Changes In the Pickup Ion Cutoff Under Variable Solar Wind Conditions

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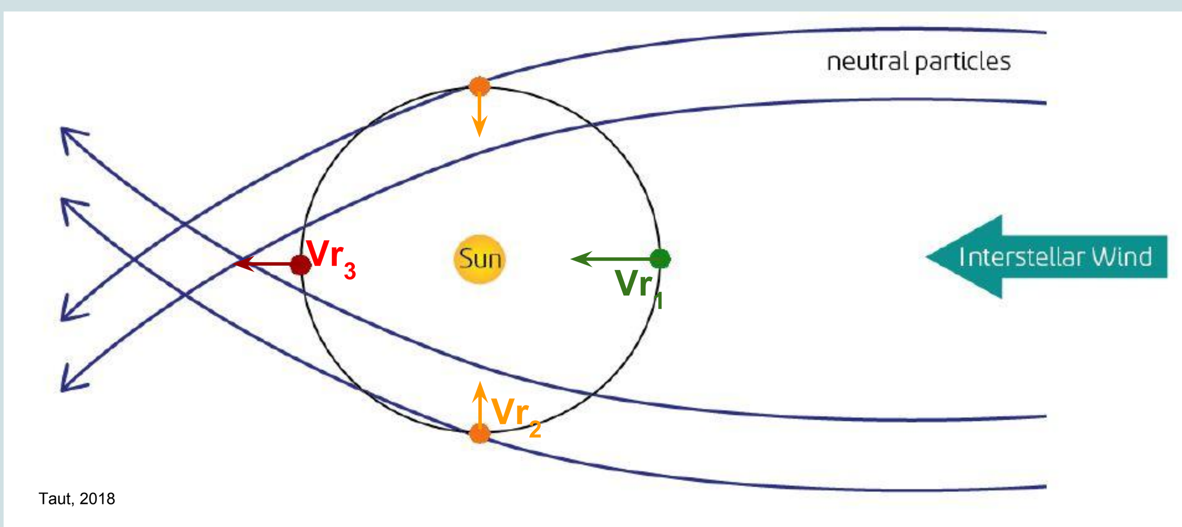
Introduction

IBEX measurement of the interstellar flow parameters yield a four dimensional parameter tube coupling the inflow longitude, latitude, speed and temperature. 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 of all of the inflow parameters. Additionally, It has been shown by Saul et al. (2003) 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 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.

The PUI cutoff



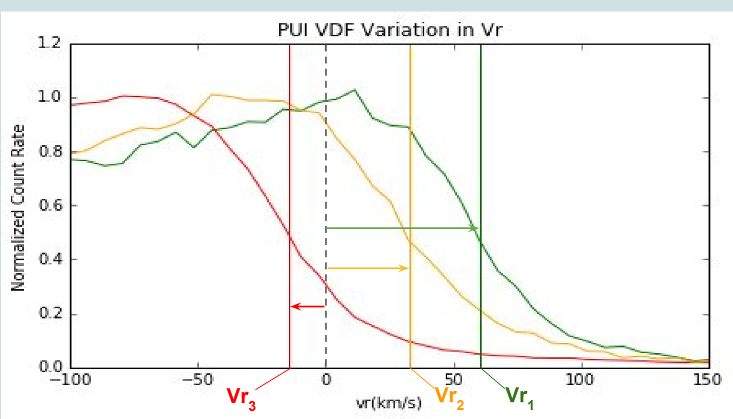


Figure 1: (Top) Sample neutral particle trajectories under the influence of the sun's gravitational pull, giving rise to longitudinal dependence of the neutral particle radial speed. (Left) Sample velocity distribution functions from three different ecliptic longitudes, with the largest shift in neutral radial speed exactly upwind

- PUI observations are sampled from 2007-2014 using 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 incoming neutral radial speed changes with ecliptic longitude due to gravitational lensing, allowing for measurement of the neutral flow direction.
- The cutoff as a function of v_r is determined through integrating PUI measurements and finding the point of steepest descent in the VDF.
  - This point can be identified through fitting, or numerical methods. Here Vr is identified by finding the location of ½ the peak height of the smoothed, interpolated VDF.
- The speed of even freshly injected PUIs can be additionally modified through heating processes such as stream interaction regions (SIR) in the solar wind that must be accounted for.
- SIRs occur when fast solar wind rams into preceding slow solar wind, resulting in a heating of the intermittent plasma

