

(Towards) Mapping the Sun's Alfvén Zone with PUNCH

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Outline

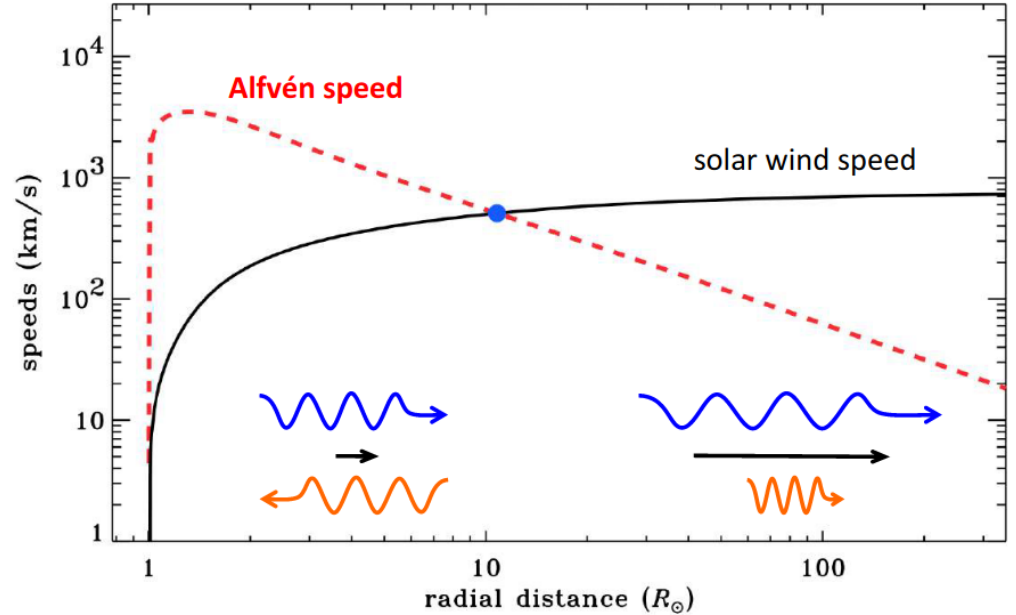
- Introduction and overview of Alfvén radius/surface/zone
- Recent insights from in-situ observations and global modeling
- Fourier motion filtering to separate inbound/outbound features in image sequences
- Preliminary results from PUNCH data

The Alfvén "radius"

r_A is distance where $U > V_A$, where

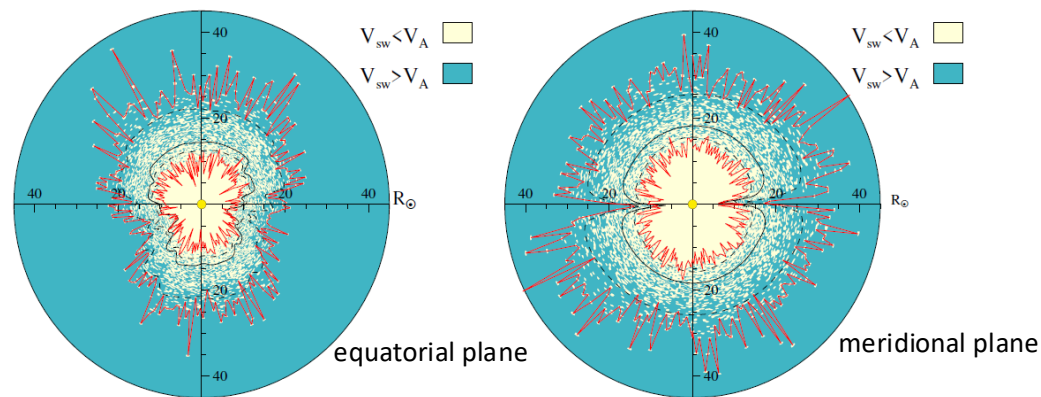
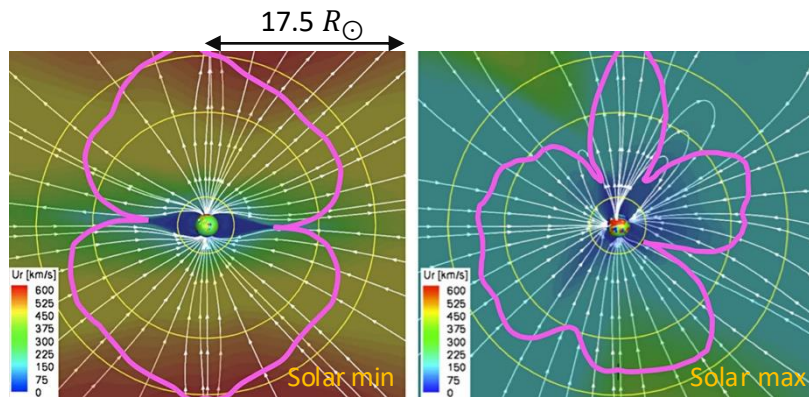
$$V_A = \frac{B}{\sqrt{4\pi\rho}}$$

- Below r_A , information (waves) can propagate both Sunward & outward.
Above r_A , the solar wind advects both inward & outward modes
- Strong transfer of angular momentum from Sun to wind below r_A ; Below r_A , magnetic field is effective in maintaining near-corotation of plasma with Sun (Weber & Davis 1967)
- In-situ dynamics like magnetic switchback formation and flocculation may "turn on" above r_A (DeForest+ 2016; Ruffolo+ 2020; Pecora+ 2022)



