PUNCH Remote Sensing to In-Situ Connections

Heather Elliott[1] (helliott@swri.edu), David Webb[2],
Nicholeen Viall[3], and Anna Malanushenko[4]

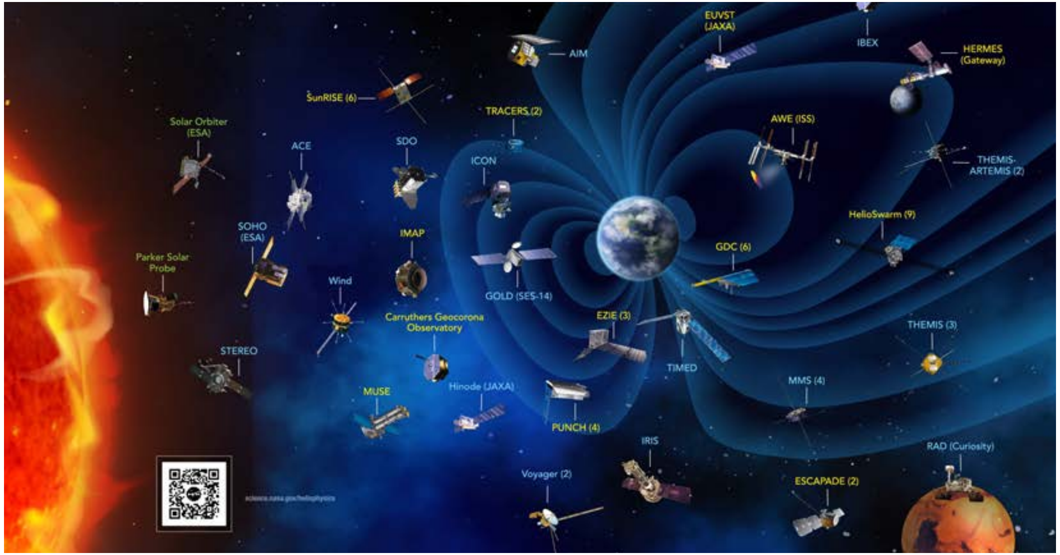
[1]Southwest Research Institute in San Antonio, [2]Boston University, [3]NASA Goddard Space Flight Center, [4]High Altitude Observatory National Center for Atmospheric Research

PUNCH 4 Science Team Meeting Boulder CO

Friday July 7, 2023 11:15am

Introduction

- Leveraging the Heliophysics System Observatory (HSO) to maximize the scientific return for PUNCH.
- Take advantage of spacecraft alignments.
- Combine data sets to improve the assimilations, tomography, and models.
- Use in situ observations to test assimilations, tomography, and models.



- Develop and test space weather products using PUNCH observations

Missions and Other Data Sources

Imaging:

- STEREO – coronagraph, EUV, heliospheric imaging; especially in quadrature
- SWFO-L1 – coronagraph
- SOHO – LASCO coronagraphs, EIT
- GOES -16 – SUVI
- Parker Solar Probe – WISPR
- Solar Orbiter - Heliospheric Imager (SoloHI), EUI

In Situ:

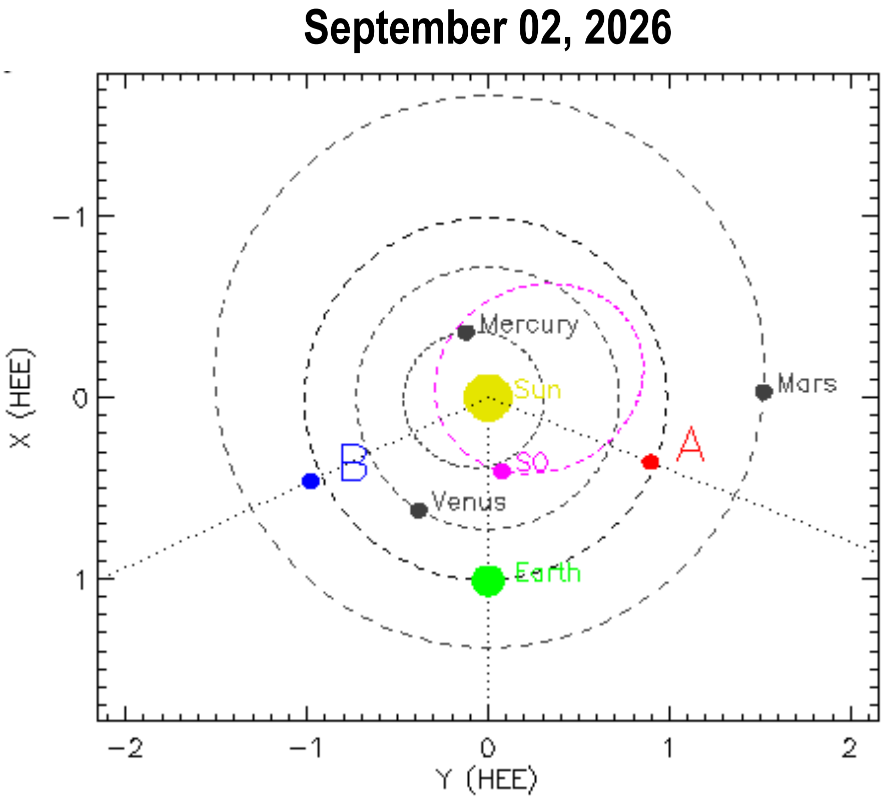
- L1/Earth - (IMAP, ACE, Wind, SWFO-L1, DSCOVR), solar wind, IMF, SEPs etc
- In situ at other locations (STEREO, Parker, Solar Orbiter, Bepi-Columbo) leverage alignments