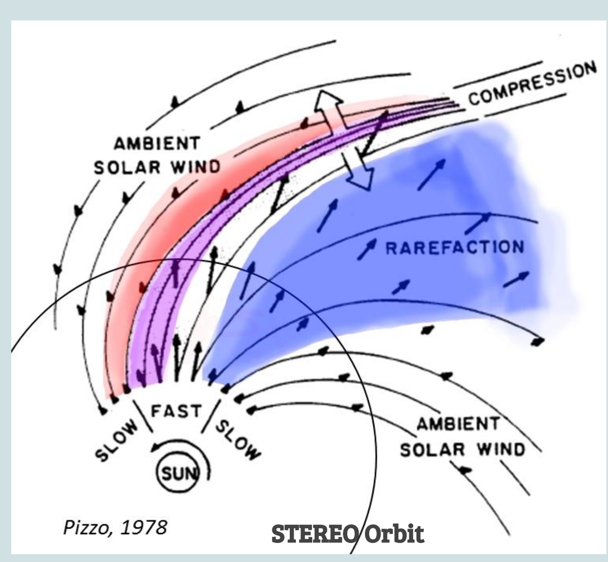


Figure 2: SIR, showing general regions of compression and rarefaction shown as red for the compressed slow wind, purple for the compressed fast wind and blue for the rarefaction region.

Goals

- Programmatically identify stream interaction regions
- Identify the evolution of the PUI VDF across these stream interaction regions
- 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