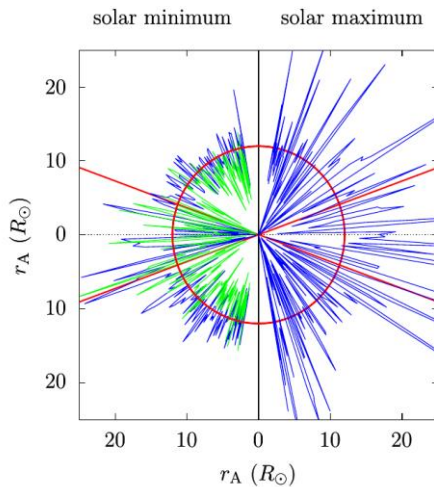
Credit: Prof. Steve Cranmer

The transition from subAlfvénic to superAlfvénic flow is complex, dynamic, and irregular. It may occur across an extended and fragmented Alfvén “zone”

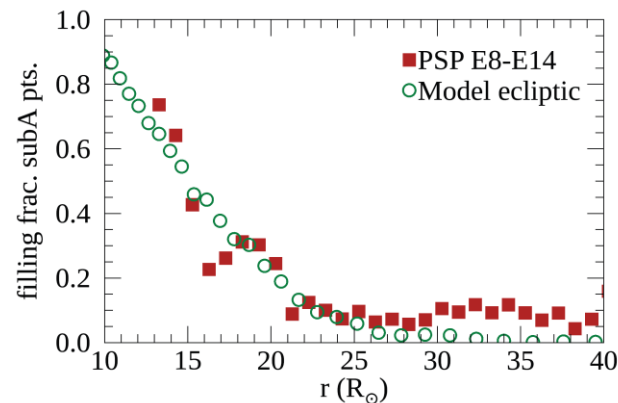


Top: Meridional planes in MHD model (Cohen 2015). Large-scale variability – solar-source related; solar activity effects

Right: Verscharen+ 2021; *Ulysses* data indicate variability in heliolatitude at finer scales

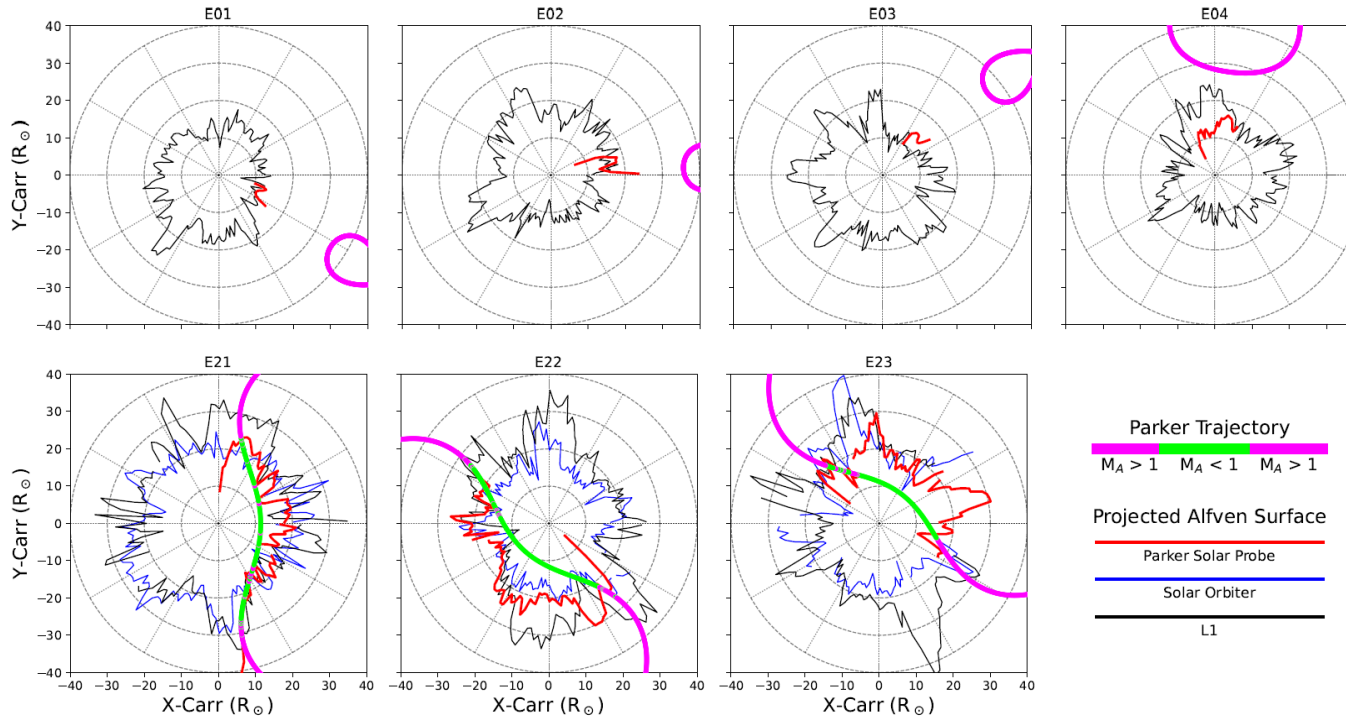


Top: Global MHD simulation with turbulence modeling (Chhiber+ 2022)
Bottom: Filling fraction of subAlfvénic points vs helioradius (Chhiber+ 2024)