Other

- Interplanetary Scintillations (IPS) – input to assimilations
- Magnetographs (GONG) –input to models and assimilations
- Radio bursts (SO, PSP, WIND)
- Ground-based Coronagraphs (Mauna Loa Solar Observatory)

Spacecraft Alignments

- **Radial Alignments**
  - Study specific solar source regions with image tracking combined with solar wind composition.
  - Study the dynamic evolution of the solar wind with tracking and solar wind and IMF observations.
- **Quadrature**
  - Improved tomography by combining PUNCH imaging with side view imaging.
- Many spacecraft alignments occur about once a year.
- Example: September 2, 2026 Solar Orbiter will be in near radial alignment with Earth/L1 when STEREO A has a side view.



Some Possible Combined In Situ and PUNCH Studies (1/2)

- Track specific parts of CMEs (sheaths, ejecta etc) and compare specific substructure features in ICMEs found in the solar wind and IMF properties and solar wind composition.

- Use tracking to understand specific sources of the background solar wind (slow, blobs, fast, moderately fast wind).

- Quantify the radial evolution of the solar wind dynamic interactions and steepening and formation of shocks.

- Quantify the amount of SEP enhancement that occurs en route as shocks develop.

Some Possible Combined In Situ and PUNCH Studies (2/2)

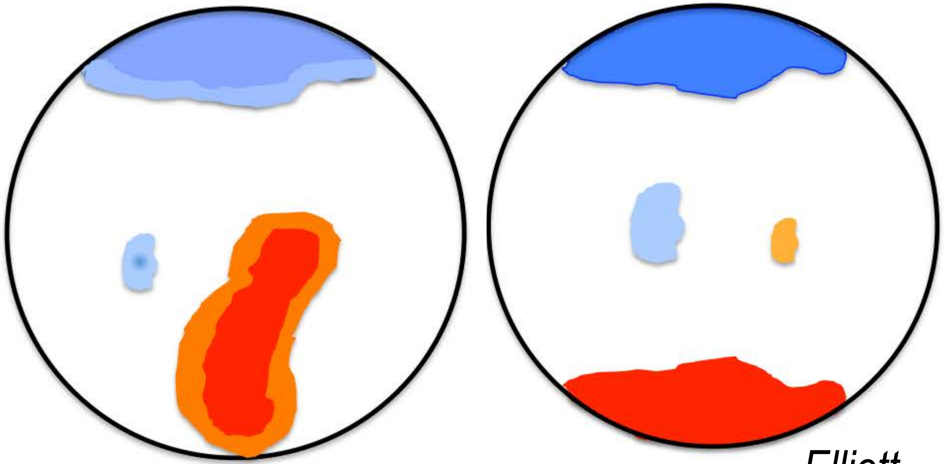
- Comet tails: How long are they?
  - Some tails have been shown to be 1 to 3 au in length.
  - Look for comet tail crossing alignments with other S/C having in situ observations.

- Use statistical relationships between solar wind and IMF parameters to constrain assimilations, tomography and models.

- Combine PUNCH results with statistical relationships to create space weather forecast capabilities.
  - Estimate the size and arrival times of CMEs and shock fronts.
  - Estimate the solar wind density, temperature, and field strength from speed measurements.
  - Estimate the magnetic field from Faraday rotation.
  - SEP enhancements at shocks linked the shock speed and compression ratio.
  - Kp and AP indices which correlates with solar speed and density.
  - ULF magnetospheric waves driven by solar wind density structures.

Source Properties & Dynamic Interactions

Source Properties

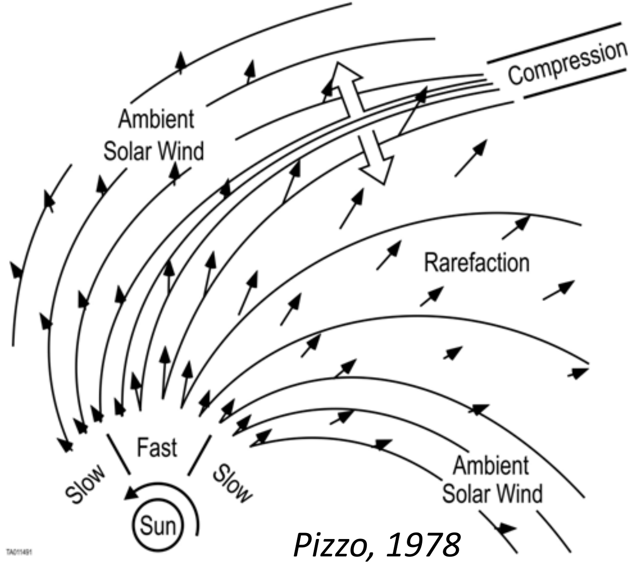


Elliott

Does the moderately fast wind come from the edges of holes or from only small holes?