Identifying Compression Regions

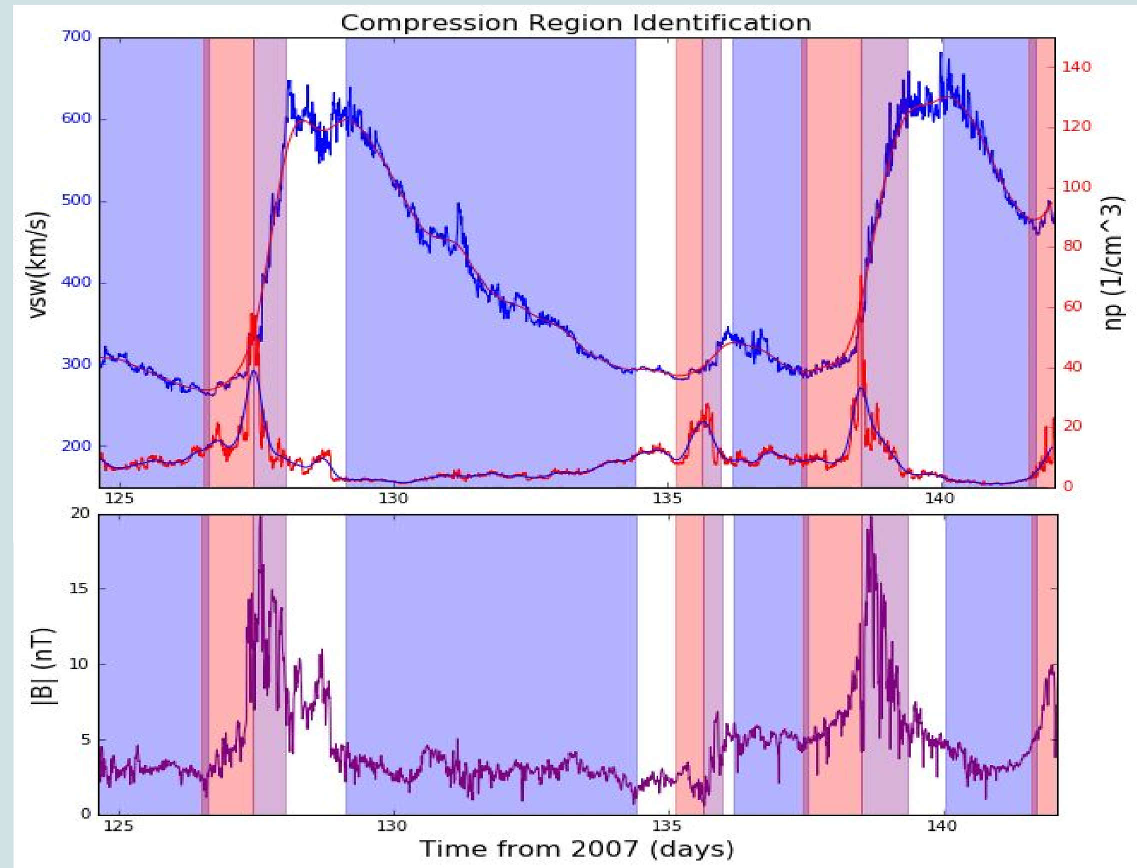


Figure 3: 5 compression regions, as seen in the solar wind velocity, the solar wind number density and magnetic field strength. The colored regions represent: Compressed slow wind (red), compressed fast wind (purple) and the rarefaction region (blue).

- Compression regions are identified explicitly using hard coded criteria utilizing the solar wind speed and number density.
  - Perform smoothing of np and vsw, every 10 pts (50mins)
  - Identify approximate stream interface (large isolated peaks in the number density) [Gosling et al., 1996]
  - Integrate PUI measurements in regions of increasing SW speed, separated by the stream interface
    - Prior to the stream interface: compressed slow SW (Red)
    - Following the stream interface: compressed fast SW (Purple)
- PUIs are accumulated in the rarefaction region (Blue) in order to Identify the effect of SW cooling
- Compression region strength is characterized using: Δnp, ΔVsw, ΔVsw/Δt, and ΔB

Average SIR

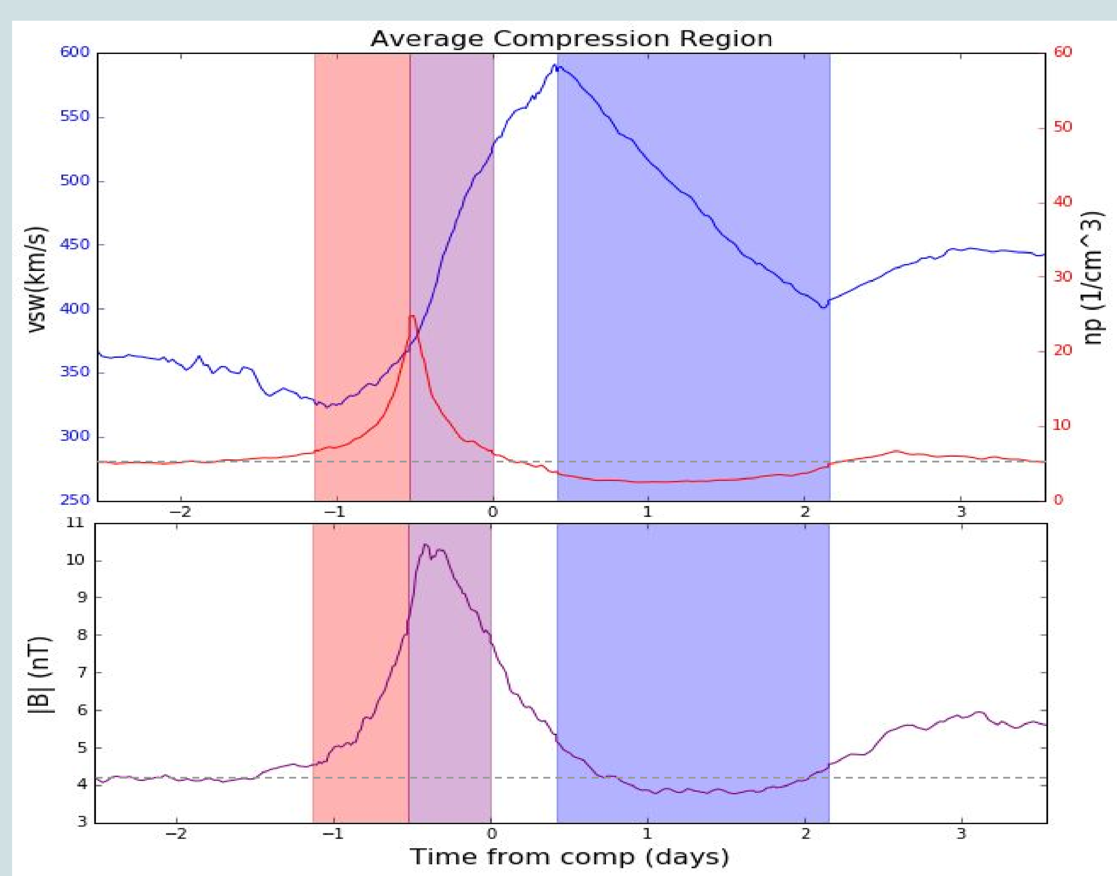


Figure 4: A typical SIR, defined in Vsw, np and B, created by a superposed epoch analysis of the top 20% (largest dvsw_dt) of the identified compressions.