Multispacecraft Measurements of the Evolving Geometry of the Solar Alfvén Surface over Half a Solar Cycle – Badman et al. 2025

- PSP, SolO, L1 observations from 2018-2025
- From in-situ observations, obtain radial profiles of speed from empirical model that incorporates acceleration; mass and magnetic flux conservation gives density and magnetic field



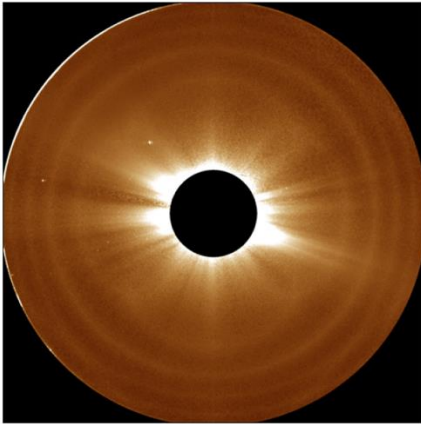
Plots show median values of r_A in 1° longitude bins

Alfven surface from coronal imaging, by separating inbound/outbound motions

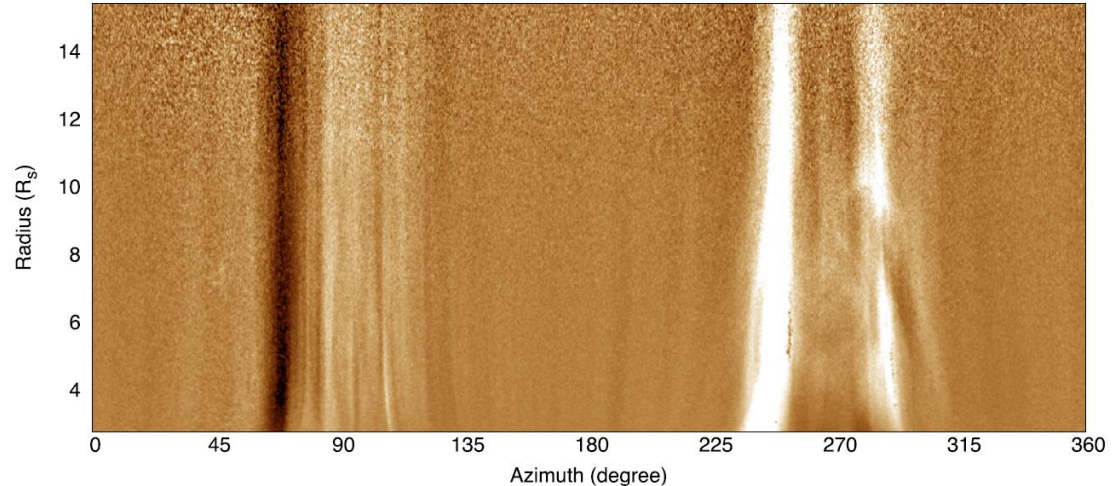
DeForest+ 2014, STEREO/COR2

- Inbound (Sunward moving) features in coronal imagers indicate subAlfvenic solar wind flow
- Fourier motion filter can separate inbound features from the (dominant) outbound ones

STEREO-A COR2 2007-08-05 22:07 (L2)



COR-2A: 2007 Aug 08 21:37



COR2 image, background and starfield removed
($\sim 3 - 15 R_{\odot}$)

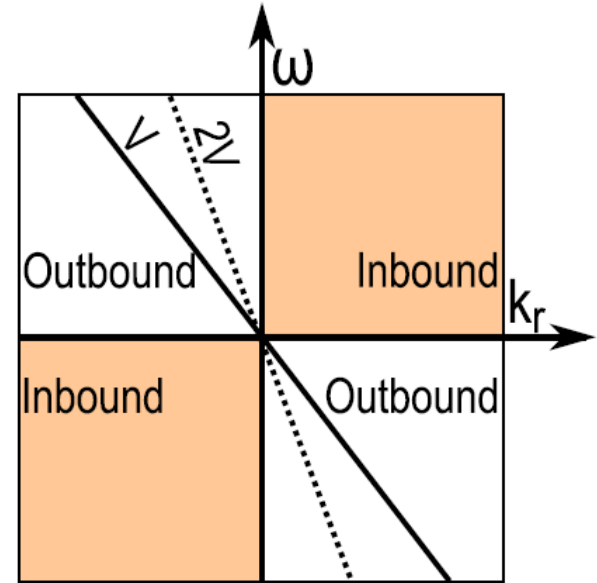
DeForest+ 2014

- Temporal sequence of such images forms 3D datacube in r, ϕ, t
- Mean gradient in brightness removed by subtracting from each “row” the mean across columns (ϕ) and time
- Normalized by standard deviation
- 3D datacube in r, ϕ, t

