The discrete structure of solar wind sources: Alfvenic switchbacks and hot, fast plasma emerging from supergranule boundaries

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Outline

- NASA's Parker Solar Probe (PSP) mission
- Short review of Alfvenic switchbacks
- A PSP *case study* showing switchbacks associated with hot, fast plasma organized by supergranulation
- More from Encounter 09 (August 2021)

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Parker Solar Probe Science Objectives

L1 Science Objectives	Sample Processes	Needed Measurements	Instruments
1. Trace the flow of energy that **heats and accelerates the solar corona and solar wind**. 2. Determine the **structure and dynamics of the plasma and magnetic fields** at the sources of the solar wind. 3. Explore mechanisms that **accelerate and transport energetic particles**. 4. ~~Dust!~~	- heating mechanisms of the corona and the solar wind; - environmental control of plasma and fields; - connection of the solar corona to the inner heliosphere. - particle energization and transport across the corona	- electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions - energetic electrons, protons and heavy ions - velocity, density, and temperature of solar wind e-, H+, He++ - solar wind structures and shocks	**FIELDS** - Magnetic Field - Electric Field - Electric/Mag Wave **ISOIS** - Energetic electrons - Energetic protons and heavy ions - (10s of keV to ~100 MeV) **SWEAP** - Plasma e-, H+, He++ - SW velocity & temperature **WISPR** - White light measurements of solar wind structures - …removed from L1

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 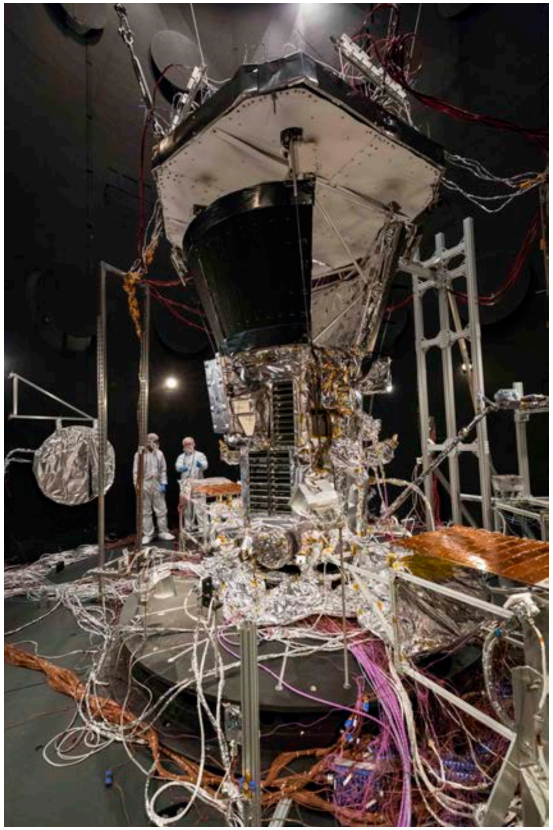 

Parker Solar Probe

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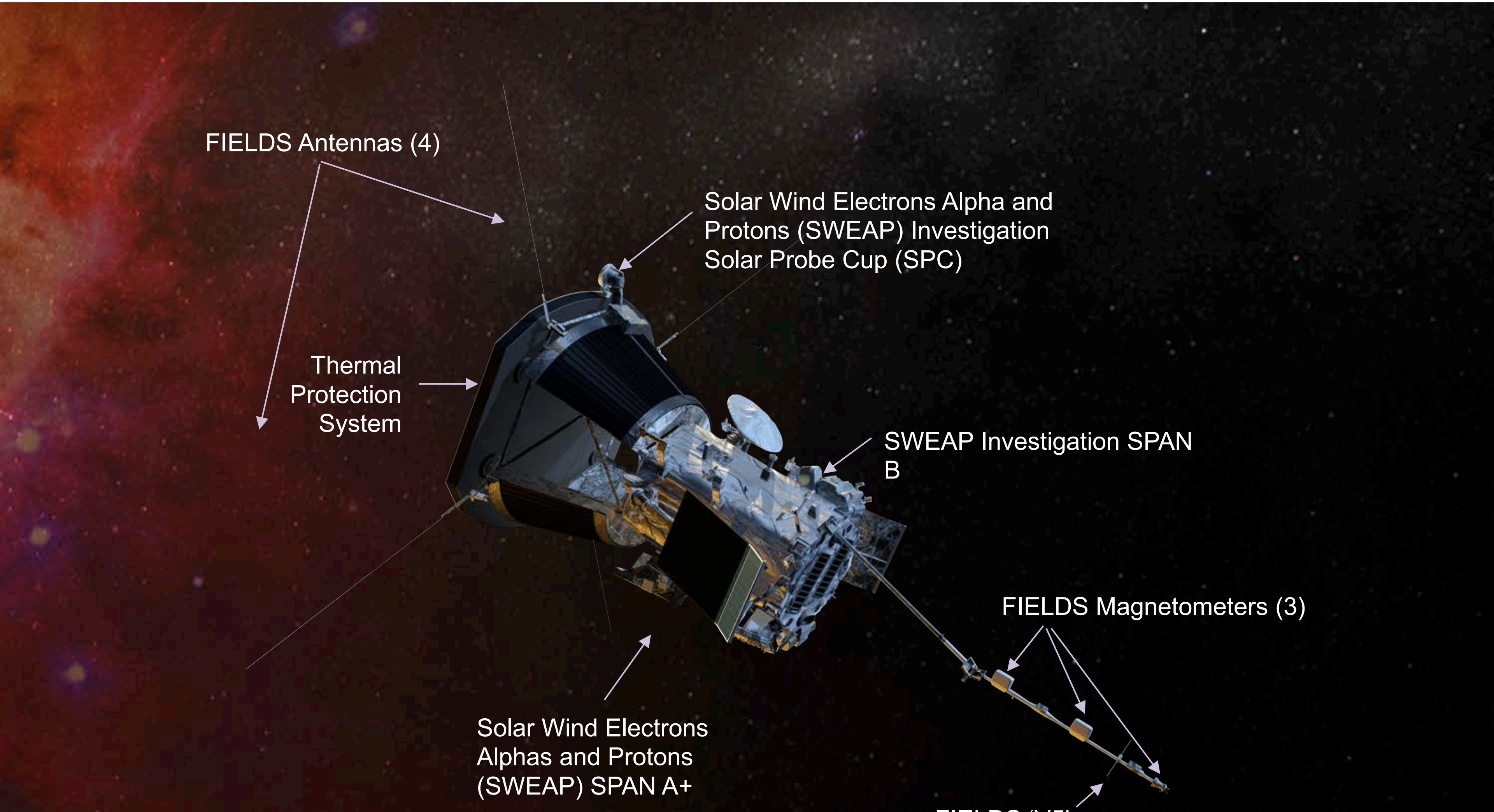
FIELDS and SWEAP Instruments



Some heroic instrument engineering…

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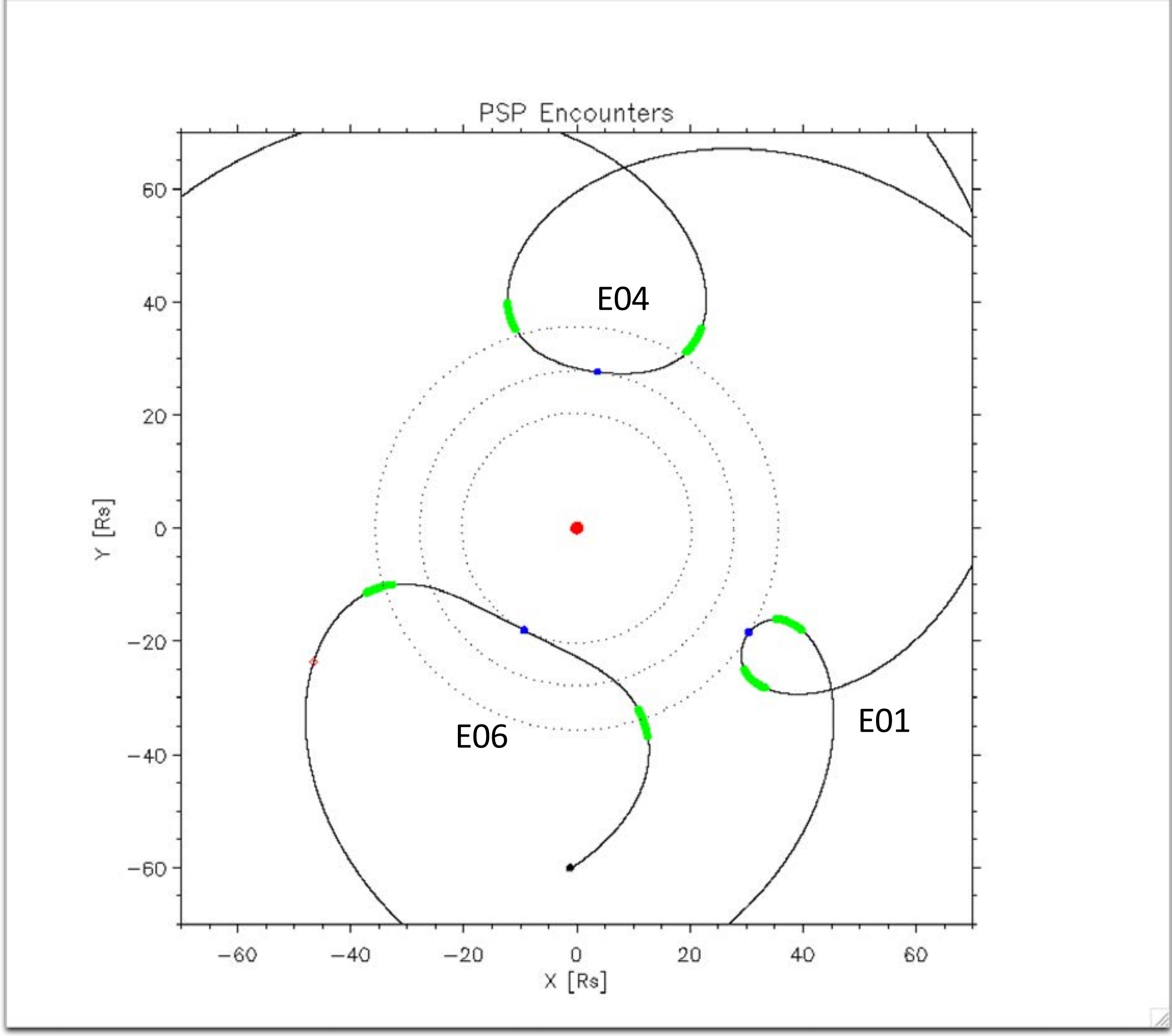
Orbit families in Carrington Coordinates



- Perihelion 01/02/03 at 35.7 Rs
- Perihelion 04/05 at 27.8 Rs
- Perihelion 06 at ~20.36 Rs on ~2020-9-27/09:16:00
- Corotation on 2020-9-24
- Corotation on 2020-9-30
- ~90° sweep in longitude

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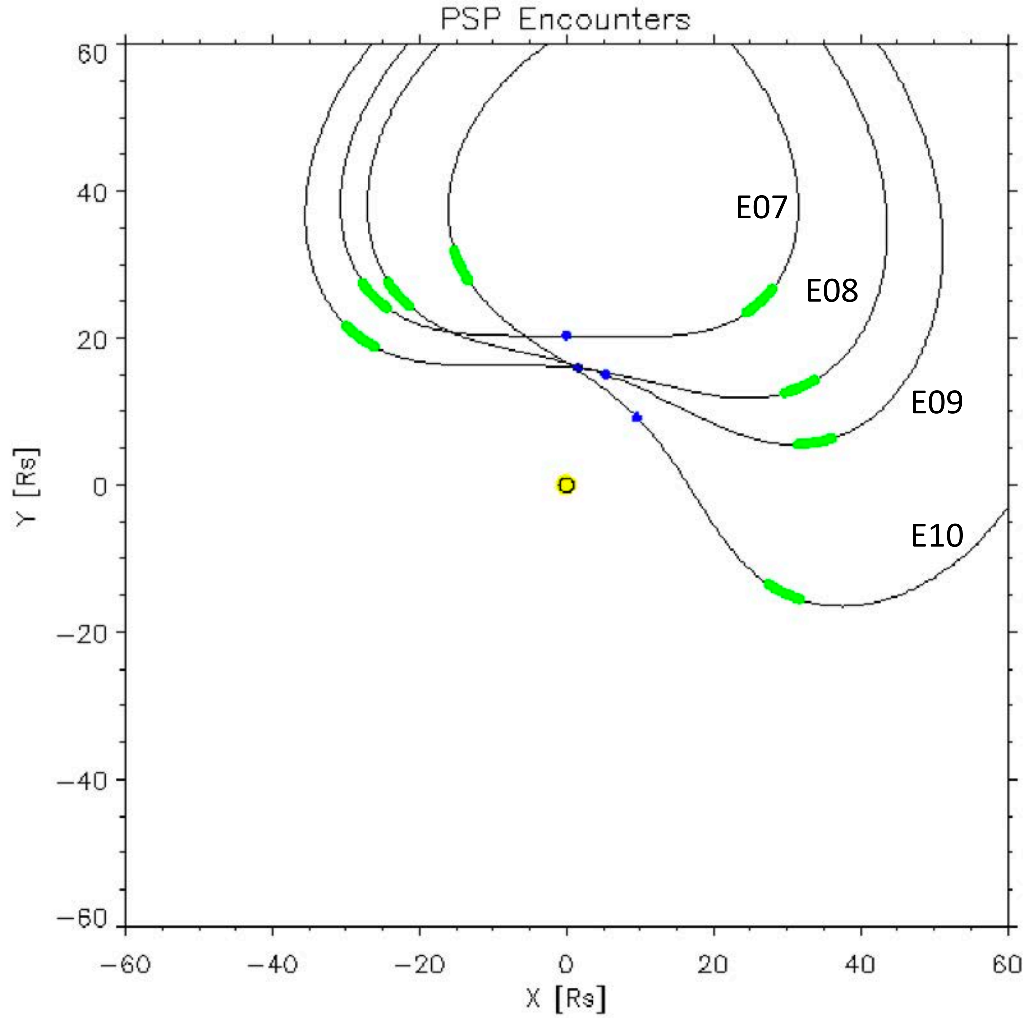
Orbit families in Carrington Coordinates

- Perihelion 07 at 20.36 Rs
- Perihelion 08/09 at 16 Rs
- Perihelion 10 at ~13.3 Rs on ~2021-11-15
- ~90° sweep in longitude