- A superposed epoch analysis (SPE) of a typical SIR, allows for the accumulation PUI measurements with similar solar wind conditions, improving statistics, and allowing for the study the effects of viations of compression parameters on the cutoff at small time scales.
  - The longitudinal dependence is removed according to modeled cutoff shifts (Lee et al) in order to isolate the effect of the compression referred to as vr_{demod}

Defined as:

$vr_{demod} = v_r - vr_{calc}$: where (v_r) is the measured radial cutoff speed and (vr_{calc}) expected radial cutoff speed

PUI VDF Evolution in SIRs

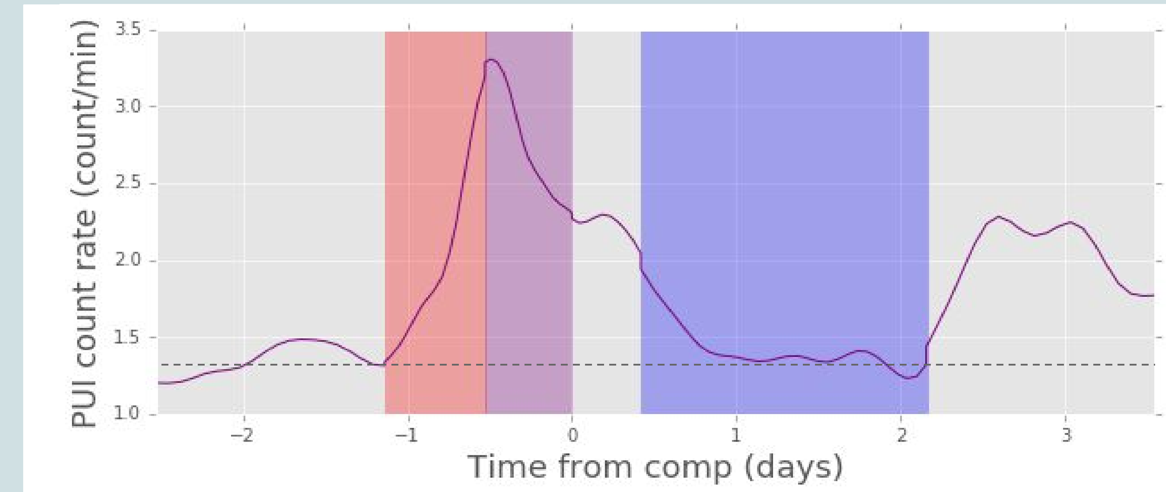


Figure 5: The PUI count rate density evolution in the SIR, showing a similar trend to that of the solar wind density, peaking in the stream interface between the compressed fast and slow wind