Is the speed of the solar wind determined in the low corona?

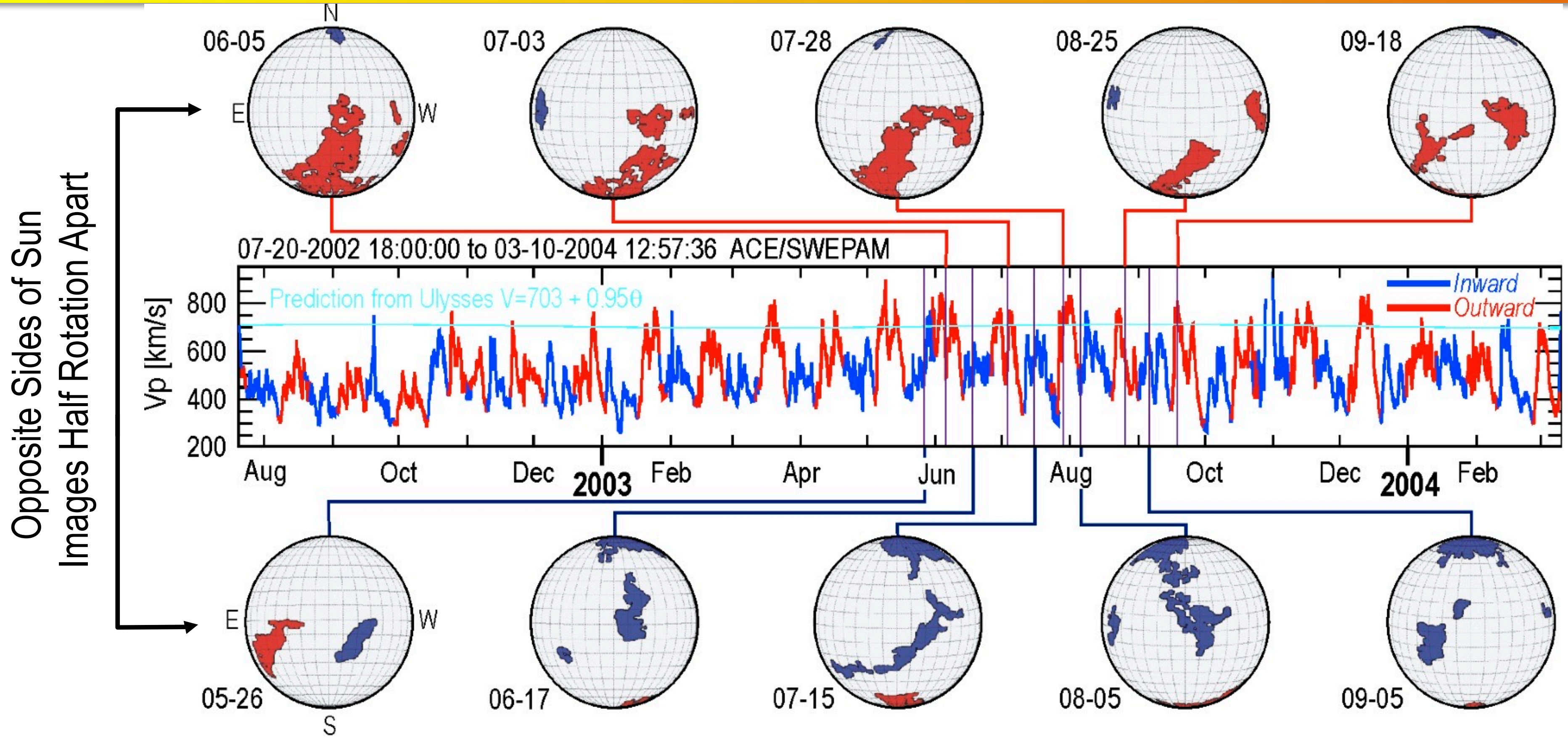
Dynamic Interactions



Pizzo, 1978

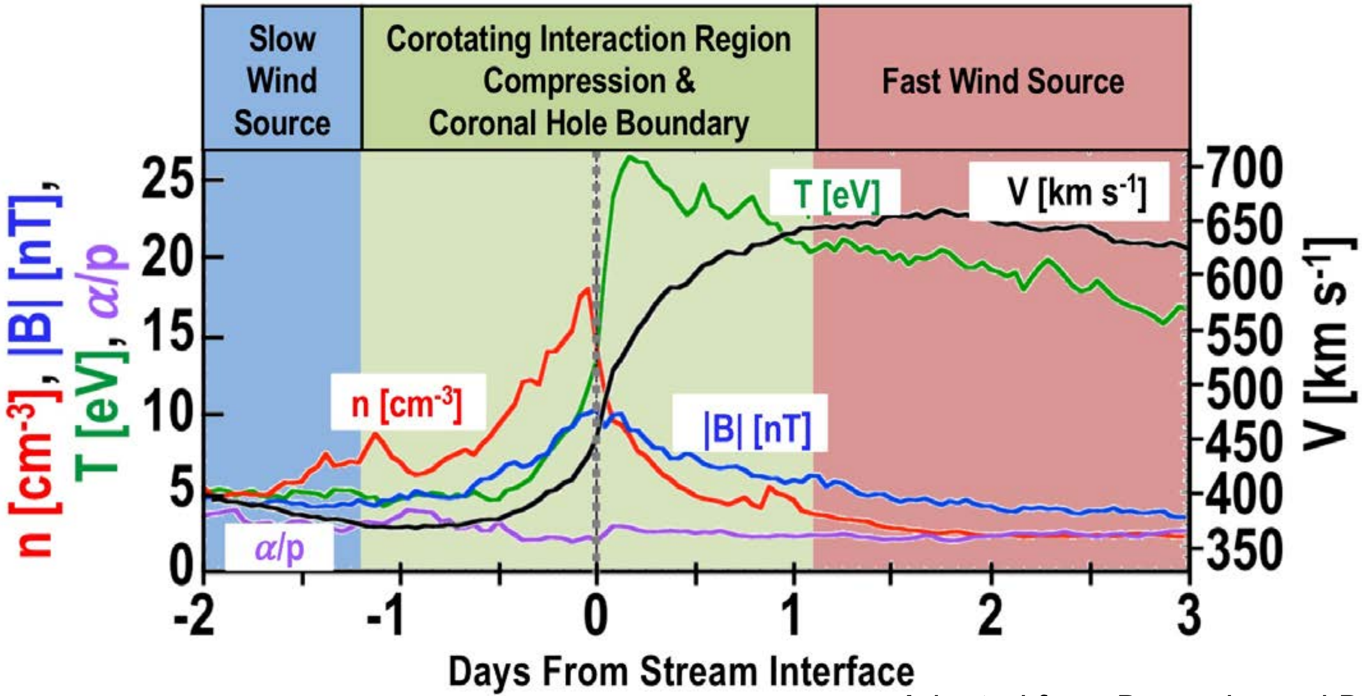
Dynamic interactions between differing speed parcels cause the plasma properties to evolve with distance.

Corona Holes Emit Wind with a Range of Speeds