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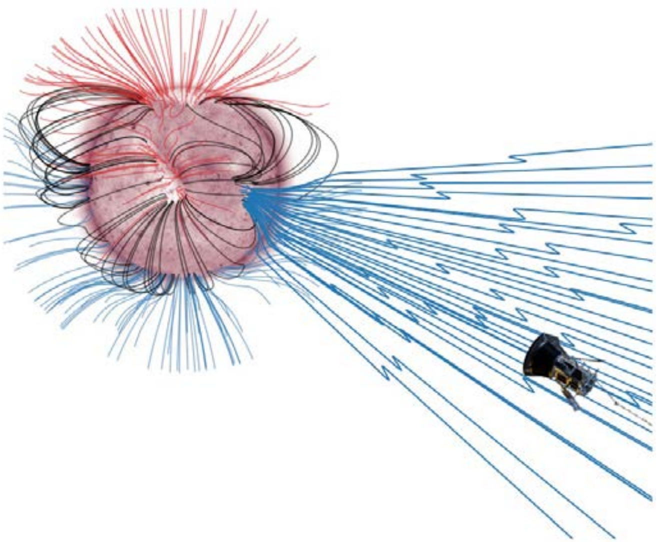
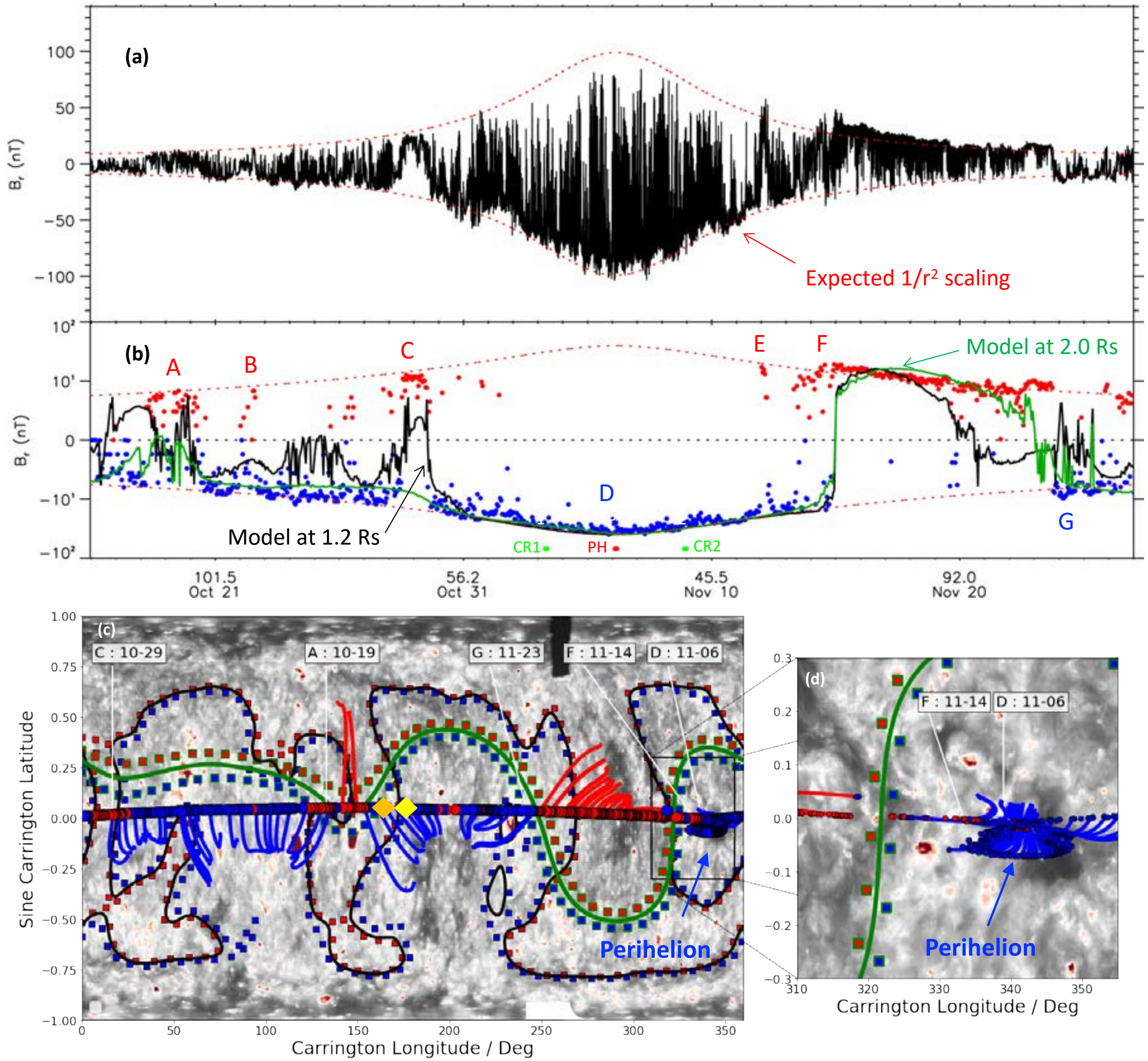
PSP Encounter 01

- Perihelion at 35.7 Rs
- Early November 2018
- Solar Minimum (!)
- Magnetically connected to a small, equatorial coronal hole
- Switchbacks + Quiet IP Field
    - These are qualitatively different
    - *NOT* so much like 1 AU

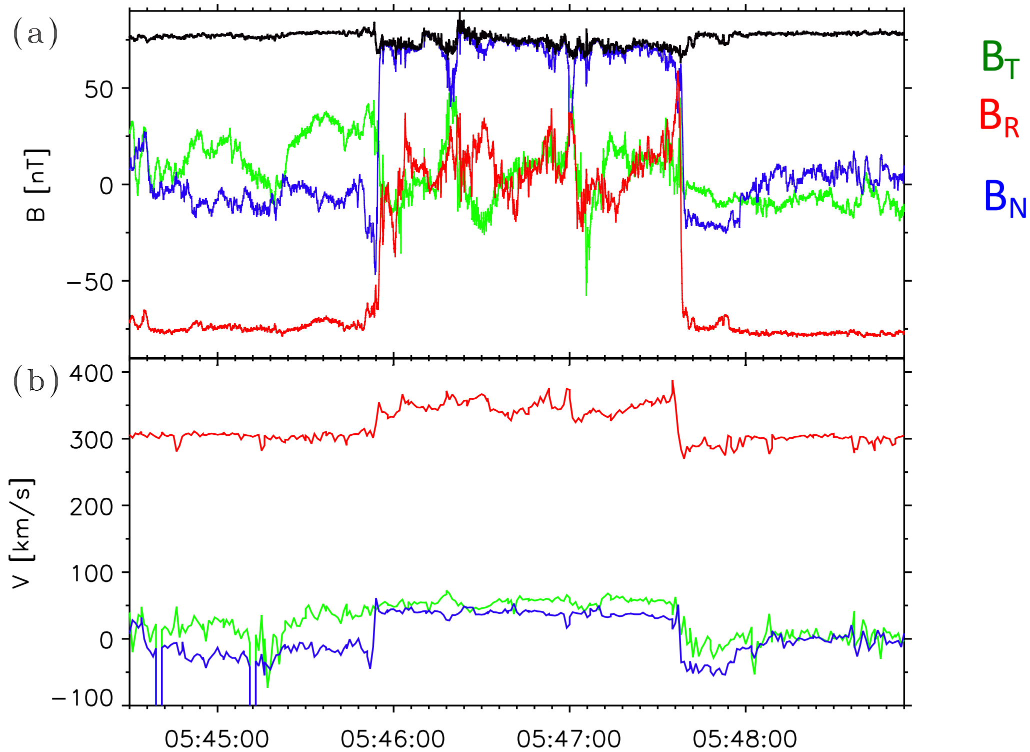




[Bale et al., 2019, Badman et al., 2020a]

What are switchbacks?

- Localised, sharp mostly *Alfvenic* fluctuations
- Outward propagation sense: enhancement in speed
- Typically sharp boundaries, but no consistent shape
- Scales of seconds to tens of minutes at s/c



(Drake et al, 2020)

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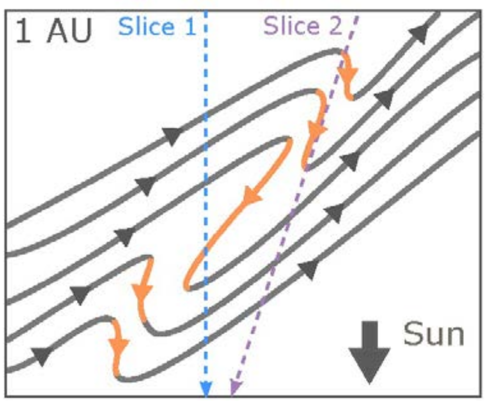
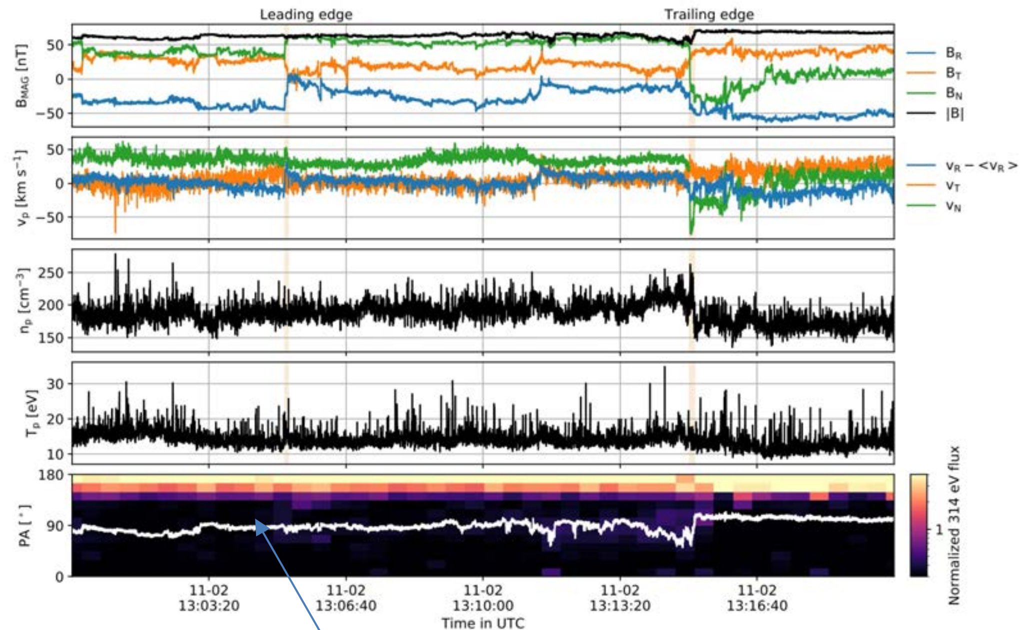
Switchbacks are folds, not polarity reversals

Evidence from:

- Cross helicity and turbulence: McManus 2020, Bouraine 2020
- Electron pitch angles: Froment 2021, Whittlesey



(MacNeil et al., 2020)

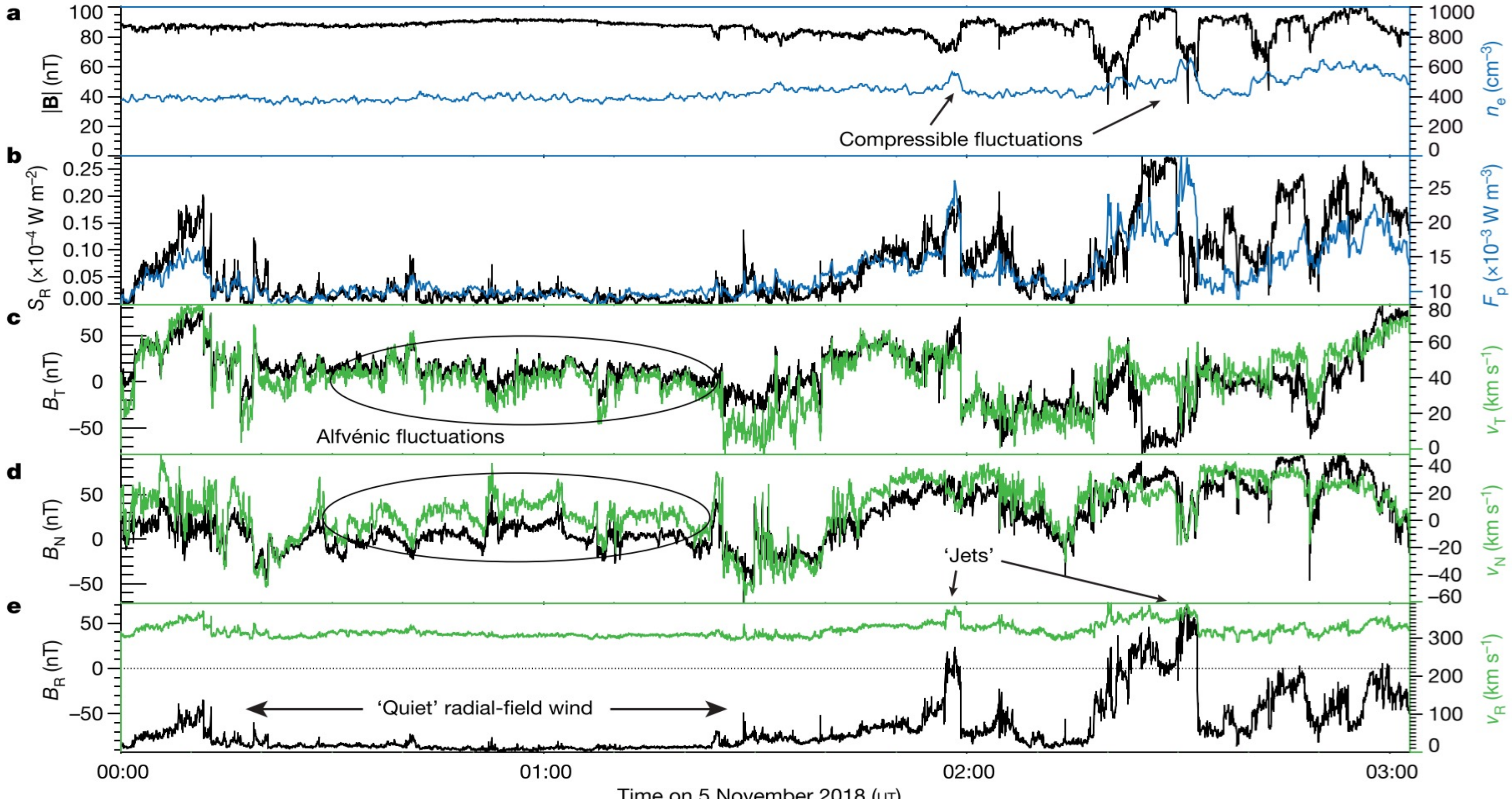


(Froment et al, 2021)