Fourier motion filter to separate inbound and outbound features

DeForest+ 2014, STEREO/COR2

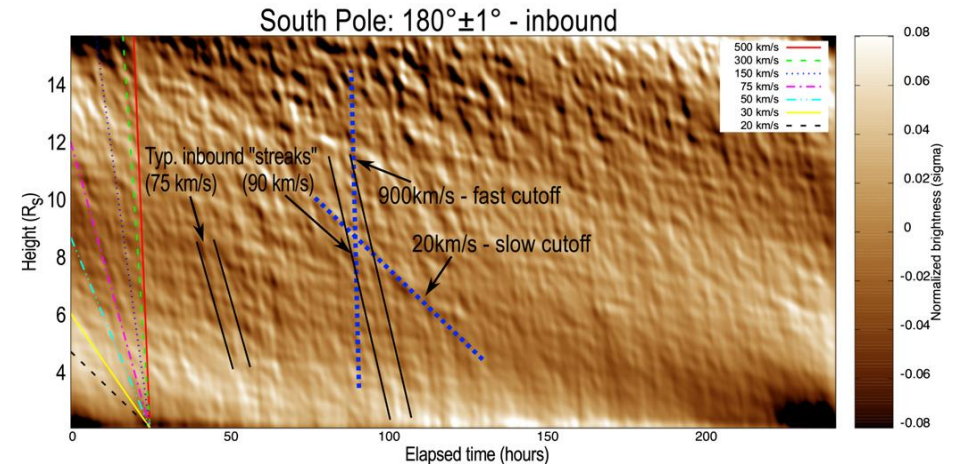
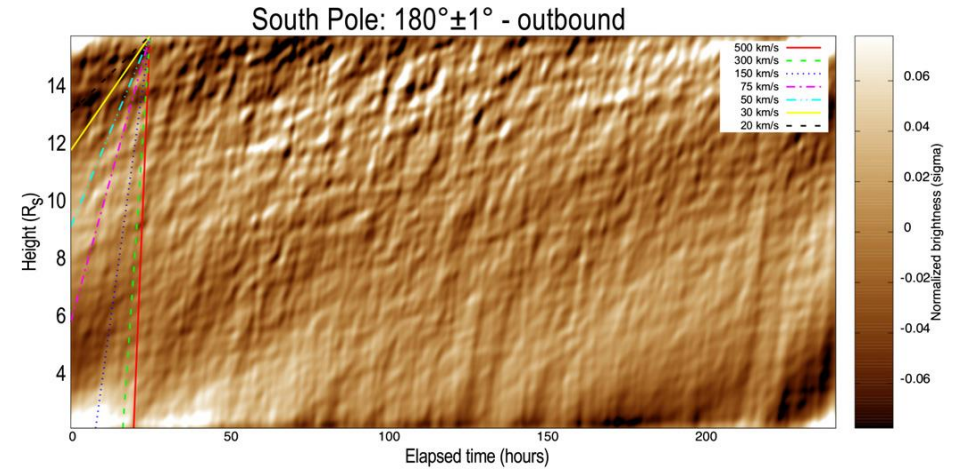
- Fourier transformation in r and t , yielding, for each ϕ , a k_r - ω distribution
- Moving features are localized by speed and direction in the k_r - ω plane, with speed $V = -\frac{\omega}{k_r}$
- Regions in k_r - ω plane with $k_r\omega > 0$ and $k_r\omega < 0$ correspond to inbound and outbound motions, respectively
- “Zero out” the appropriate regions in k_r - ω plane and reverse Fourier transform to real space