Elliott et al. 2012

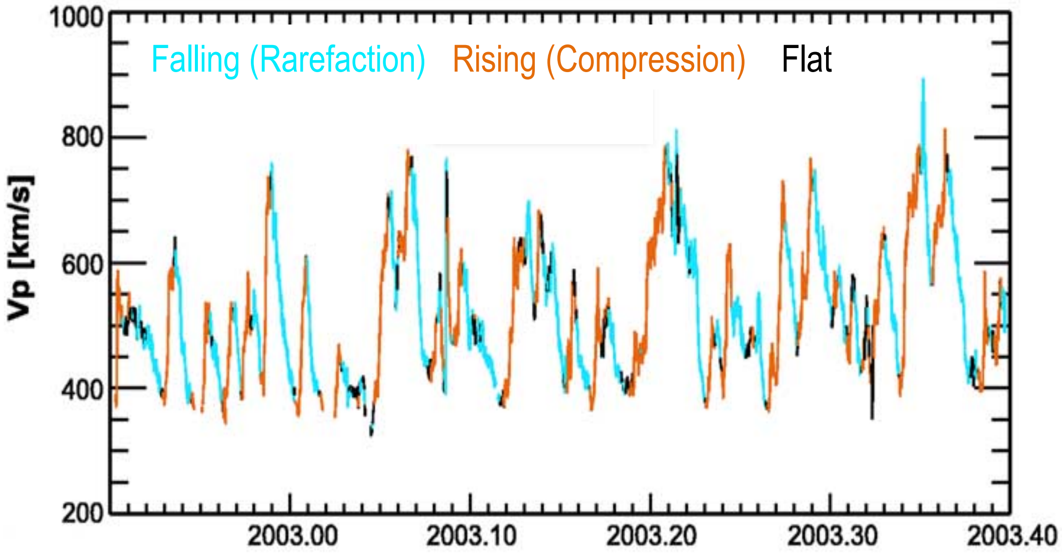
Dynamic Interactions & Source Properties



Adapted from Borovsky and Denton, 2010

Superposed epoch analysis of 27 CIRs illustrates contributions of source properties and dynamic interactions, which produce correlations amongst solar wind and IMF parameters.