Pitch angle not reversed in switchback

Patches and occurrence

(Bale et al, 2019)



Switchbacks occur in patches separated by smooth, quiet wind

‘Patches’: $T_{||}$ is modulated by SB patches

Proton $T_\perp$ is strongly correlated to Vsw

Proton $T_{||}$ is enhanced within *patches* of SBs, but not necessarily individual SBs

(Woodham et al., 2021, Wooley et al., 2020)

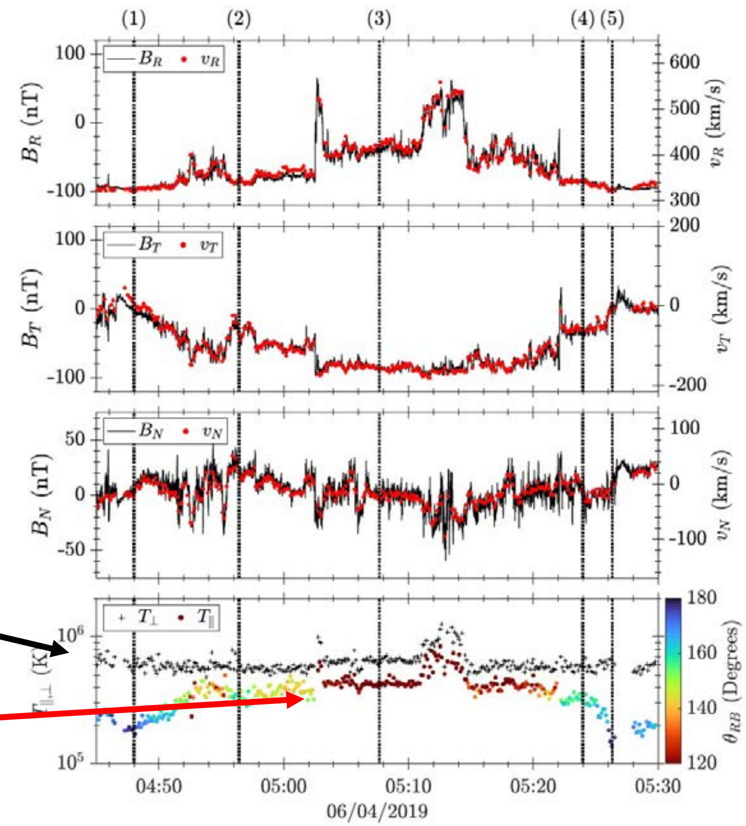


Fig. 3. Single patch from PSP observations. First panel: radial component of the magnetic field, B_R, and proton core velocity, v_R. Second and third panels: same as the first panel, but for the tangential and normal components, respectively. Last panel: $T_{p,\parallel}$ and $T_{p,\perp}$, where the colour-scale of $T_{p,\parallel}$ is the angle θ_{RB}. The vertical dashed lines indicate the times of the distributions plotted in Figure 4.

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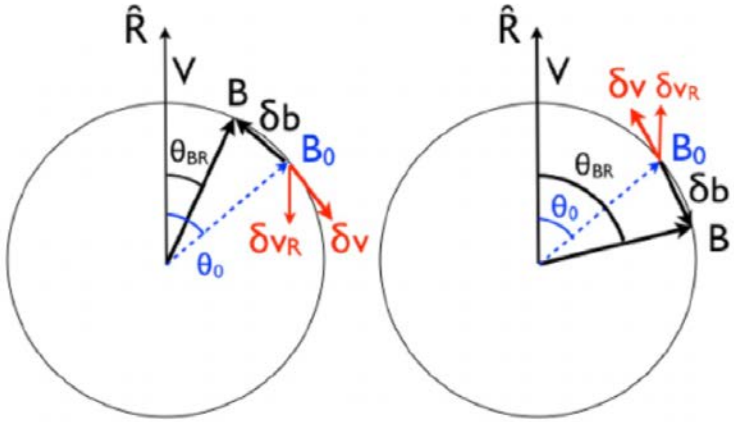
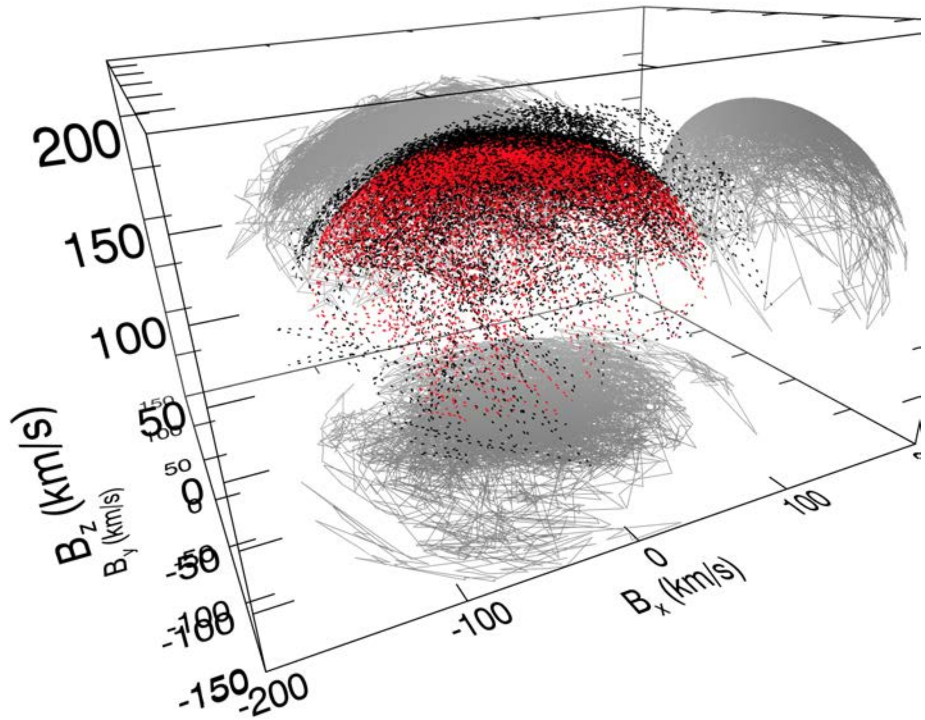
Switchbacks are spherically/arc polarized

- The magnetic field moves on the tip of a sphere
- As expected for |B| ~ const.





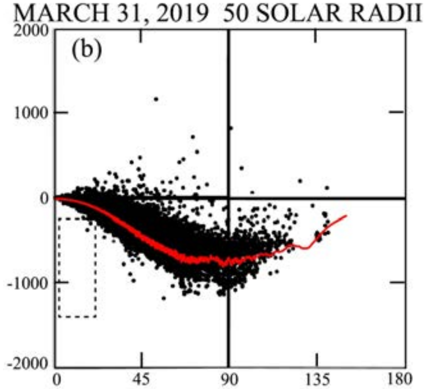
(Matteini et al, 2014; Bowen et al, 2021)

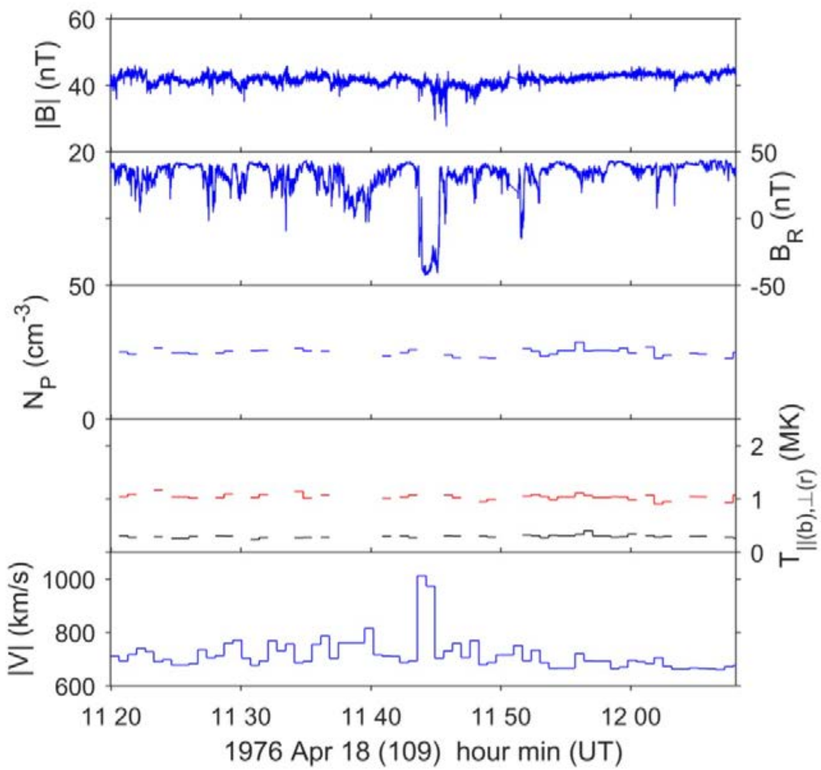
Energy content of switchbacks

- Proton core can carry more than twice the kinetic energy than ambient wind nearby
- How fast can a switchback go? $V_{SW} + 2V_A \geq 1000\ km/s$
- Has anyone calculated a full energy budget (KE and thermal of core, beam, alphas; Poynting flux, etc) of switchbacks?

Poynting flux – in and out of SB

(Mozer et al., 2020)





(Horbury et al, Helios)

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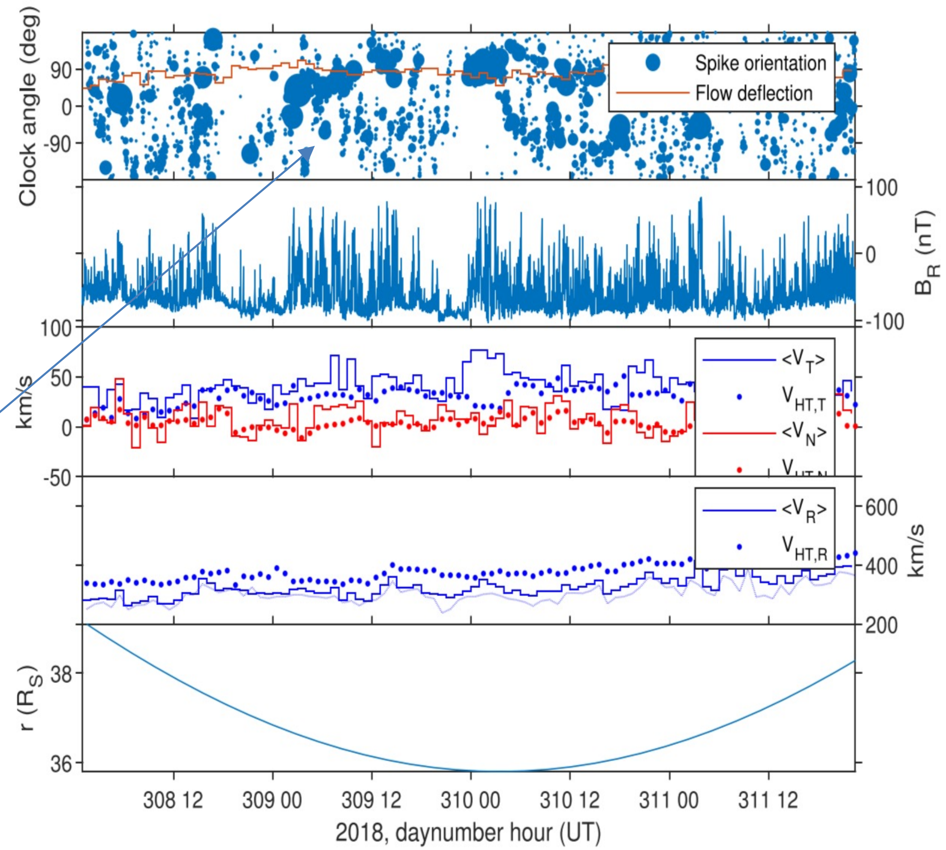
Deflection direction

- Some evidence for consistent deflection direction of switchbacks within patches
- Is this related to flow deflections?
- Unclear

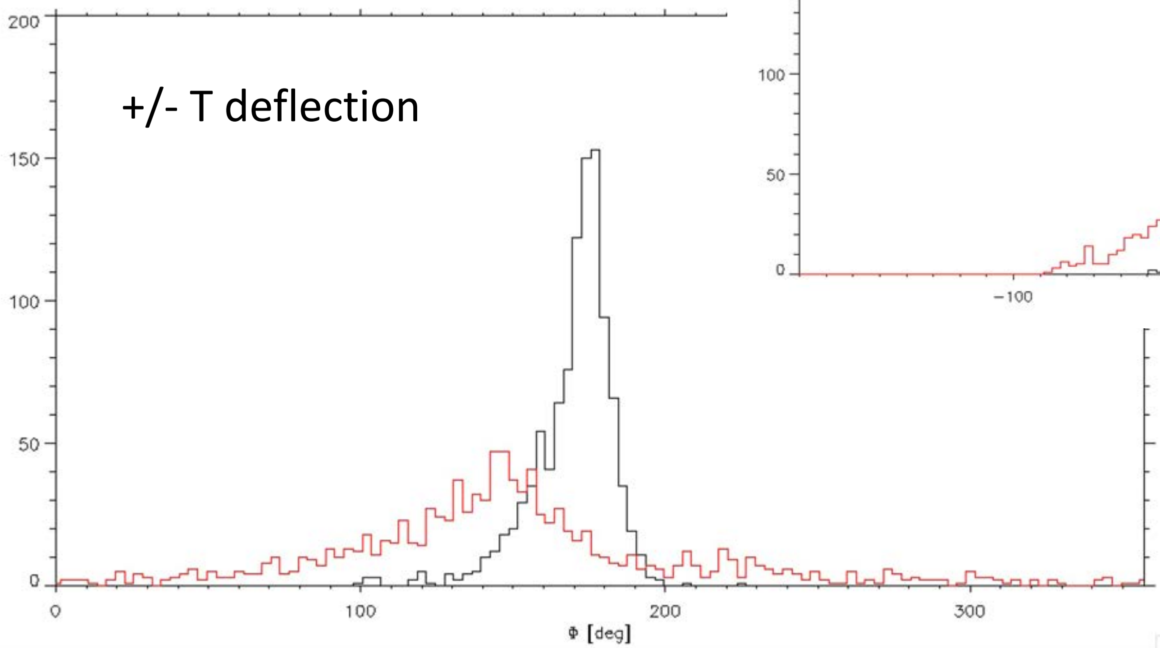


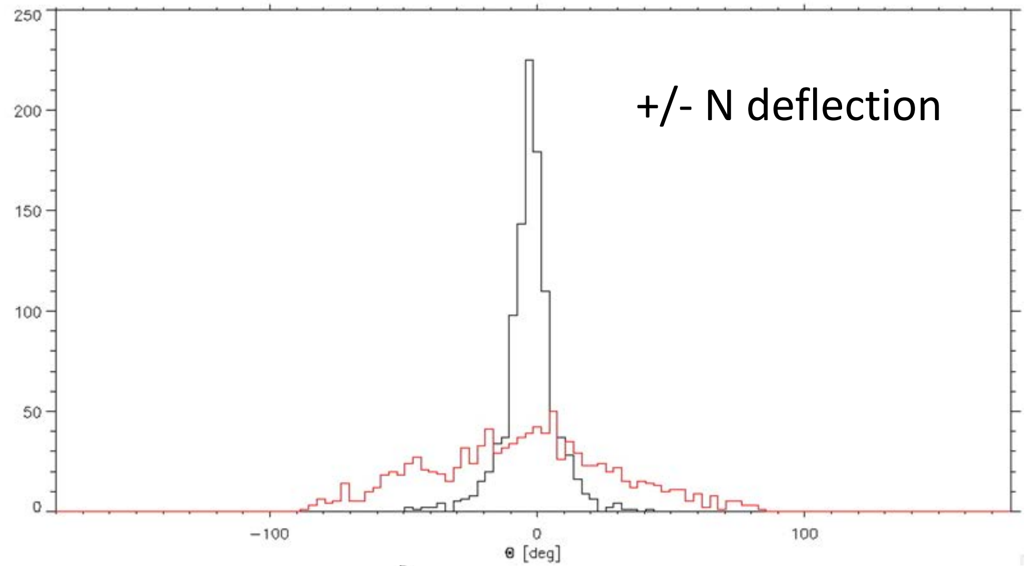
Patches of switchbacks with the same deflection direction