Alfven surface from coronal imaging, indicated by inbound features

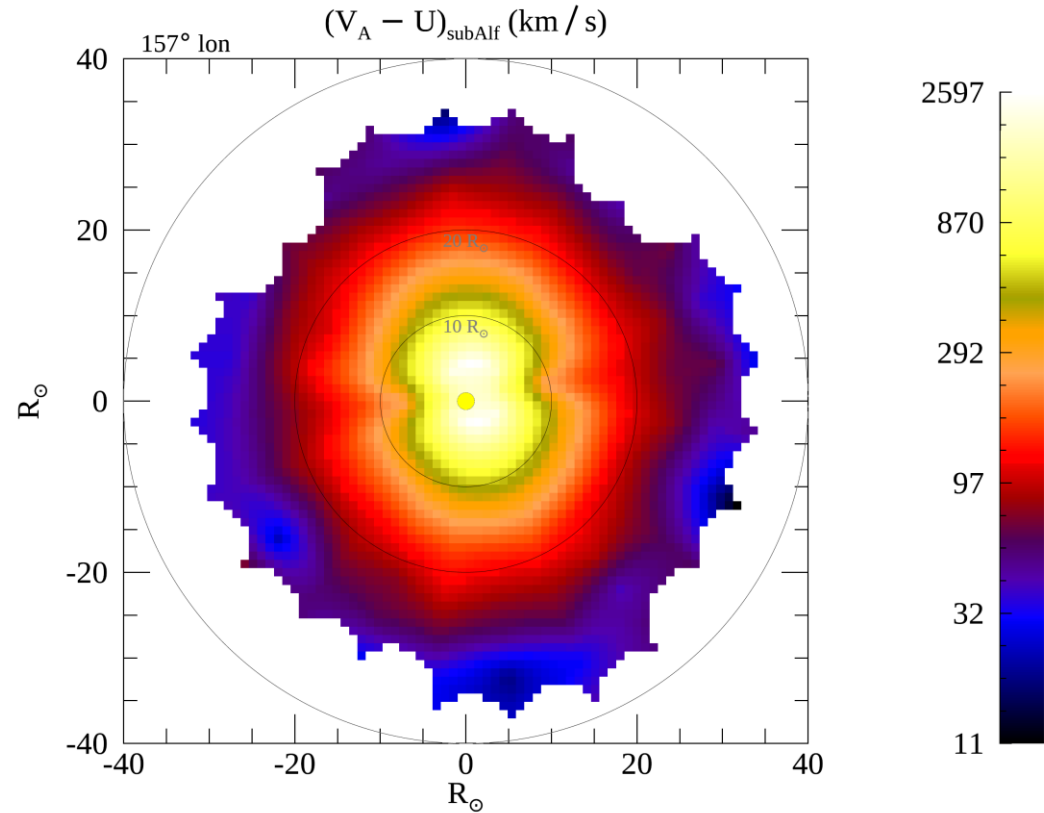
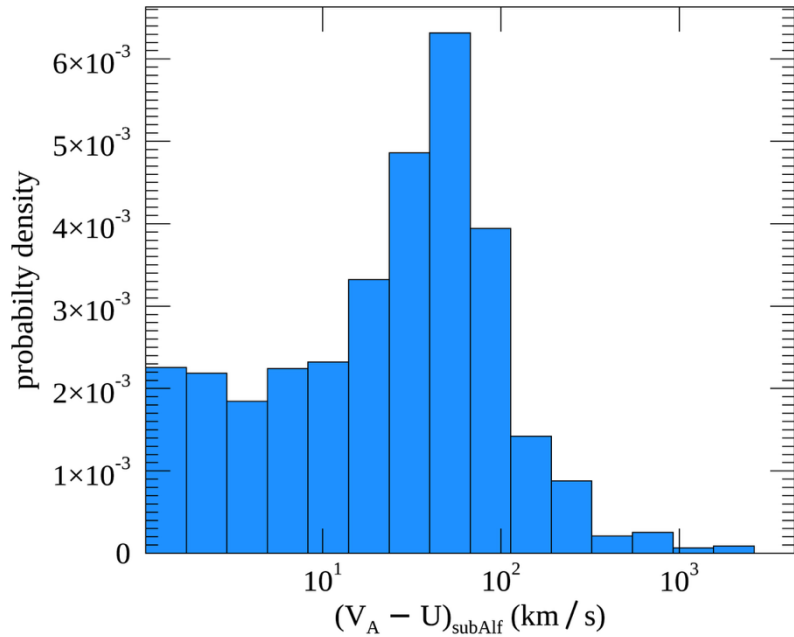
DeForest+ 2014, STEREO/COR2

- *Right:* Height vs time plots for outbound and inbound cases, at fixed ϕ
- Lower bounds for r_A estimated at ~ 12 to $15 R_\odot$
- Can estimate speeds of typical inbound “streaks”



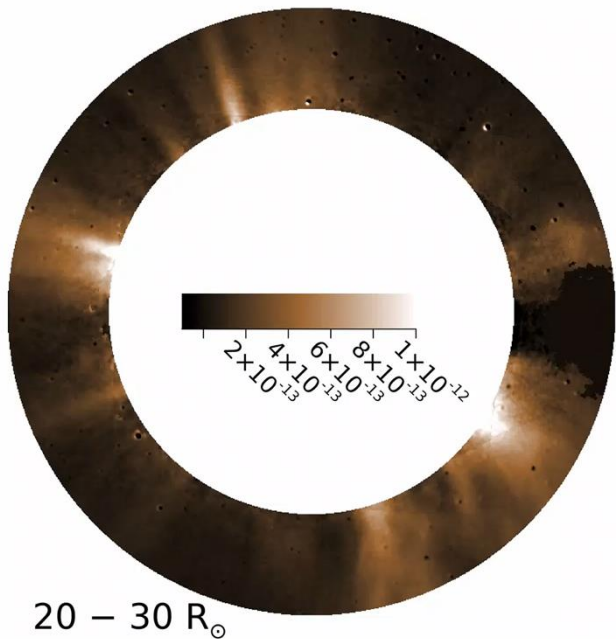
Inbound flow speeds from global modeling

$(V_A - U_{sw})_{\text{subAlfvenic}}$ (km/s)



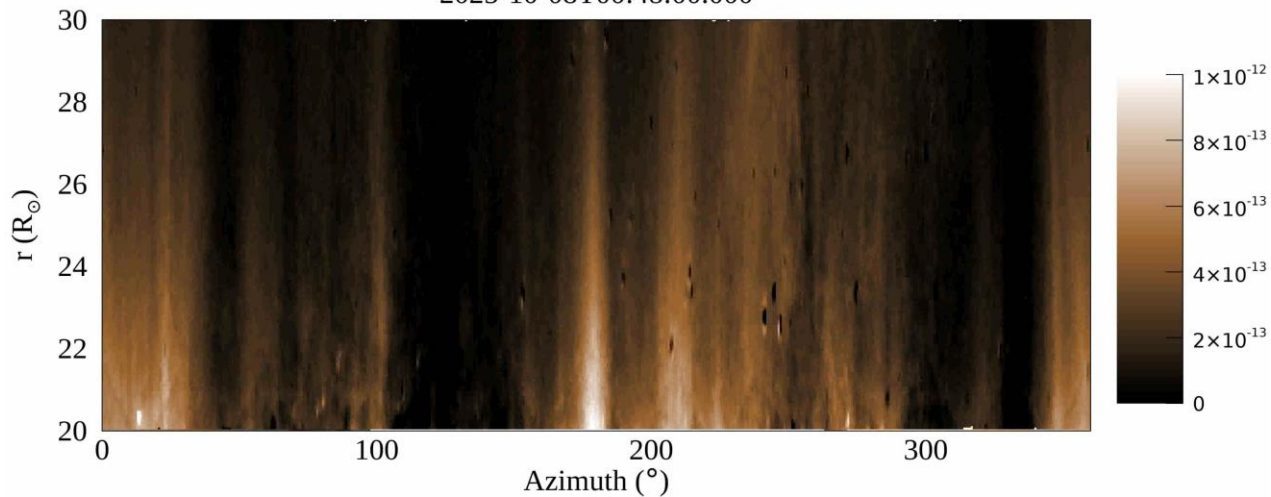
Fourier motion filtering applied to PUNCH observations