Revealing Dynamic Interactions

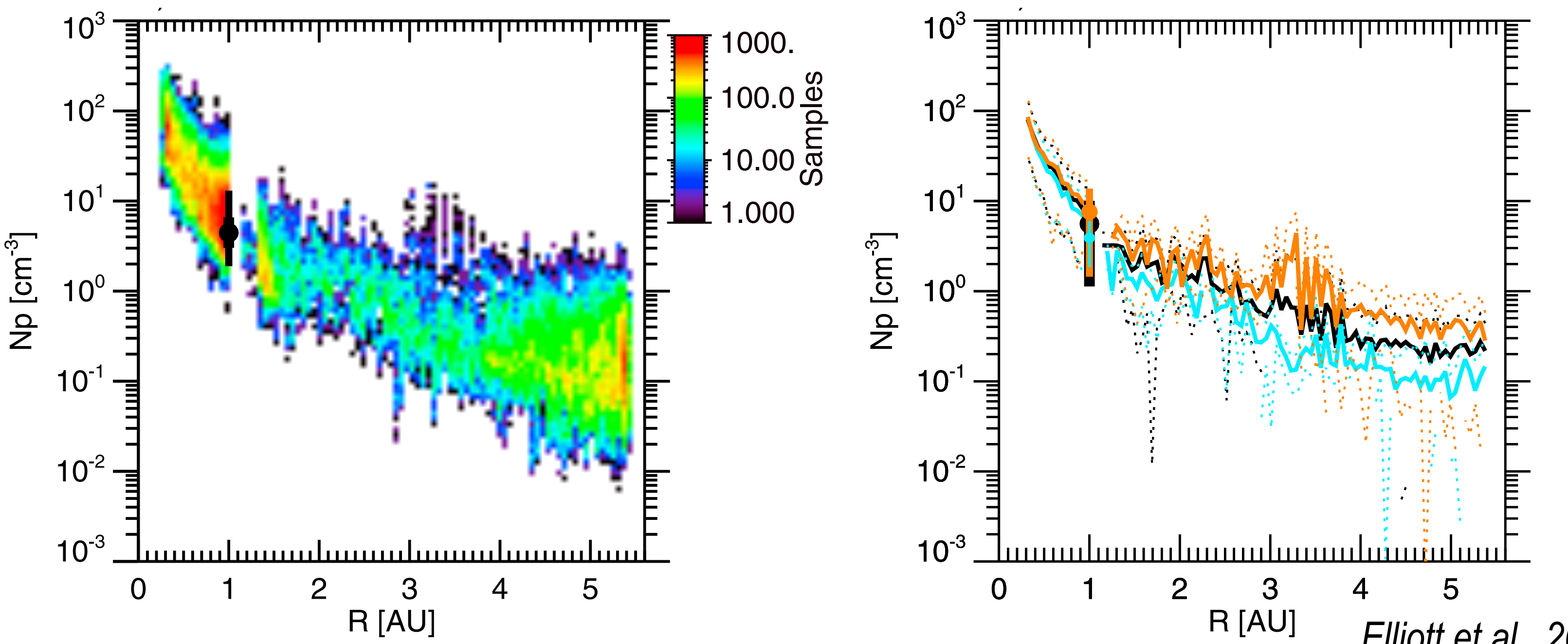


Elliott et al., 2005

We can use the steepness (dV/dt) of the rise and fall of the solar wind speed profile to identify compressions (rising) and rarefactions (falling).

This kind of sorting by steepness can be used to illustrate the radial evolution of the dynamic interactions.

Radial Evolution of Dynamic Interactions Illustrated in the Density Radial Profile