(Horbury et al., 2020)

Switchback deflect preferentially

A preference for +T deflection





Black – background
Red - switchbacks

(Bale, Laker, in progress)

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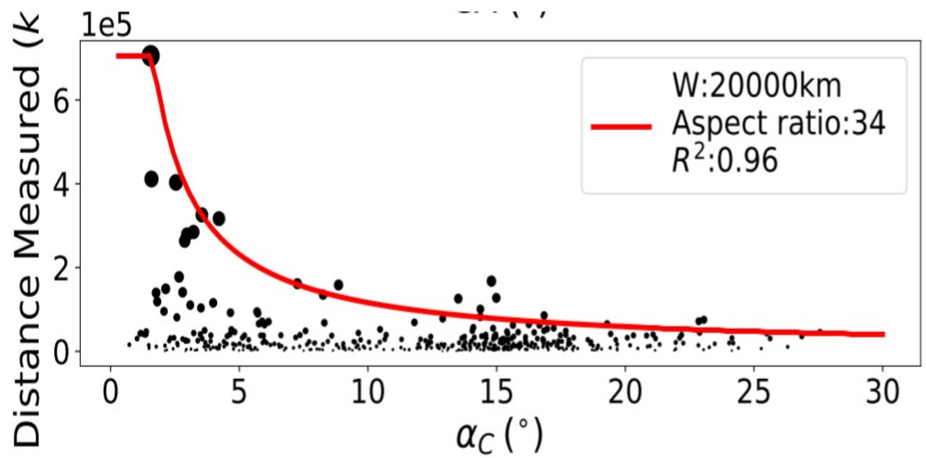
Switchbacks are long and thin

- Widths 10^4km at 30 R
- Lengths up to 1 R_S
- Aligned with local Parker spiral

- Very short events at s/c are not necessaril, short structures



(Laker et al, 2021)

This is the true aspect ratio of a switchback

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Where do we see switchbacks?

Fewer and weaker switchbacks nearer to the Sun

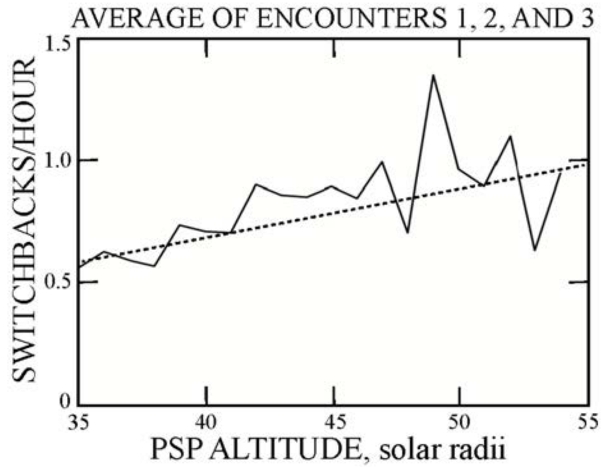
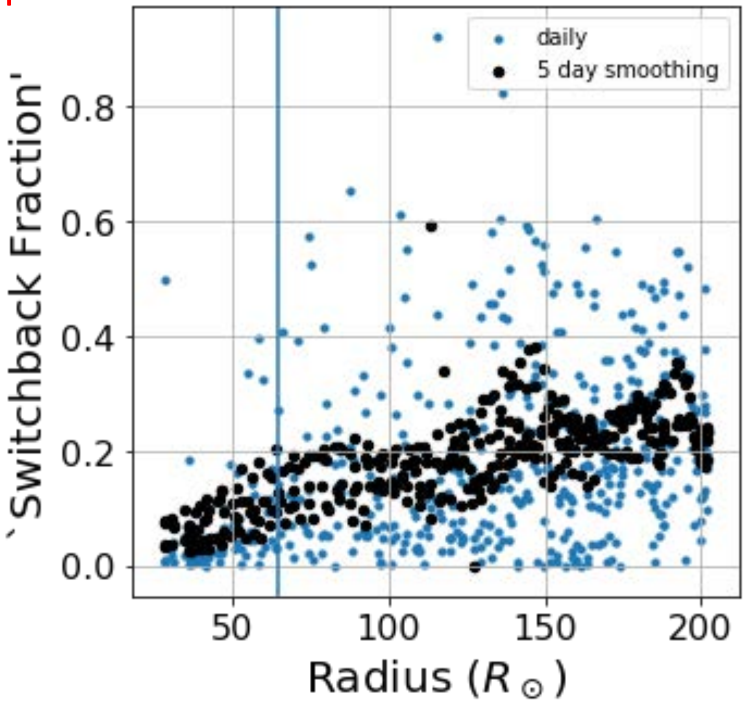


Figure 3. The average switchback rate as a function of solar radius, as obtained by averaging the inbound and outbound observations from three perihelion passes. The dashed line is the rate expected if the probability of forming a switchback is constant between the Sun and 55 solar radii at the value of 0.017 switchbacks/hour/unit radius.

(Mozer et al., 2021)



(Badman et al., 2021 – Br opposite to mode(Br)

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A solar source of Alfvénic magnetic field switchbacks:
in situ remnants of magnetic funnels on supergranulation scales

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ABSTRACT

One of the striking observations from the Parker Solar Probe (PSP) spacecraft is the prevalence in the inner heliosphere of large amplitude, Alfvénic magnetic field reversals termed 'switchbacks'. These $\delta B_R/B \sim \mathcal{O}(1)$ fluctuations occur on a range of timescales and in *patches* separated by intervals of quiet, radial magnetic field. We use measurements from PSP to demonstrate that patches of switchbacks are localized within the extensions of plasma structures originating at the base of the corona. These structures are characterized by an increase in alpha particle abundance, Mach number, plasma β and pressure, and by depletions in the magnetic field magnitude and electron temperature. These intervals are in pressure-balance, implying stationary spatial structure, and the field depressions are consistent with overexpanded flux tubes. The structures are asymmetric in Carrington longitude with a steeper leading edge and a small ($\sim 1°$) edge of hotter plasma and enhanced magnetic field fluctuations. Some structures contain suprathermal ions to $\sim$85 keV that we argue are the energetic tail of the solar wind alpha population. The structures are separated in longitude by angular scales associated with supergranulation. This suggests that these switchbacks originate near the leading edge of the diverging magnetic field funnels associated with the network magnetic field - the primary wind sources. We propose an origin of the magnetic field switchbacks, hot plasma and suprathermals, alpha particles in interchange reconnection events just above the solar transition region and our measurements represent the extended regions of a turbulent outflow exhaust.

In press, ApJ

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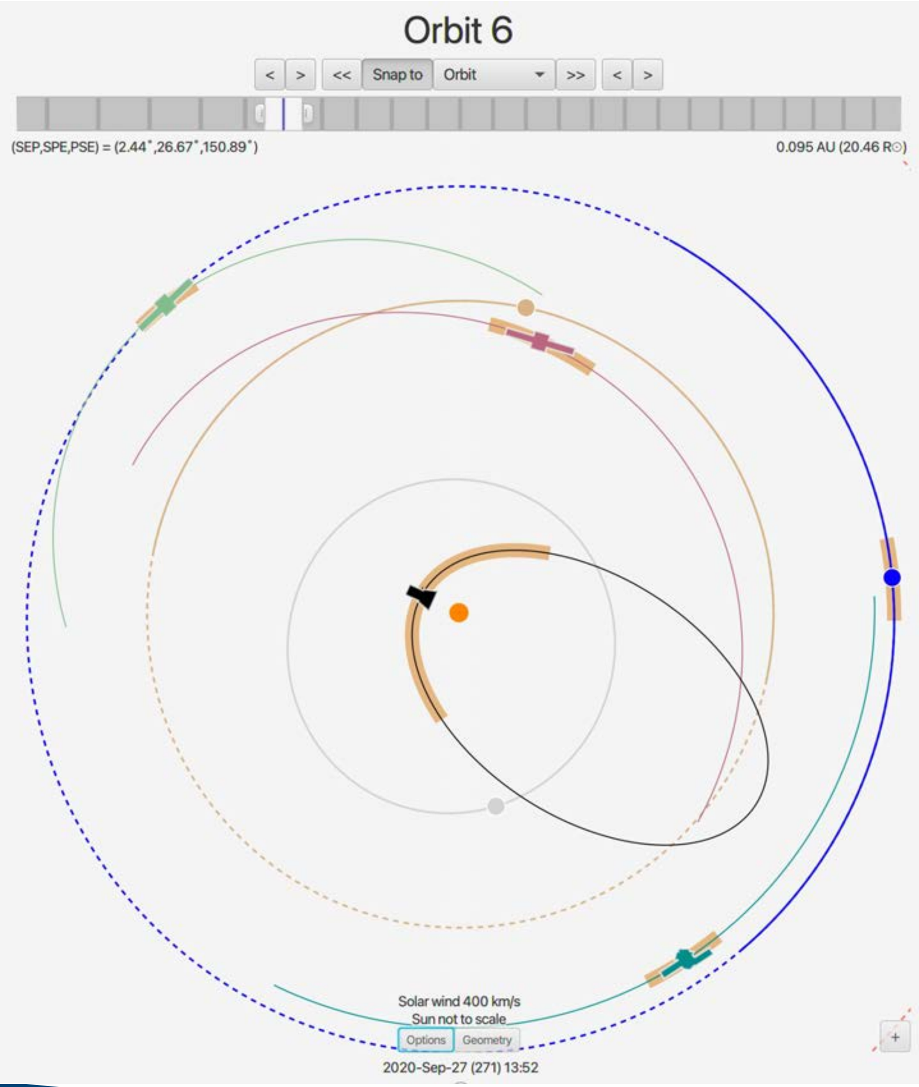
Parker Solar Probe Encounter 06



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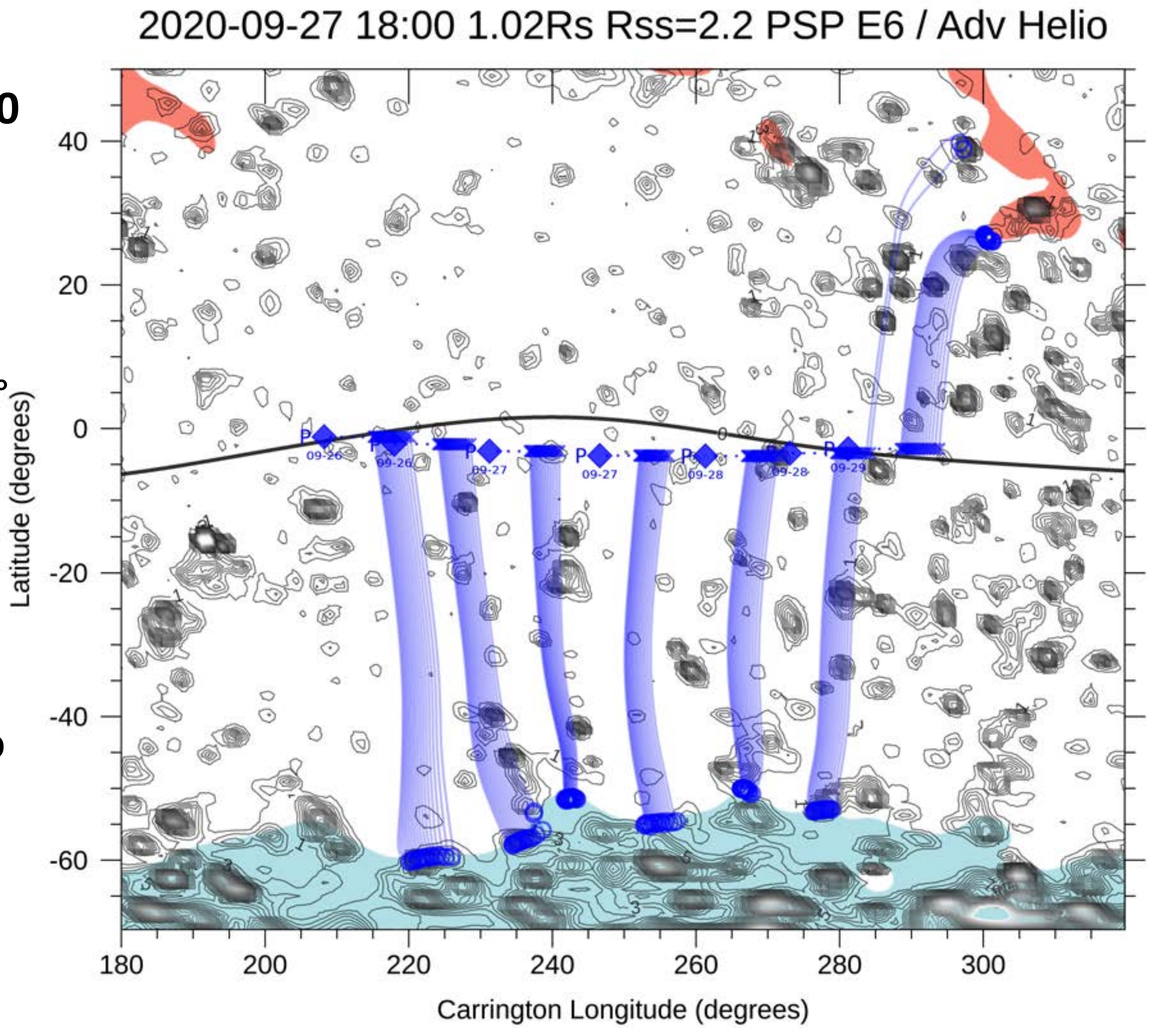
Parker Solar Probe Encounter 06