2025-10-01T00:16:00.000



10 days of v0k CAM images (32 min cadence)

2025-10-08T00:48:00.000

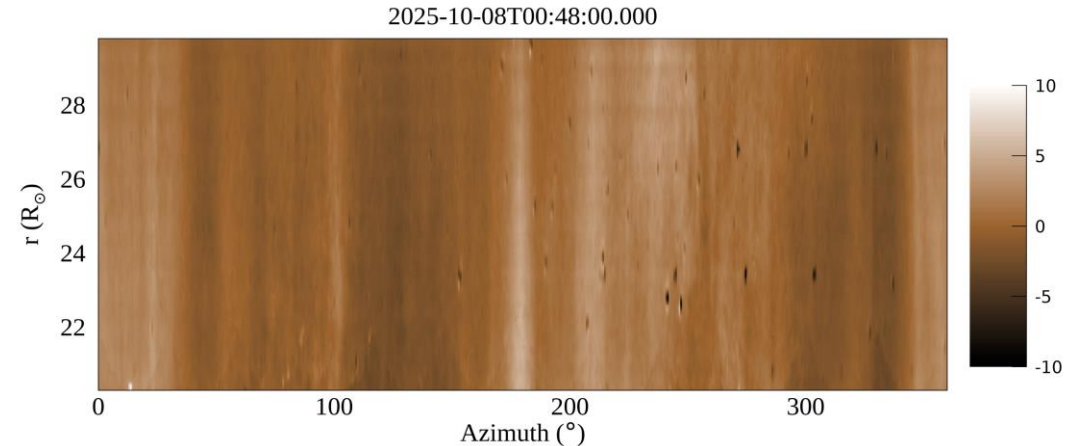
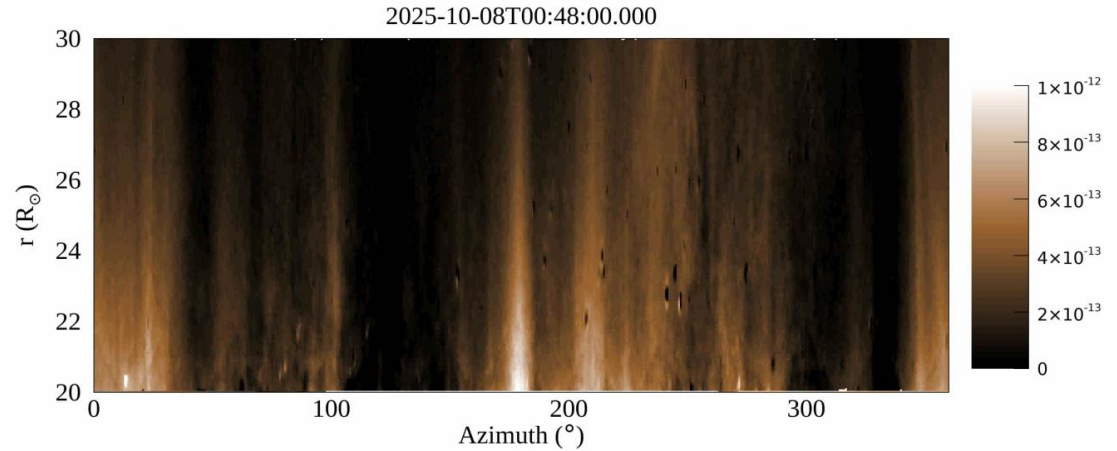


Interpolated to regular r - ϕ grid

Fourier motion filtering applied to PUNCH observations

Ten days of these images (32 min cadence) form a 3D datacube in r , ϕ , time

- Mean gradient in brightness removed by subtraction of mean across ϕ and time, at fixed r
- Normalized by standard deviation, similarly computed