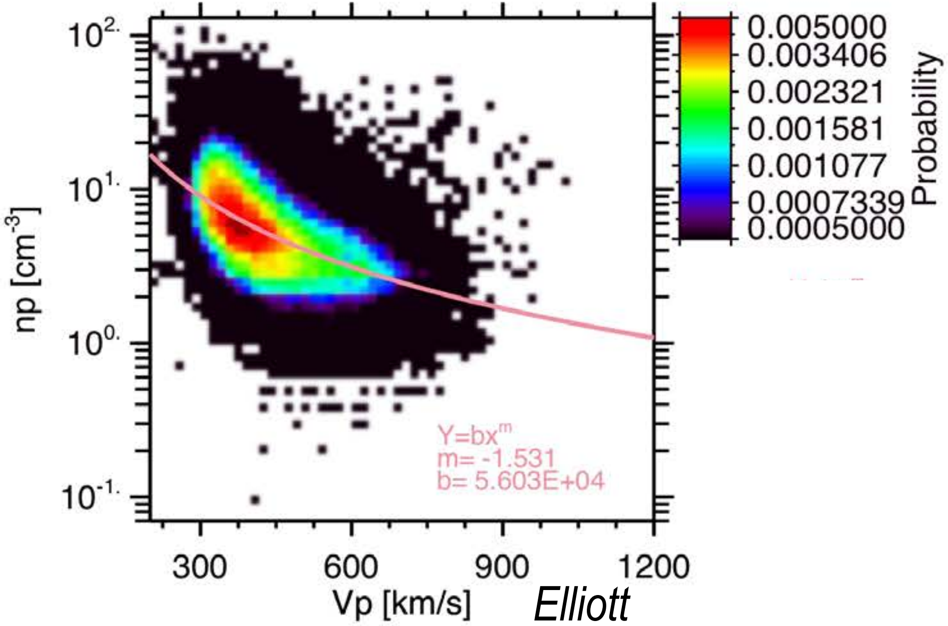
Elliott et al., 2012

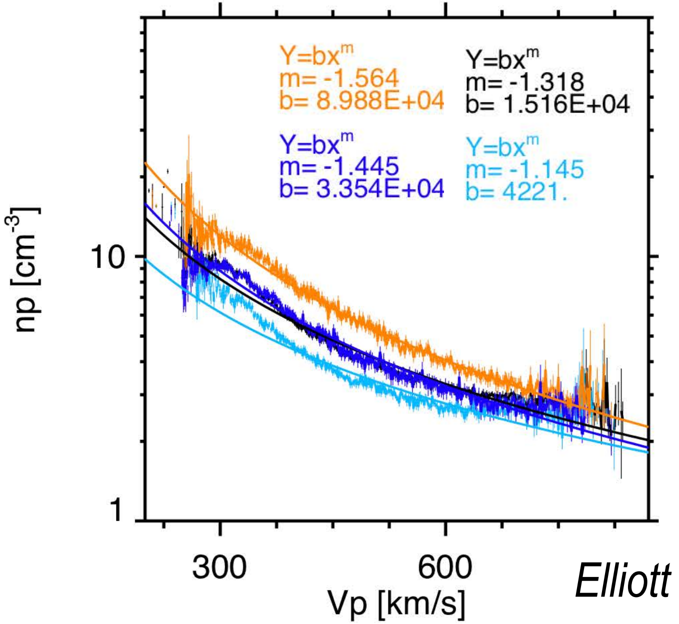
- The density generally decreases at the spherical expansion (r^{-2}).
- Dynamic interactions cause some of the slight deviations from spherical expansion (r^{-2}) that increase with distance until about 3 au.

n-V Relationship

ICMEs Removed

01/01/1963 00:00 06/03/2019 07:00

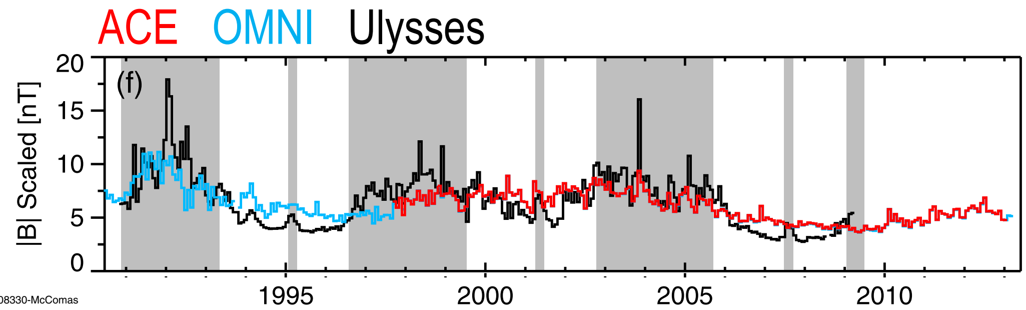




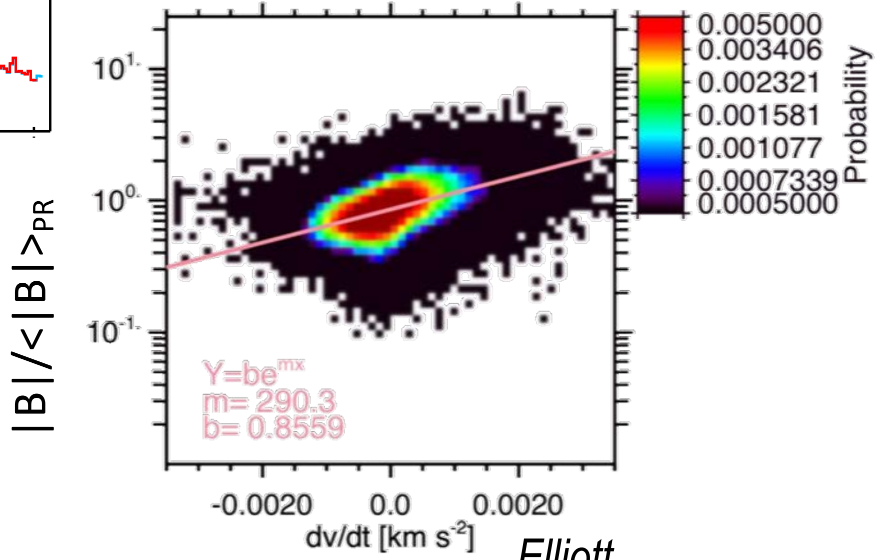
- **Power Law** relationship between n and V.
- Sorting by the 2-day average of $\langle dV/dt \rangle_{2day}$ improves the ability to reproduce T and V.