Perihelion at 20 Rs
PFSS Connectivity on Sept 27, 2020

- Rss = 2.2 Rs
- PSP is connected to a southern coronal hole (CH) at around -60°
- Black contours are magnetic pressure at 14 Mm altitude
  - Network magnetic field
- This is a quiet solar interval – no flares, radio bursts, big ARs



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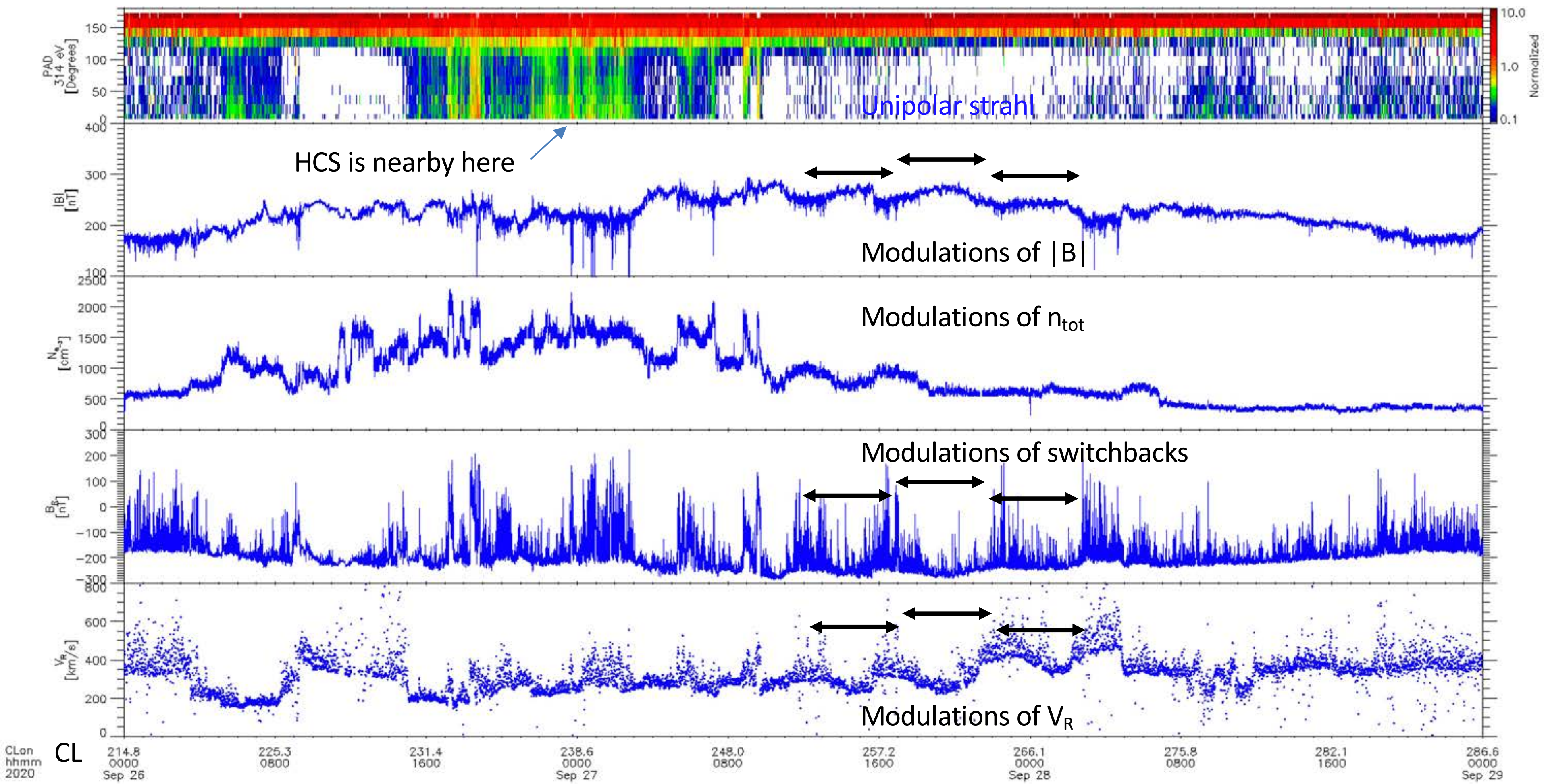
PSP Encounter 06



Angular scale is supergranulation scale – a few degrees

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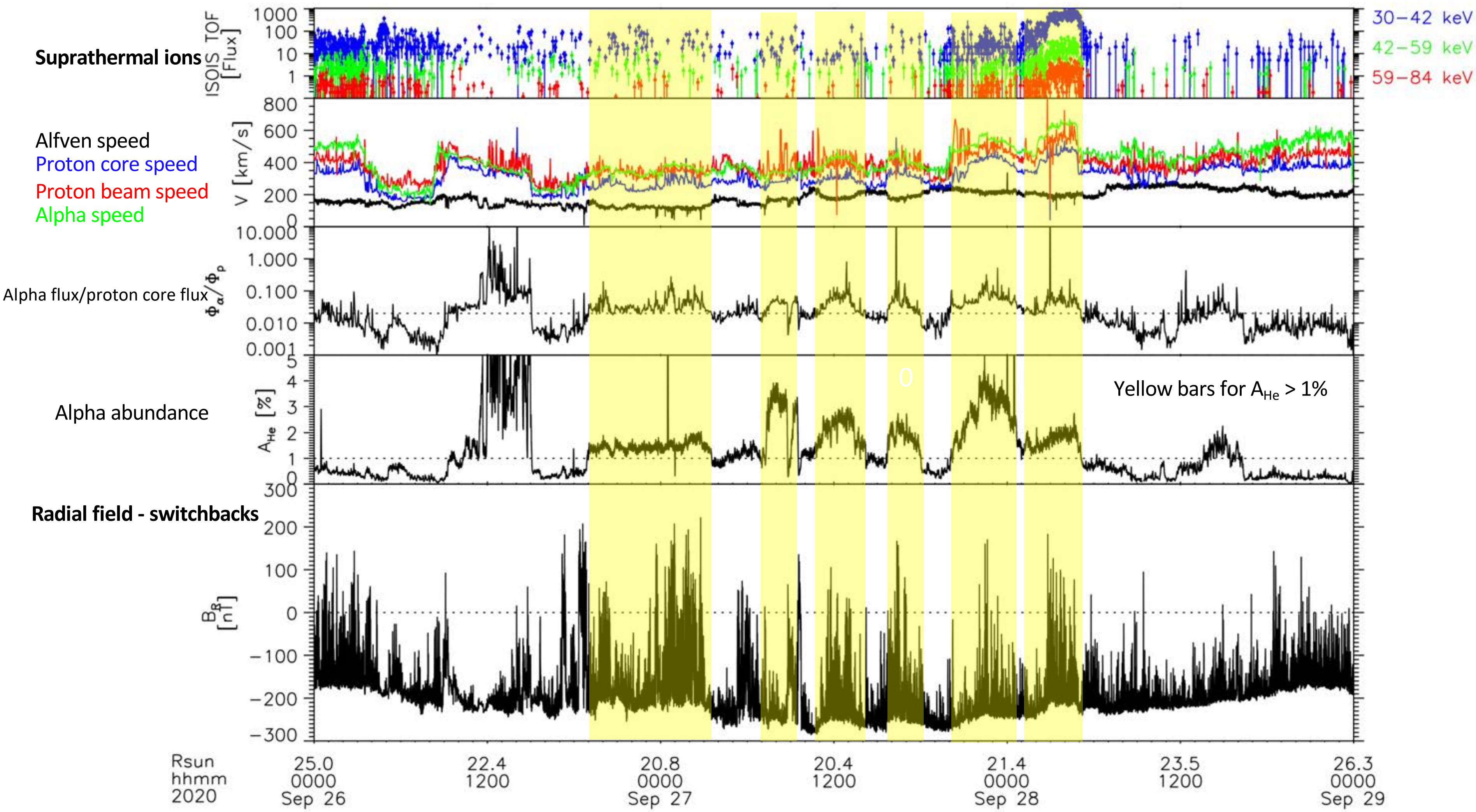
Suprathermals, enhanced A_{He} and higher Mach radial flows



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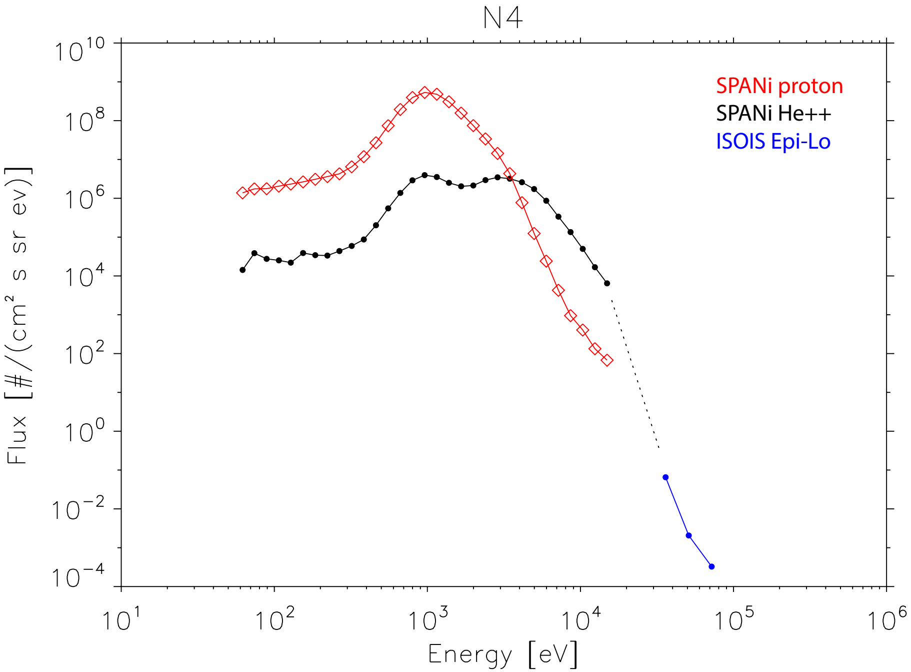
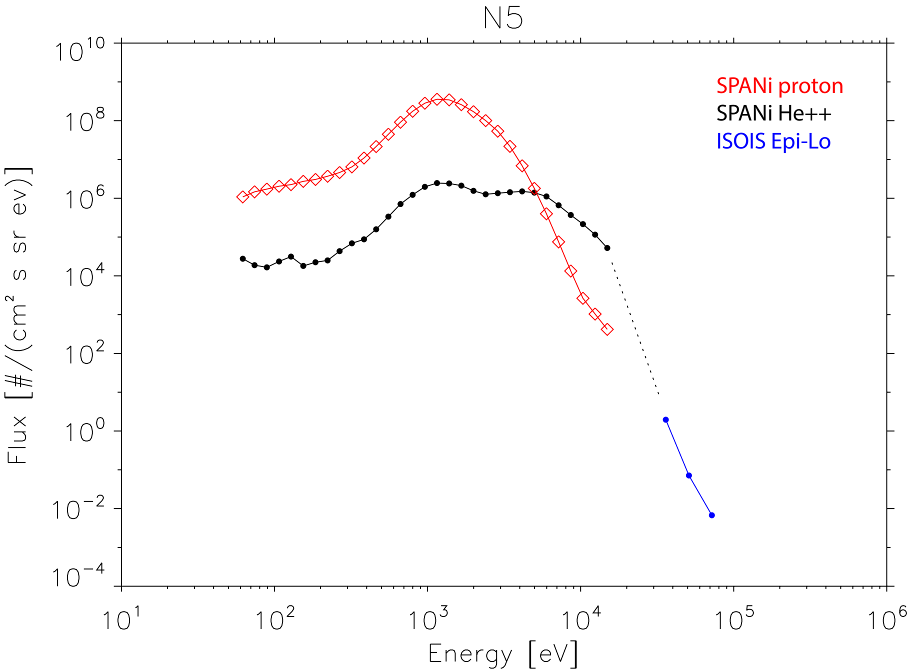
Suprathermal ions to ~85 keV





SPANi Mass-resolved thermals
Epi-Lo TOF suprathermals
He++ or O+ or both

We suggest alphas/He++ to 85 keV

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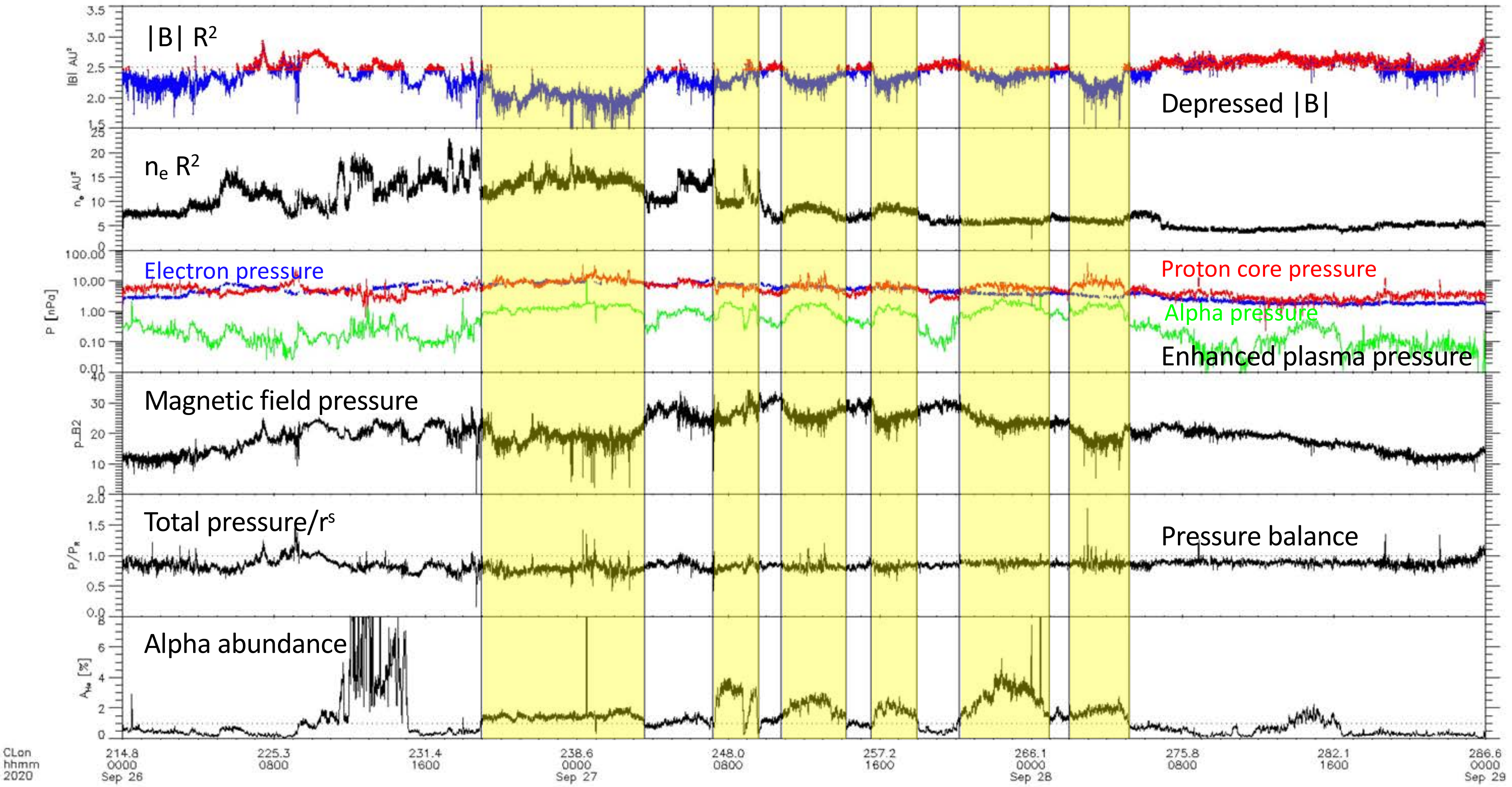
Structures are pressure-balanced



