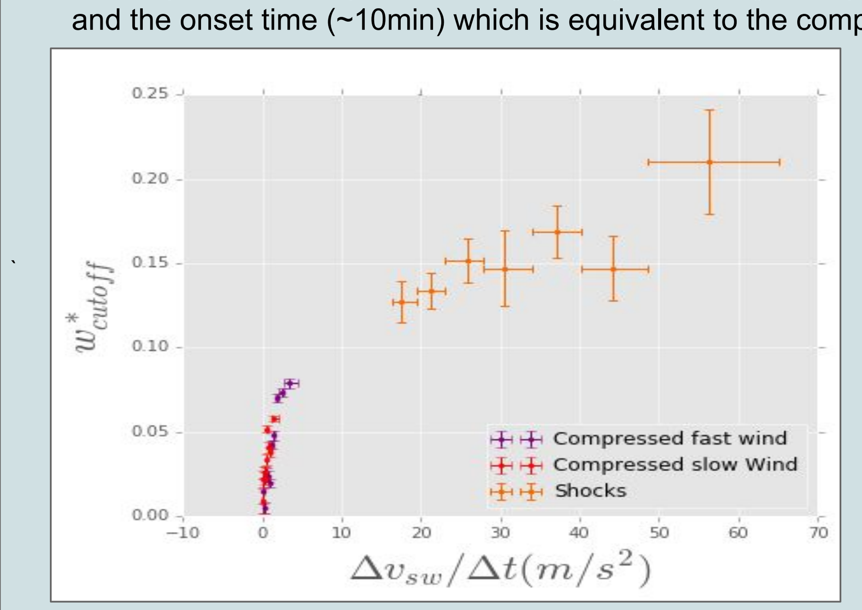


Figure 6: Variation of the PUI cutoff shift as a function of the speed jump across SPE shock, displayed in comparison to heating trends in the compressed slow and fast wind.

- Cutoff shift increases approximately linearly with speed jump across shock
- Shock transition results in more substantial heating than across compression.

Conclusion

- The highly dynamic environment of the SW substantially influences the PUI cutoff, even when viewing freshly injected particles.
- Restriction of the PLASTIC viewing of the PUI torus to quasi perpendicular field orientations may lead to selection bias when studying heating mechanisms.
- The PUI cutoff shift increases with the magnitude of the solar wind speed increase across compressions as well as IP shocks.
- Positive cutoff shifts in the SPE rarefaction regions imply substantial transport effects, or turbulent heating processes.
  - Due to the PUI limited mobility, turbulent heating is more likely.
- Both SPE shocks and compressions exhibit signs of adiabatic and turbulent heating.
- If magnetic heating is the primary reason for the increase in cutoff value, why is that not directly reflected in the PUI VDF across the SIR?
- Further analysis and simulation is needed to decouple the heating processes observed in the compression regions.

References & Acknowledgements

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