- Rising profiles (orange) $\langle dV/dt \rangle_{2day}$ > 7000km/s/year
- Falling profiles (light blue) $\langle dV/dt \rangle_{2day}$ < - 7000km/s/year
- Flat profiles (dark blue) $|\langle dV/dt \rangle_{2day}| \leqq$ 7000km/s/year
- All the data (black)

Estimate the |B| Using the Steepness in the Speed-Time Profile



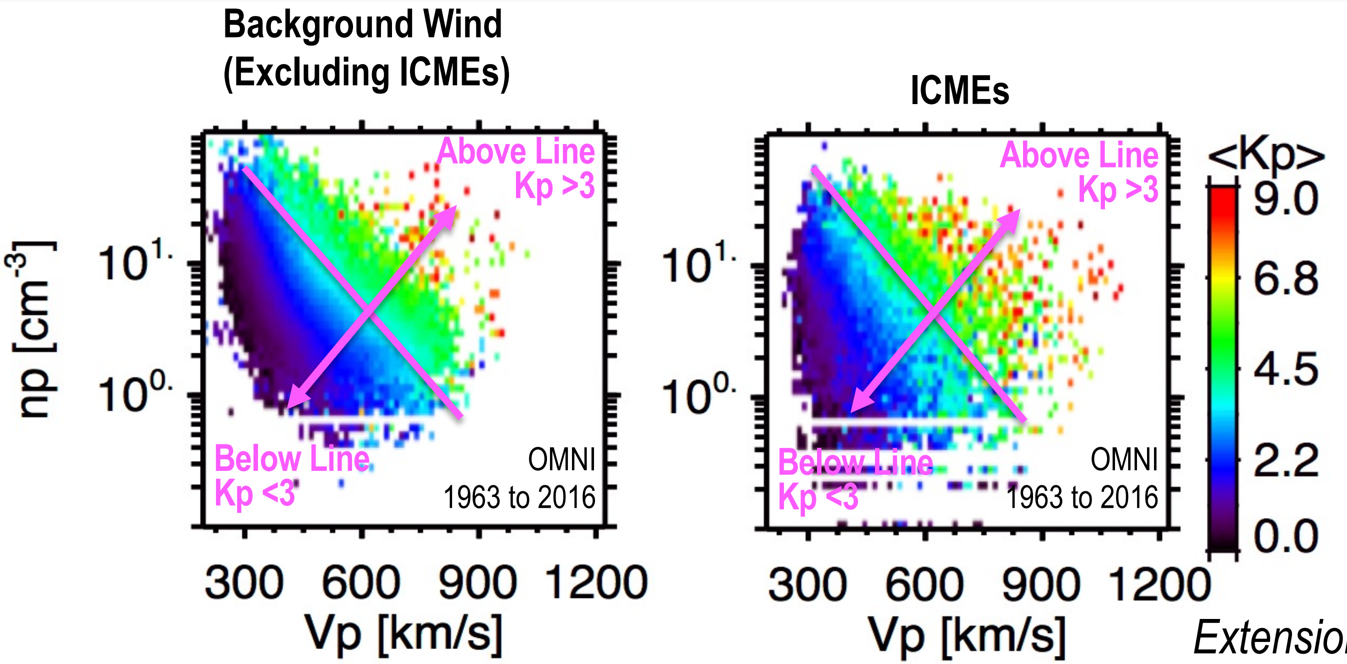
McComas et al. 2013



Elliott

- Normalize interplanetary magnetic field strength (|B|) by the average value over the prior solar rotation to remove most of the very long term trends (solar cycle and greater) present in |B|.