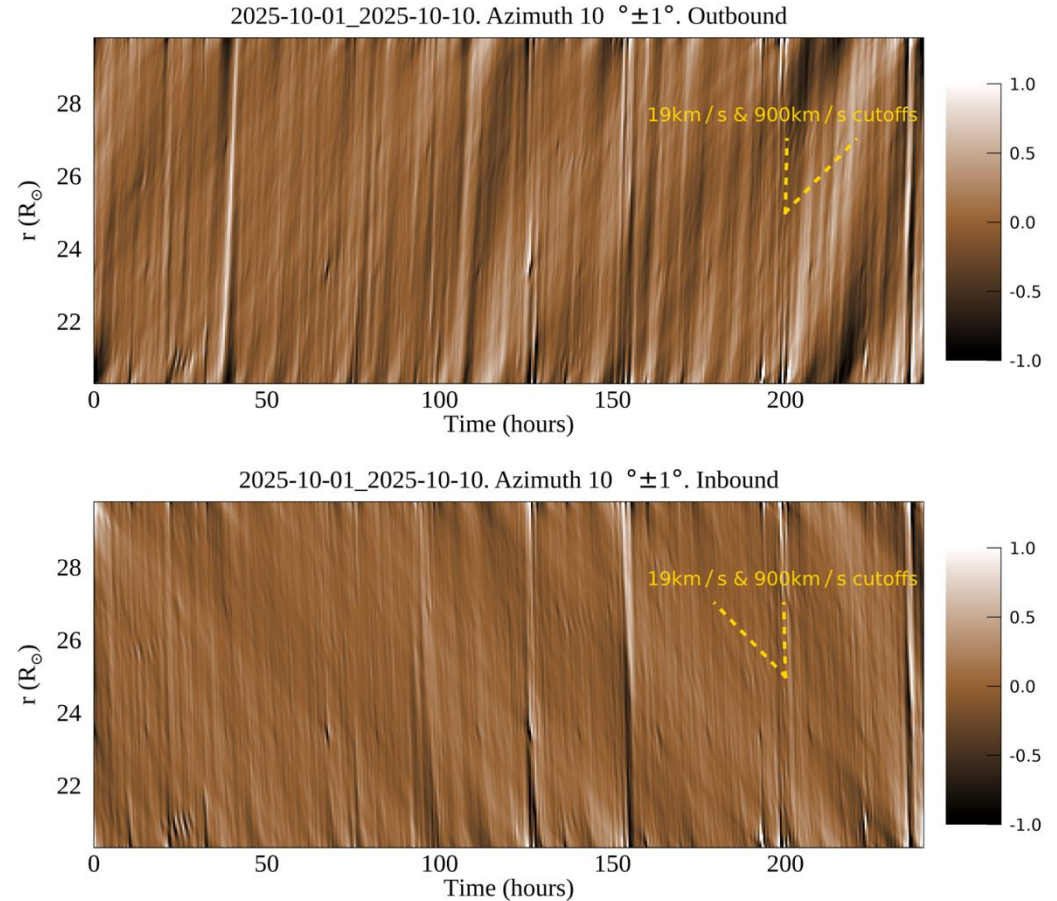


Fourier motion filtering applied to PUNCH observations

- Fourier transformation in r and t , yielding, for each ϕ , a k_r - ω distribution
- Apply speed cutoffs at 19 km/s and 900 km/s
- “Zero out” inbound/outbound regions in k_r - ω plane and reverse Fourier transform to real space to obtain temporal sequence of outbound/inbound images

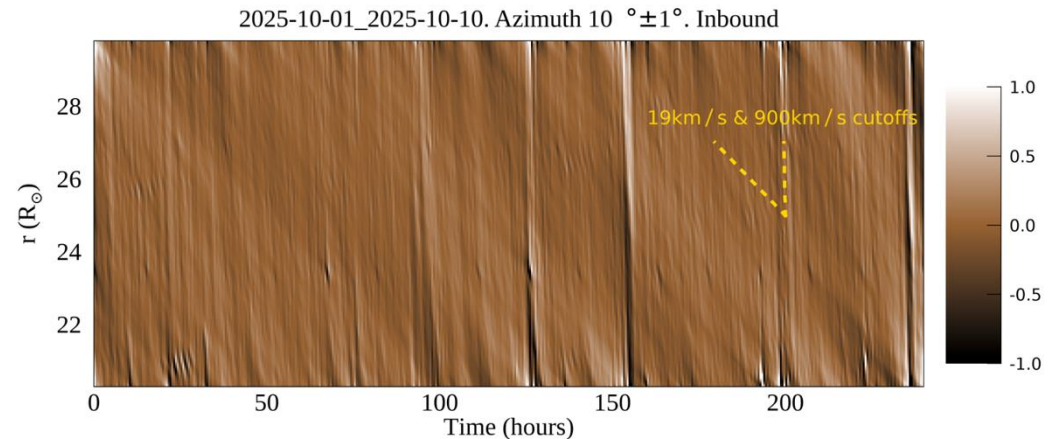
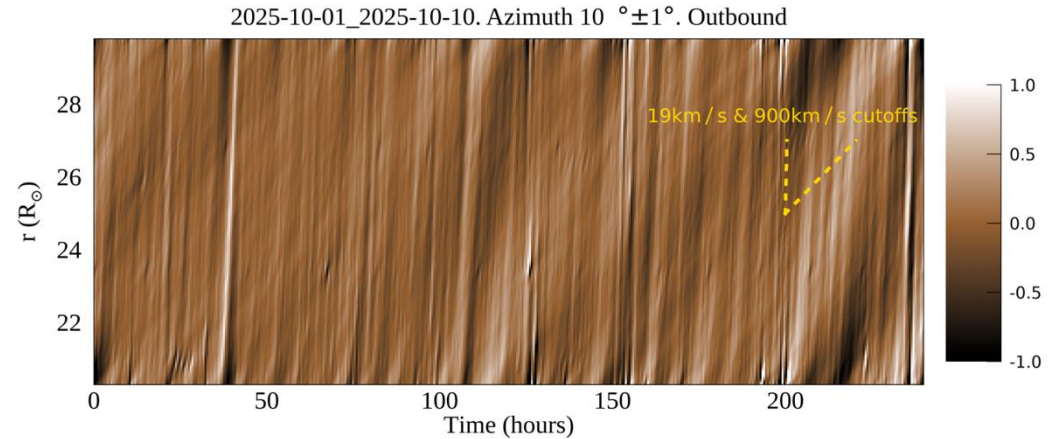
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- Example radius-time plots at $\phi = 10^\circ$ are shown on the right