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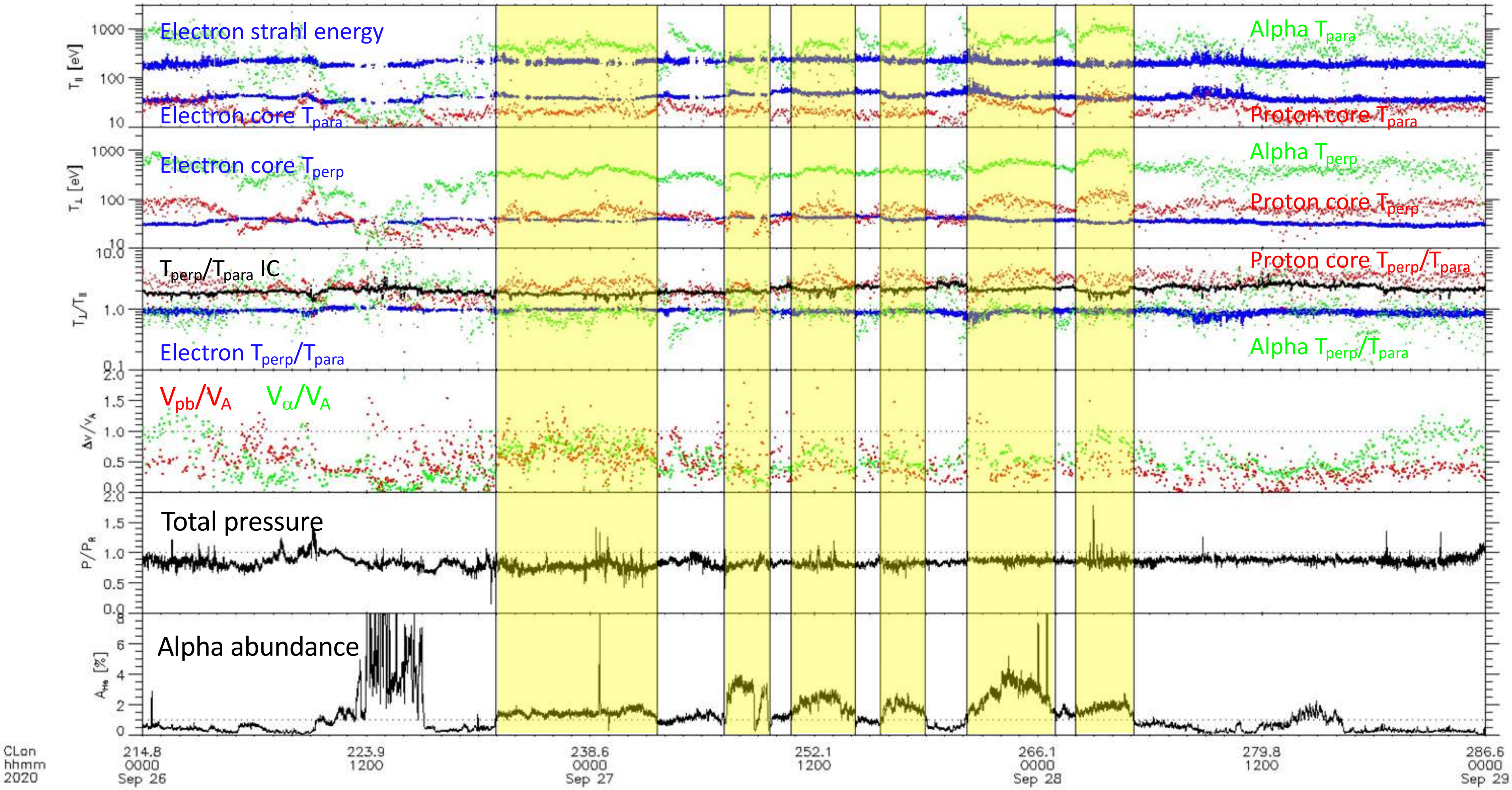
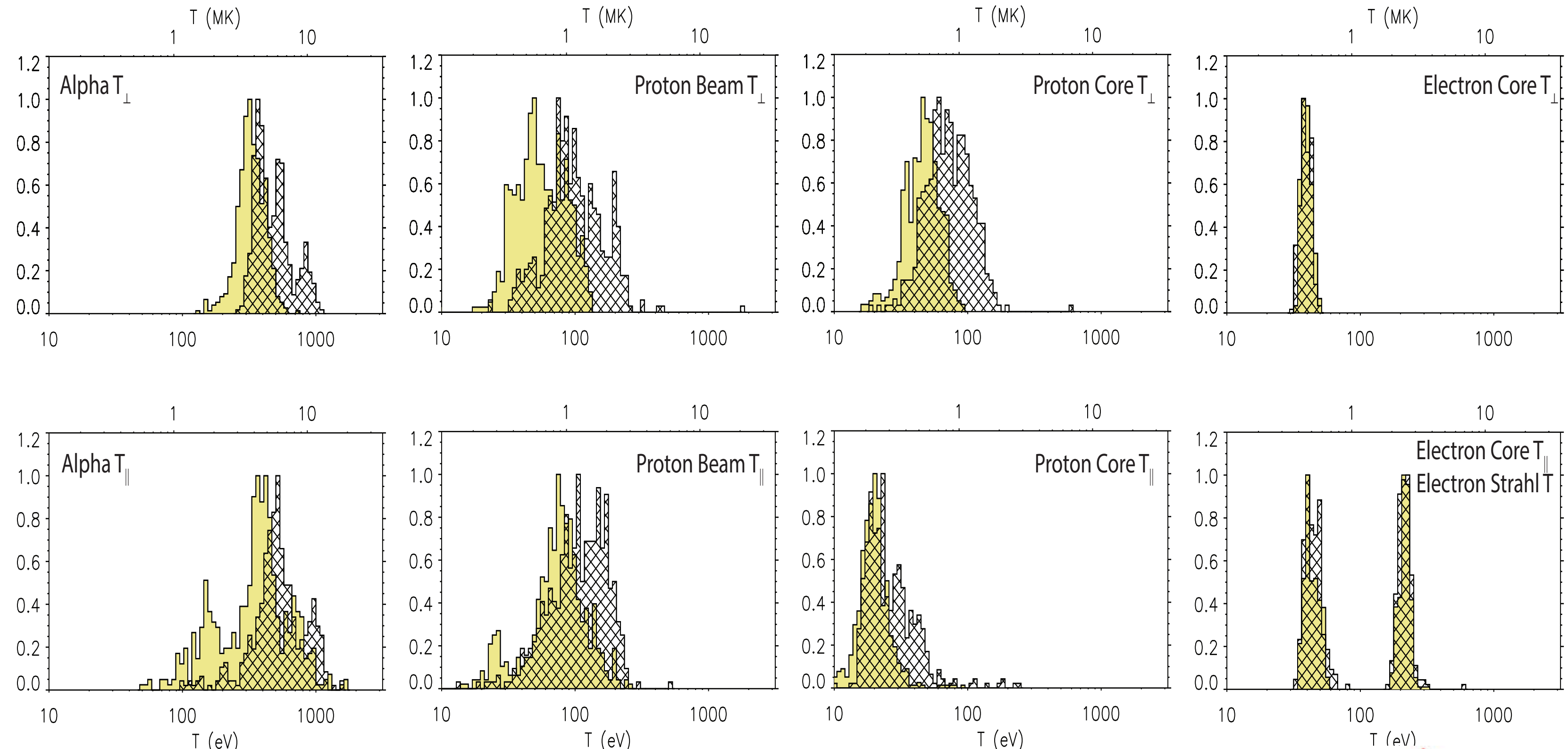
Ion temperatures are elevated, electron temperatures are depressed



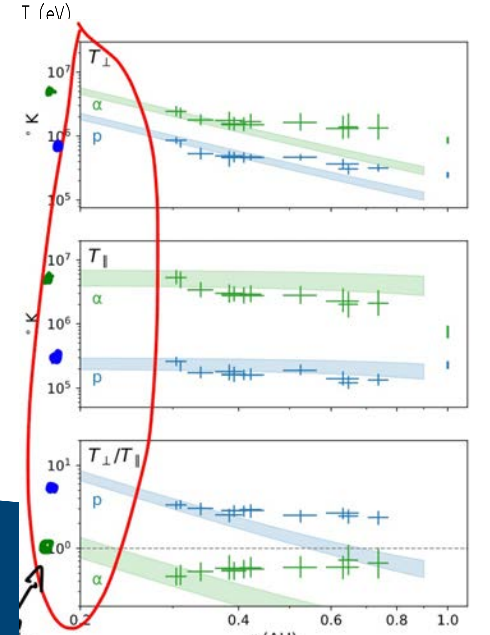


Ion temperatures are elevated within these structures

- compares well to Helios (e.g. Stansby et al, 2019)

Electron temperatures are slightly depressed

- like fast solar wind



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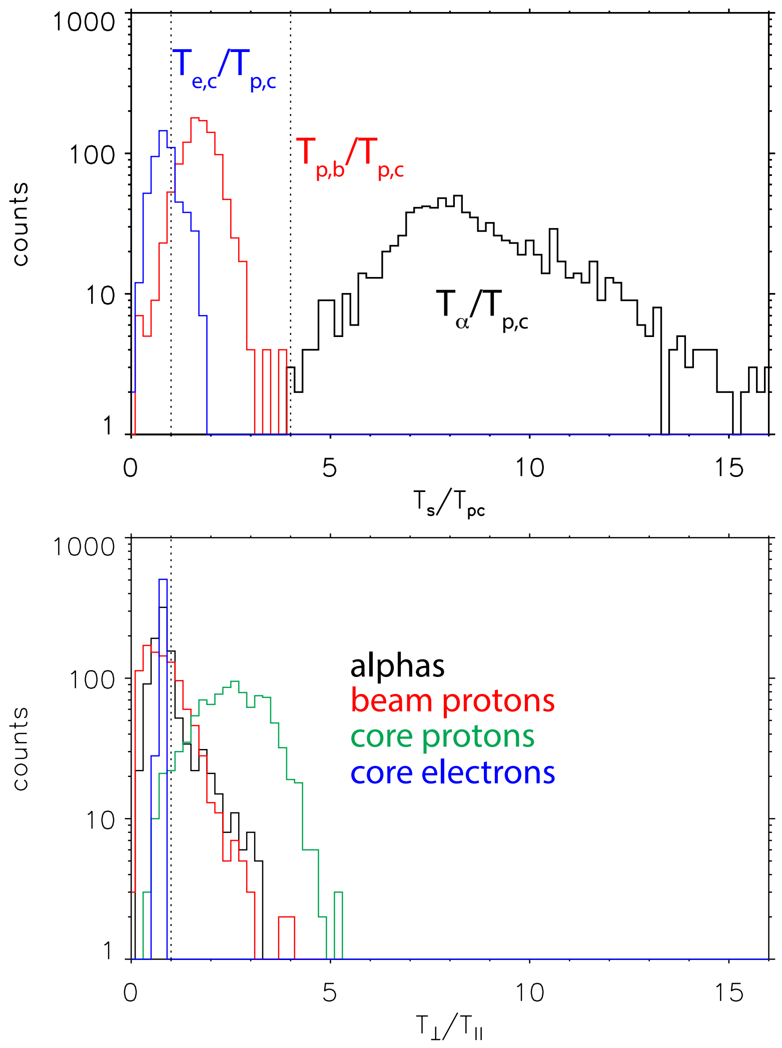
Alphas are hot $T_\alpha/T_p > 5$ – peaks at $T_\alpha/T_p \sim 8$
Alphas are mostly isotropic

Proton beam is warm – $T_{p,b}/T_{p,c} > 1$
Proton beam is mostly isotropic

Proton core is very anisotropic $T_{perp}/T_{para} >= 2$

Electrons are cooler $T_e/T_p < 1$
Electrons are mostly isotropic

Alphas and beam protons have a similar distribution of anisotropy and heating (per mass) – a common mechanism?