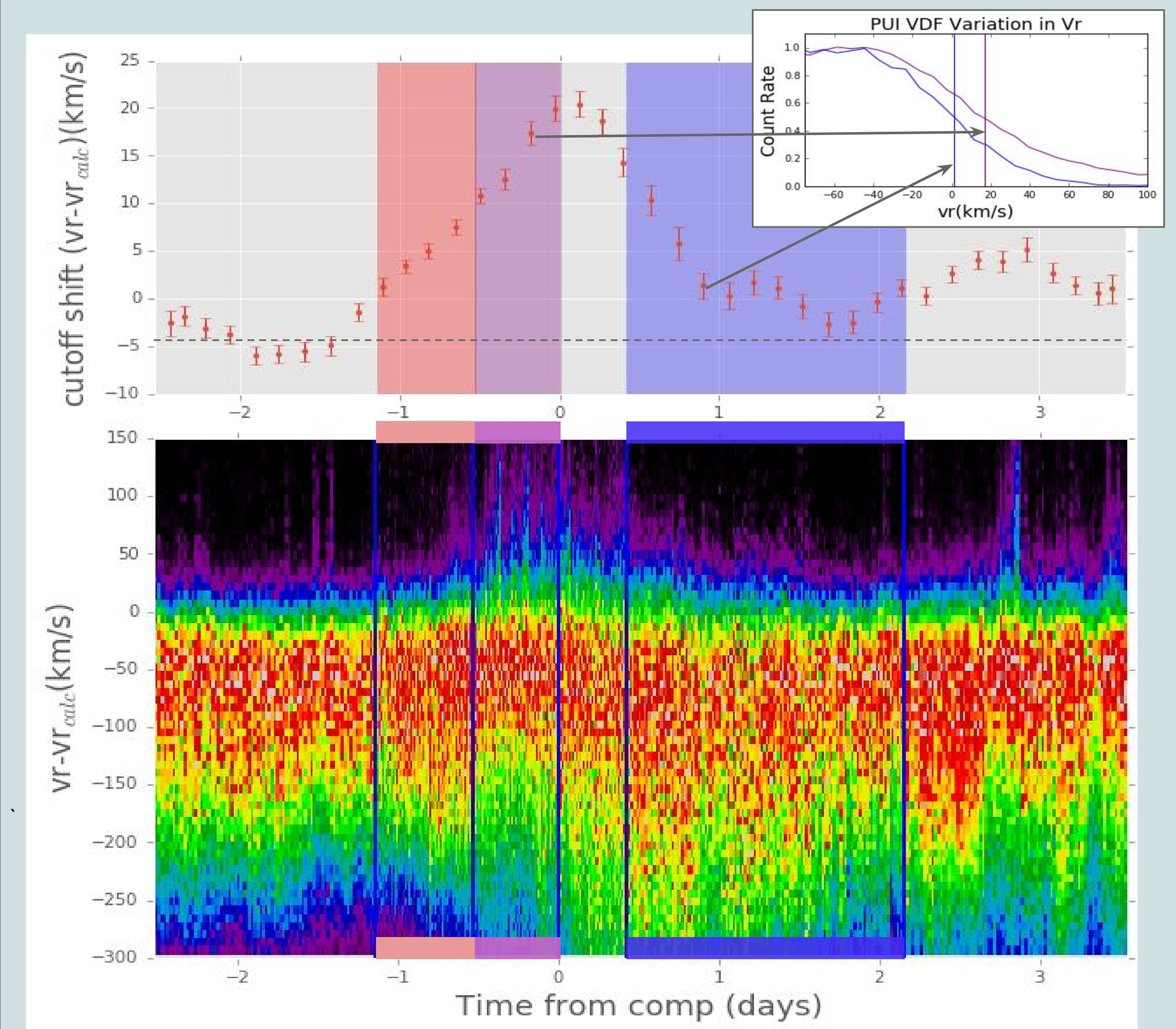


Figure 6: PUI cutoff (top) and VDF (bottom) evolving across a compression, created by accumulating PUI measurements across the SPE average SIR.

- The PUI count rate strongly reflects the compression structure of the SW density
- We see a large positive shift in the cutoff associated with the compression, that persists well into the rarefaction region
- Effect of heating in the rarefaction region can be seen in the evolution of the PUI cutoff in an SPE averaged compression
- Rarefaction region shows largely heated PUIs up to a day after the compression, in an area where the SW is cooling.

To test whether the persistence of apparent PUI heating in the rarefaction region is tied to high solar wind speeds, we normalize the PUI distribution.

$w_{demod} = vr_{demod}/v_{vsw}$: where (w_{demod}) is the normalized cutoff speed with the dependence of ecliptic longitude removed

Evolution of Cutoff Normalized to SW Speed:

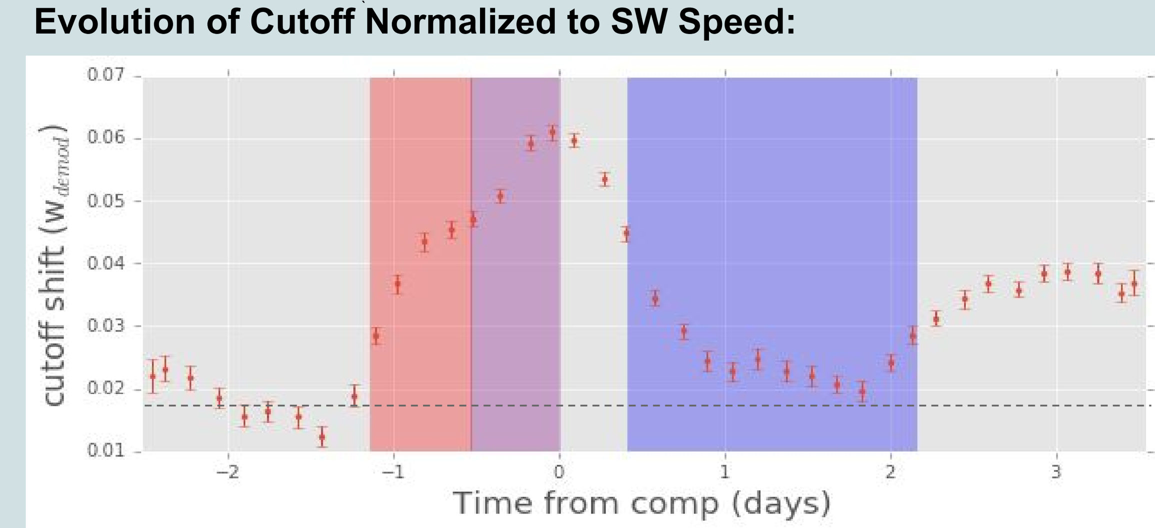


Figure 7: The PUI cutoff shift evolution across the SPE average SIR normalized to the local sw speed.

- With the the PUI cutoff normalized to the solar wind speed the, positively shifted cutoff values in the rarefaction region are not substantially affected, while cutoff values in the slow compressed wind are increased.

SW Parameter Dependence

SPE compression Region Results

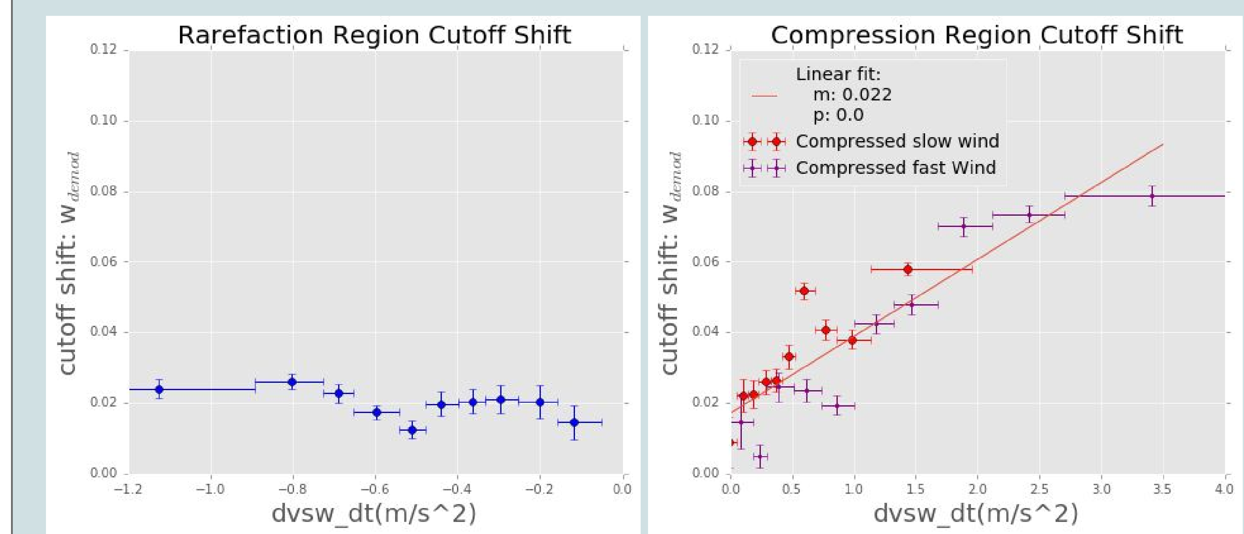


Figure 8: Variation of the PUI cutoff shift as a function of the speed of the SIR vsw increase (right) and steepness of Vsw in the rarefaction region (left).