Fourier motion filtering applied to PUNCH observations - CAVEATS

- Preliminary data and preliminary analyses (see also poster by Mateo Admire)
- Prime region of interest for Alfvén zone may be 10 to 20 R_{\odot} ; NFI data desirable
- Careful analysis of signal to noise is required (DeForest+ 2014)

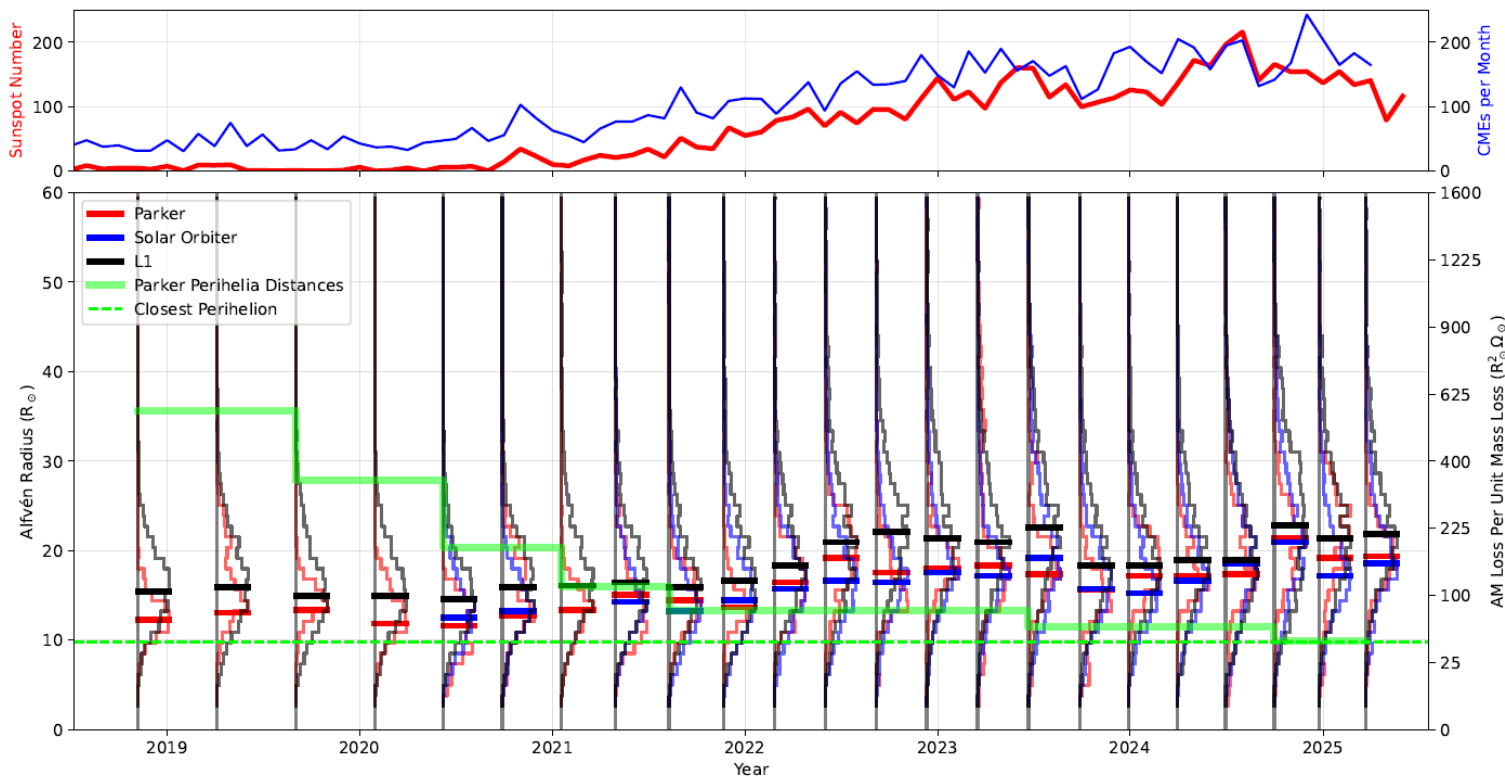


Looking ahead...

- Concurrent in-situ (PSP) and remote observations of the Alfvén zone (PUNCH and others) are available; very interesting period for researchers interested in understanding the properties of this key astrophysical interface
- Upcoming studies with v1 PUNCH data, esp. NFI
- CMEs may “push out” the Alfvén region to WFI FoV (Badman+2025; Jagarlamudi+ 2025; Gurram+ 2026)

Multispacecraft Measurements of the Evolving Geometry of the Solar Alfvén Surface over Half a Solar Cycle – Badman et al. 2025

- Evolution of Alfvén “radius” with sunspot number, and associated doubling of angular momentum ($L = \Omega_{\odot} r_A^2$)



Multispacecraft Measurements of the Evolving Geometry of the Solar Alfvén Surface over Half a Solar Cycle – Badman et al. 2025

- Evolution of “thickness” and “asphericity” of Alfvén surface with sunspot number