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In Carrington Longitude…

B_T, B_N in upper panel
V_T, V_N in lower panel

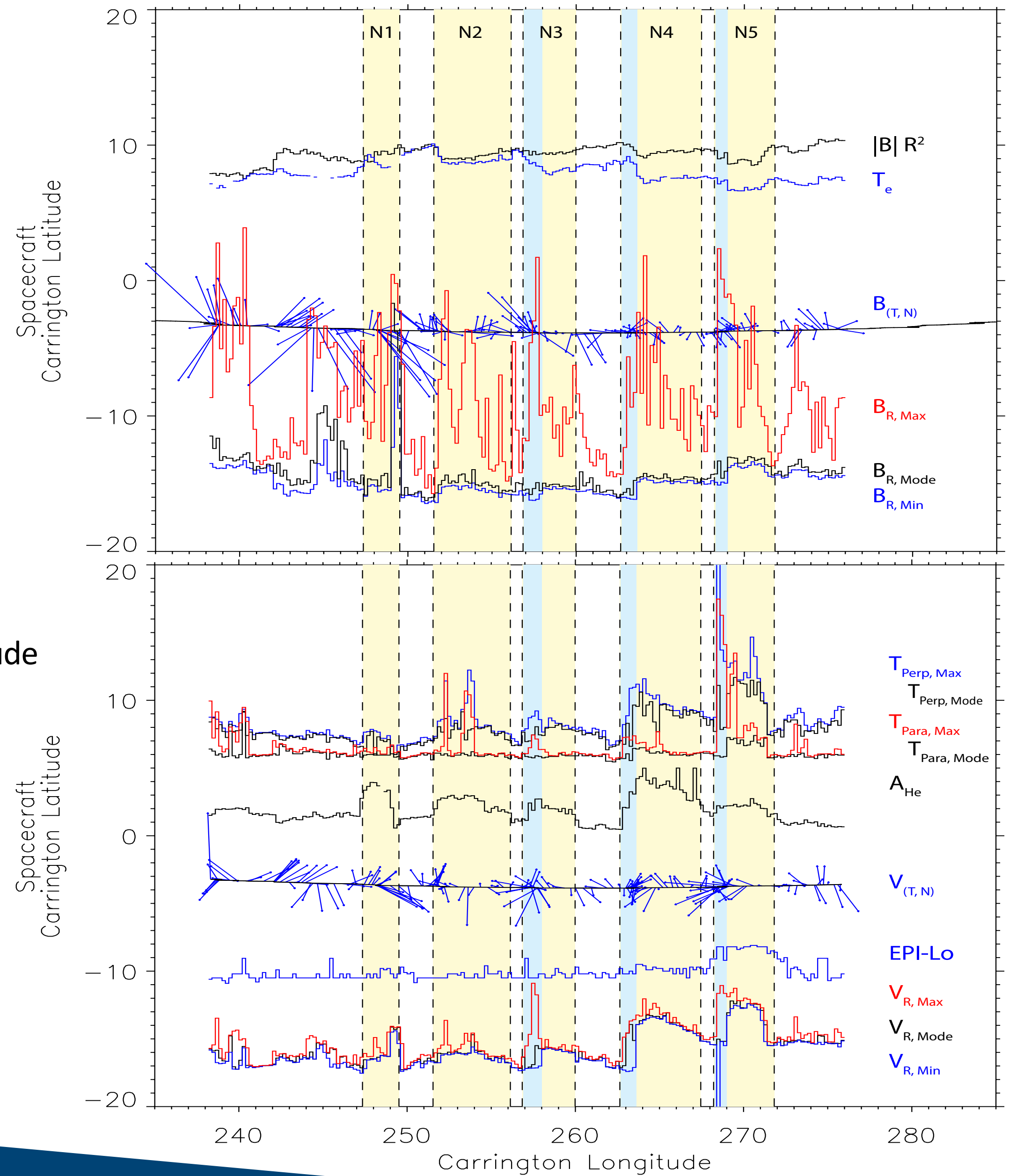
|B| in upper panel
B_R in upper panel

A_{He} in lower panel
V_R in lower panel
Proton temperatures in lower panel
EPI-Lo ions in lower panel

Mapped ballistically into Carrington longitude

Yellow bars are enhanced A_{he}
Blue bars are hotter leading edge

- Structure is clustered near boundaries
- Switchbacks are clustered near leading edge



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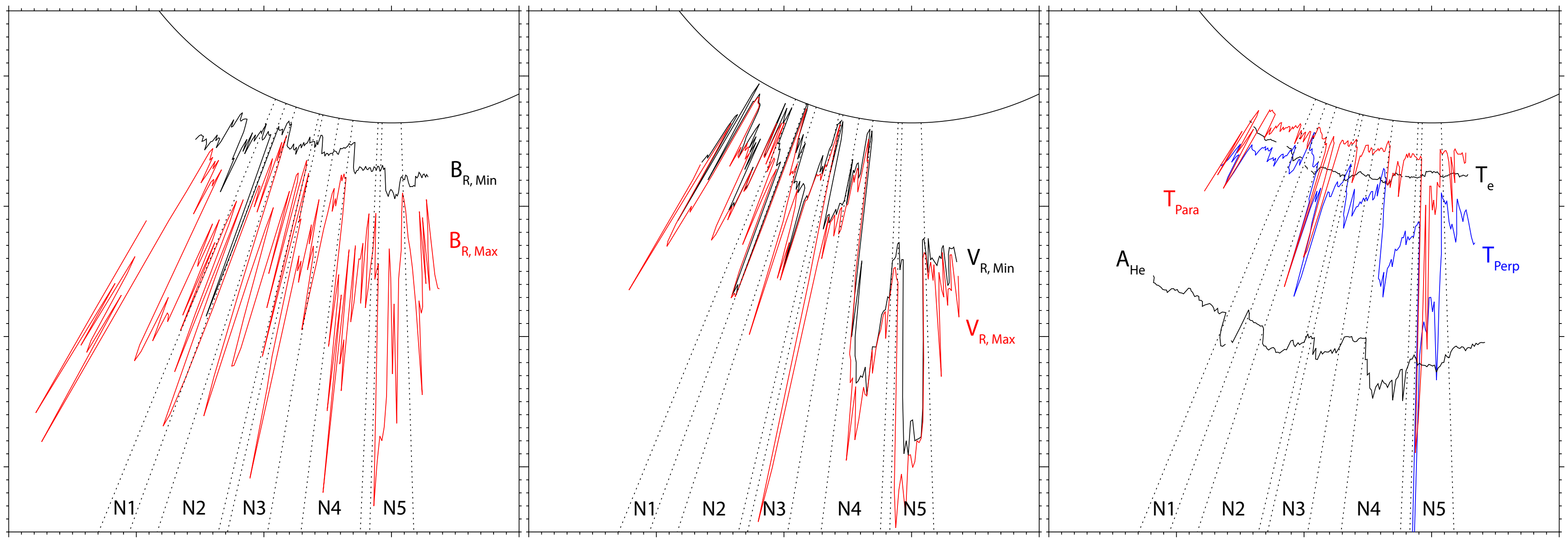
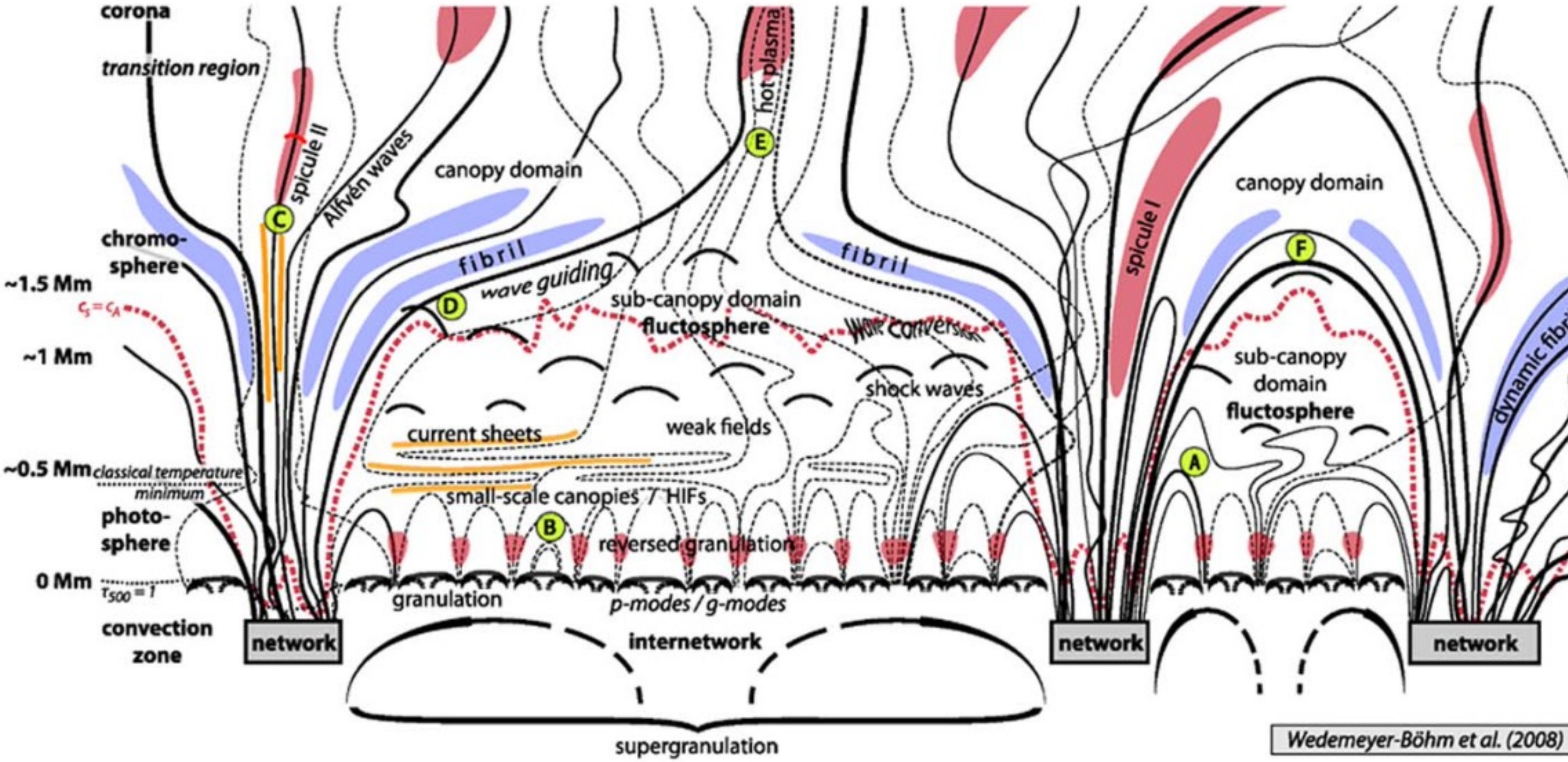
Polar representation



Magnetic ‘funnels’ at network field concentations



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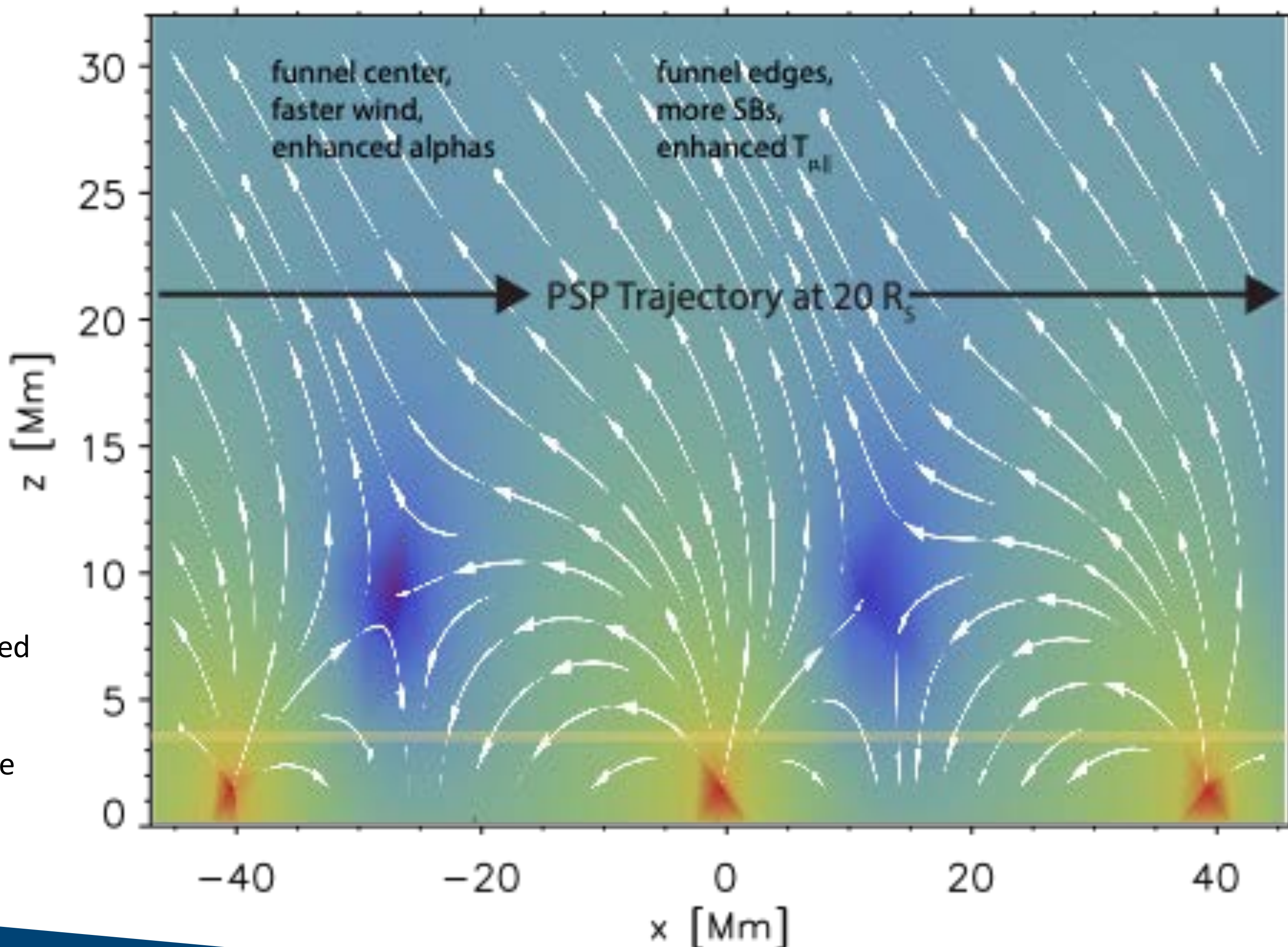
Potential field solution with shear field – (a la Hackenberg and Mann, 2000)

Superradial expansion gives |B| depression in center
- B_R ~ 1/A
- B_(T,N) ~ 1/sqrt(A)

- Cusp regions between nodes
- Cusps have antiparallel geometry (in 2D)
- Cusp altitude is controlled by shear field
- Cusp altitude might control alpha abundance