- The PUI cutoff shift is correlated with the strength of the solar wind speed increase for both compressed slow and fast wind.
- In the rarefaction region, one would expect to see cooling of the PUI VDF, but no such trend is observed
- In order to test to see if this effect is due to magnetic or adiabatic heating, we need to look further into the effect of the B field on w_{demod}.

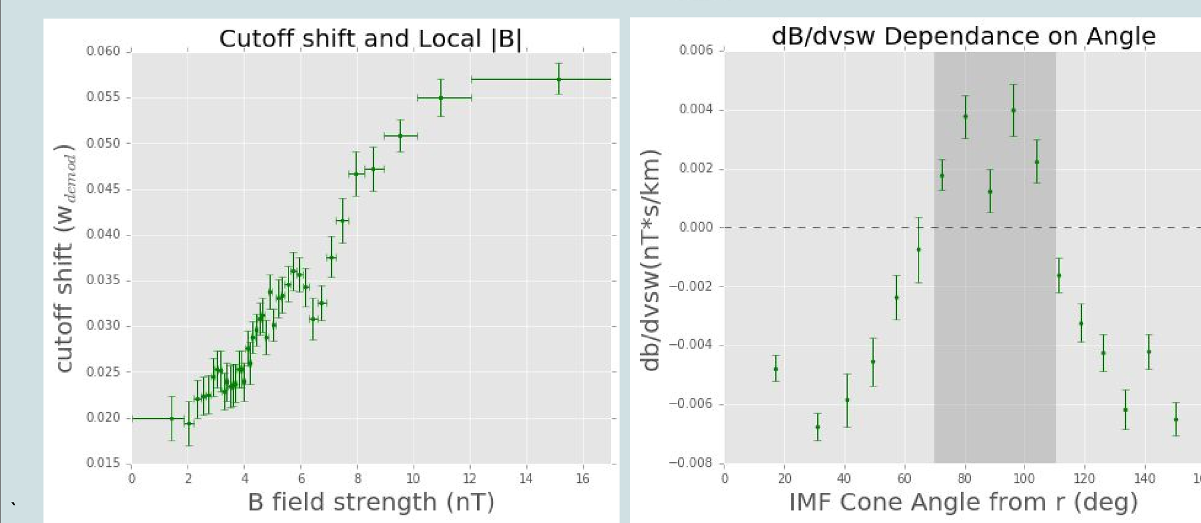


Figure 9: Relationship between fluctuations in b and vsw as a function of IMF angle. The gray box is the quasi-perpendicular region where STEREO sees the ring beam, showing a positive correlation between ***dvsw*** and ***dB***.

- STEREO FOV restricts us to viewing the PUIs in only quasi- perpendicular field configurations, where we can see that changes in |B| and vsw are directly correlated.
- The cutoff increases substantially with the strength of local |B|, regions typically inside compressions
- In these regions we see that the cutoff strongly correlates with the slope of the solar wind velocity, by proxy slope of the |B| field, and with |B|, suggesting that magnetic heating plays a substantial role in the increase in the PUI cutoff.
- Further tests are needed to see if the effect of this magnetic heating obeys the adiabatic invariant

Conclusion

- While v_r remains the most effective for measuring the inflow direction, w_{demod} allows for the most effective study of heating.
- The highly dynamic environment of the SW substantially influences the PUI cutoff, even when viewing freshly injected particles.
- When using the PUI VDF to probe the ISM, one must consider the effect of
  - Increases in the SW speed, both locally and due to large scale SW structures
  - The B field strength
- Since STEREO can only view the PUI ring beam in quasi-perpendicular field configurations, we must stay aware of selection biases when studying heating mechanisms in the solar wind
- When removing compression regions to measure the inflow, we must remove regions from the start of the compressed slow wind, into the rarefaction region.
- 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?

References & Acknowledgements

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- Taut, A., et al. 2018, Accepted, Astronomy and astrophysics
- Fahr, 2008, Ann. Geophys., 25, 2649–2659
- Moebius, M., Lee, M., Drews, C., 2015, Astrophysical Journal, 815:20
- Pizzo, V., 1978, Journal of Geophysical Research: Space Physics, 83, Issue A12
- L. Saul, et al., 2003, AIP Conf. Proc. 679, 778

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