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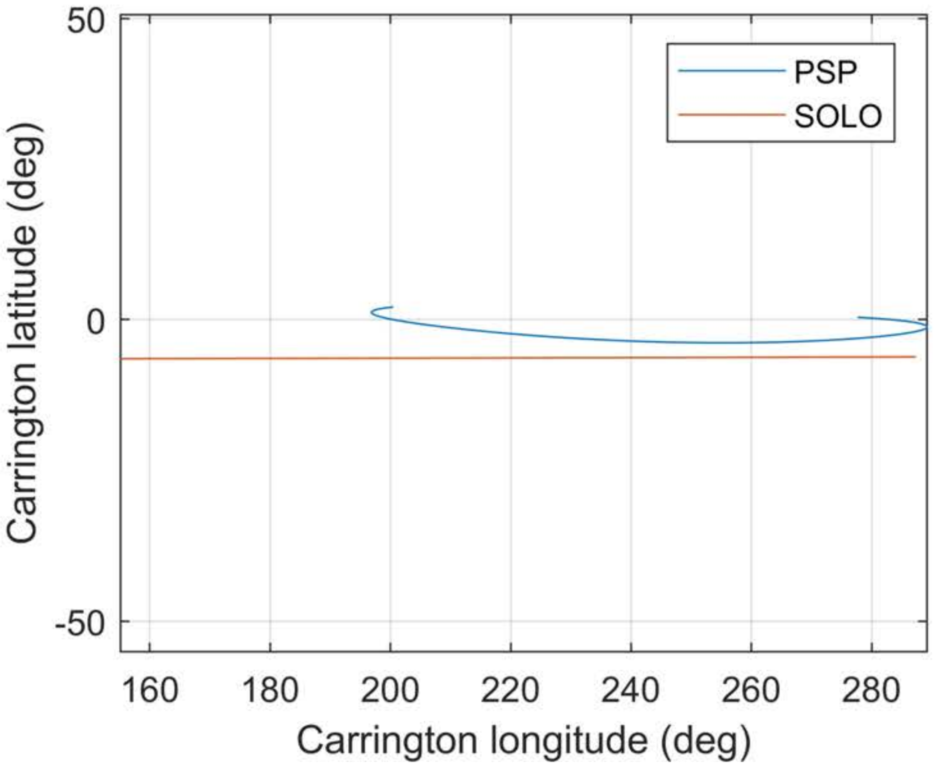
Solar Orbiter and PSP

- Similar Carrington longitudes during E6
- Measured solar wind from same sources
  - But not wind released at the same time!
- Importantly, also very similar latitude



(Horbury et al)

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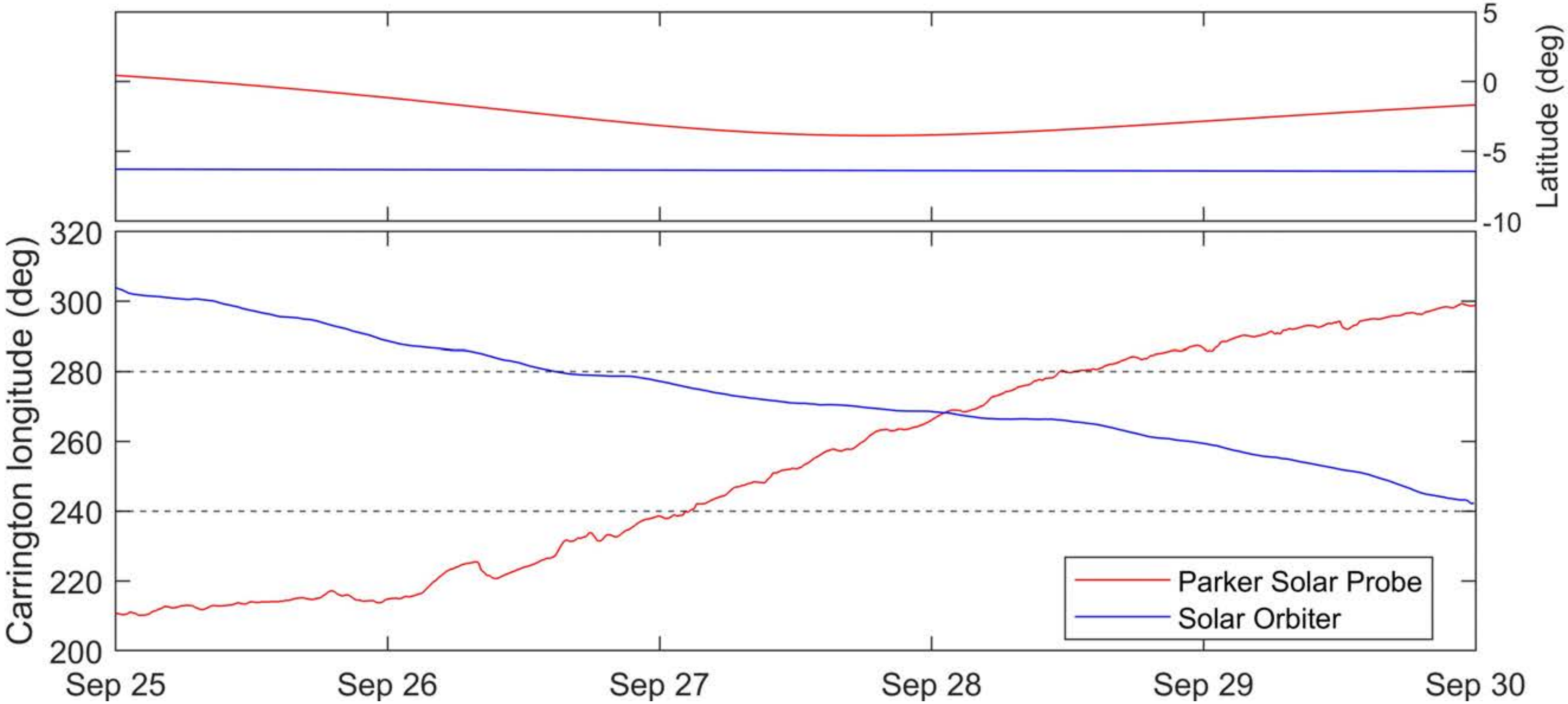
Ballistic mapping to $2.5R_S$ source surface



(Horbury et al)

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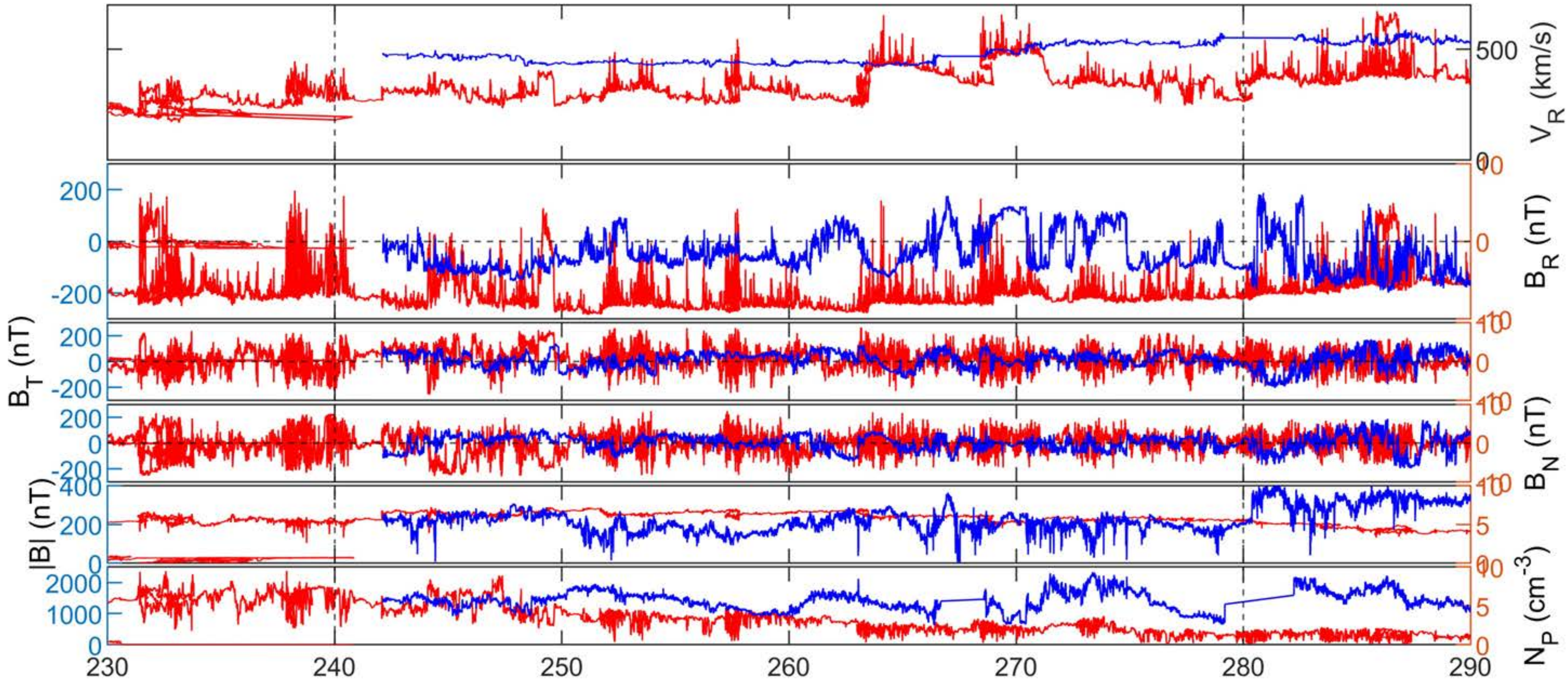
Parker
Orbiter



Source Carrington longitude (deg)

(Horbury et al)

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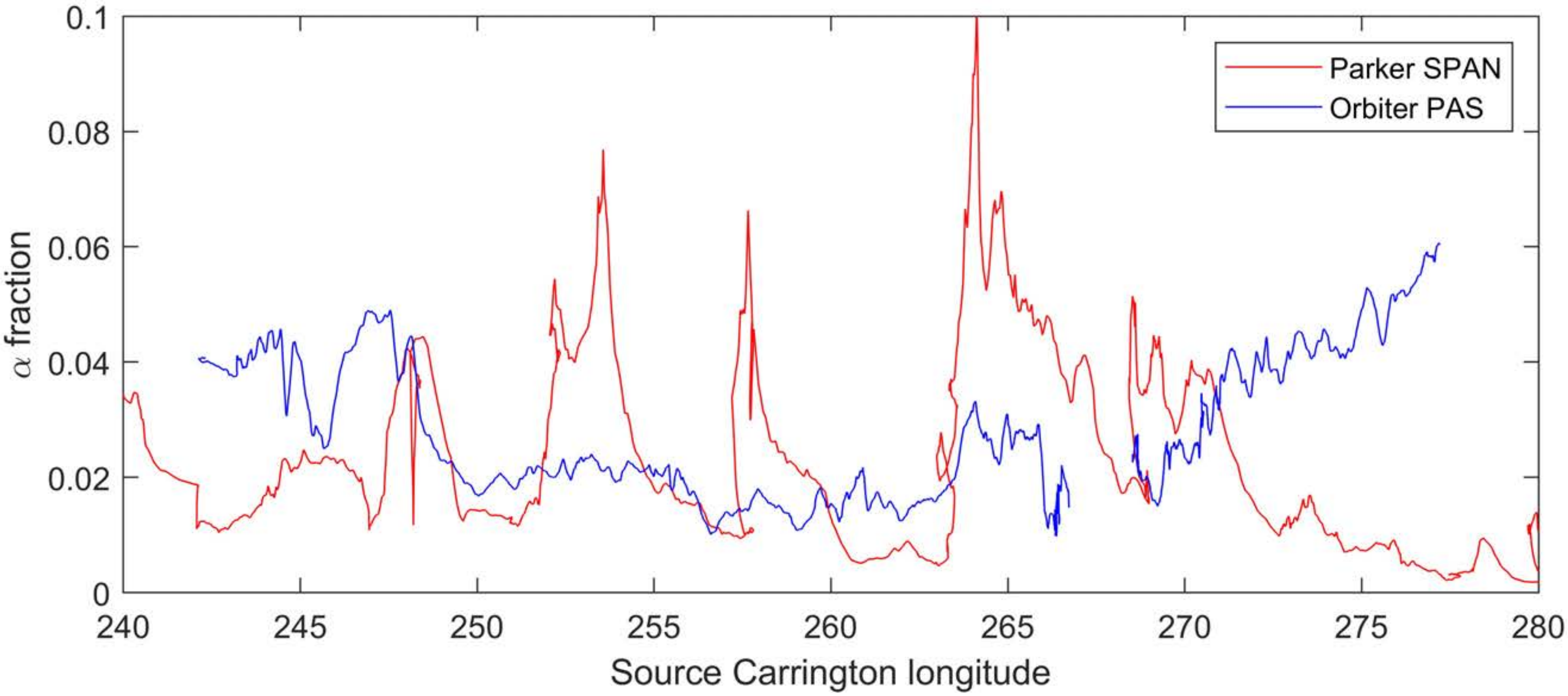

(Horbury et al)

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Observations

- Switchbacks are modulated on supergranulation angular scales
- Photospheric field has B^2 modulations on similar scales
- Pressure balanced – spatial structure at 20 Rs
- Fast wind-like (higher) A_{He} and lower strahl energy – frozen-in from source, associated with open magnetic field
- Higher β, hotter ions, and flow speed within structures
- Suprathermal ions to 85 ~keV
- Depressed |B| – overexpansion of magnetic field below PSP – funnels
- $v_p \sim v_{HT}$ (not shown)
- Structure is **mostly evolved away** by 200 Rs
- Similar events for Encounters 07, 08, and 09
  - Why not before? Dispersion of alpha population maybe?

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CrossMark

Characteristic Scales of Magnetic Switchback Patches Near the Sun and Their Possible Association With Solar Supergranulation and Granulation

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Parker Solar Probe (PSP) data recorded within a heliocentric radial distance of 0.3 au have revealed a magnetic field dominated by Alfvénic structures that undergo large local variations or even reversals of the radial magnetic field. They are called magnetic switchbacks, they are consistent with folds in magnetic field lines within a same magnetic sector and are associated with velocity spikes during an otherwise calmer background. They are thought to originate either in the low solar atmosphere through magnetic reconnection processes or result from the evolution of turbulence or velocity shears in the expanding solar wind. In this work, we investigate the temporal and spatial characteristic scales of magnetic switchback patches. We define switchbacks as a deviation from the nominal Parker spiral direction and detect them automatically for PSP encounters 1, 2, 4, and 5. We focus in particular on a 5.1 day interval dominated by switchbacks during E5. We perform a wavelet transform of the solid angle between the magnetic field and the Parker spiral and find periodic spatial modulations with two distinct wavelengths, respectively consistent with solar granulation and supergranulation scales. In addition we find that switchback occurrence and spectral properties seem to depend on the source region of the solar wind rather than on the radial distance of PSP. These results suggest that switchbacks are formed in the low corona and modulated by the solar surface convection pattern.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Solar physics (1476); Wavelet analysis (1918); Supergranulation (1662); Solar granulation (1498); Solar magnetic fields (1503)

Supporting material: figure set

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