Forecasting Kp Index

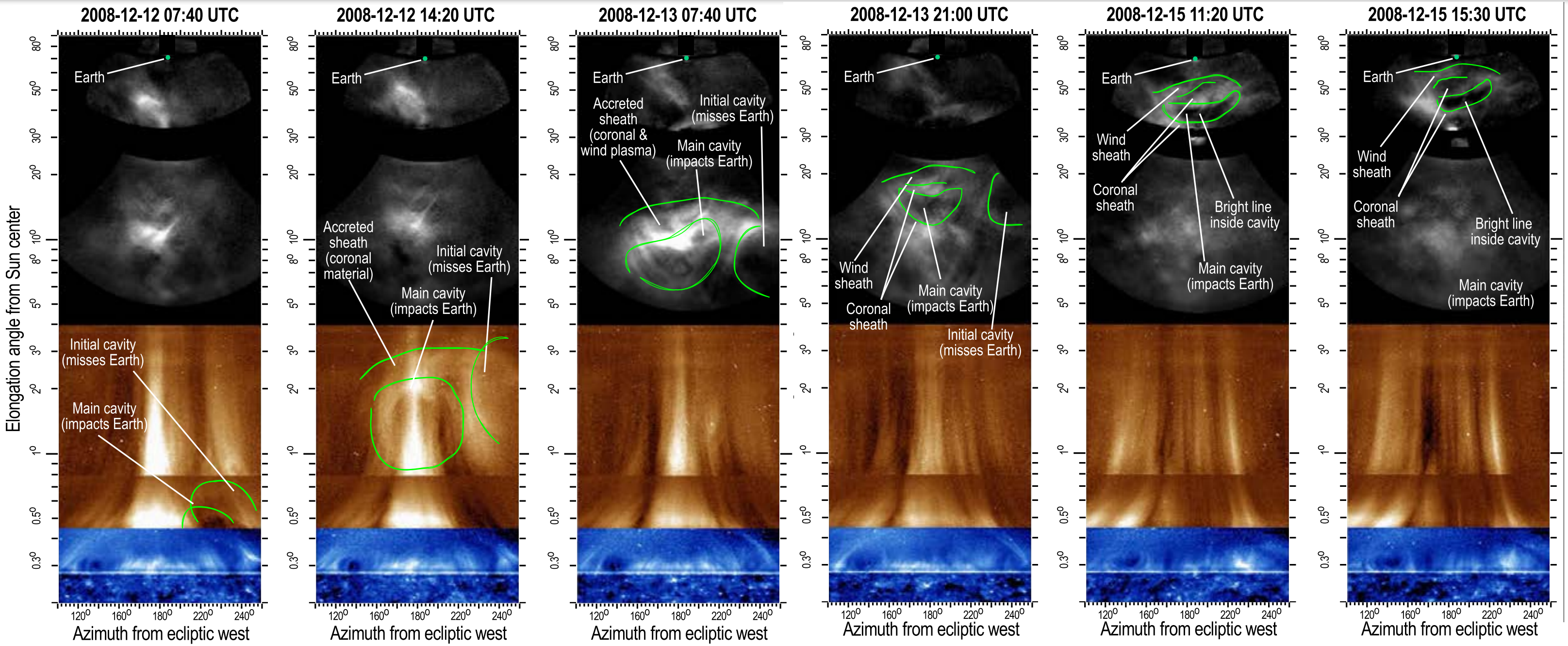


Kp Index
Lookup table of Kp binned by both n_p & V_p

Extension of Elliott et al. 2013

- To determine if Kp is high or low, you only need to determine if V and n (or another measure compression e.g. dV/dt) are high or low.
- CME tracking the imaging that includes polarization information such that both n and V can be determined.

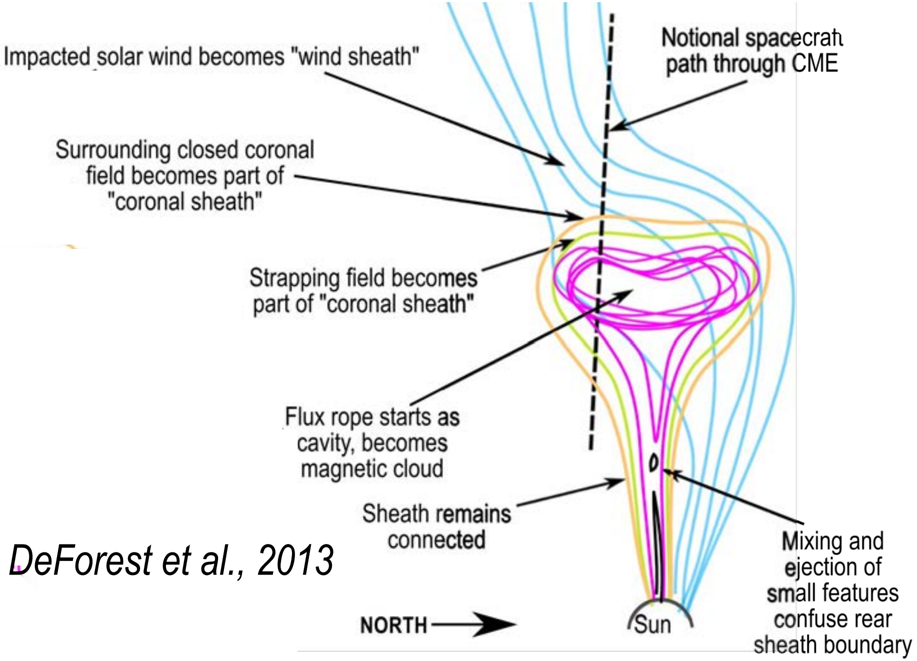
Tracking CME Features in Imaging



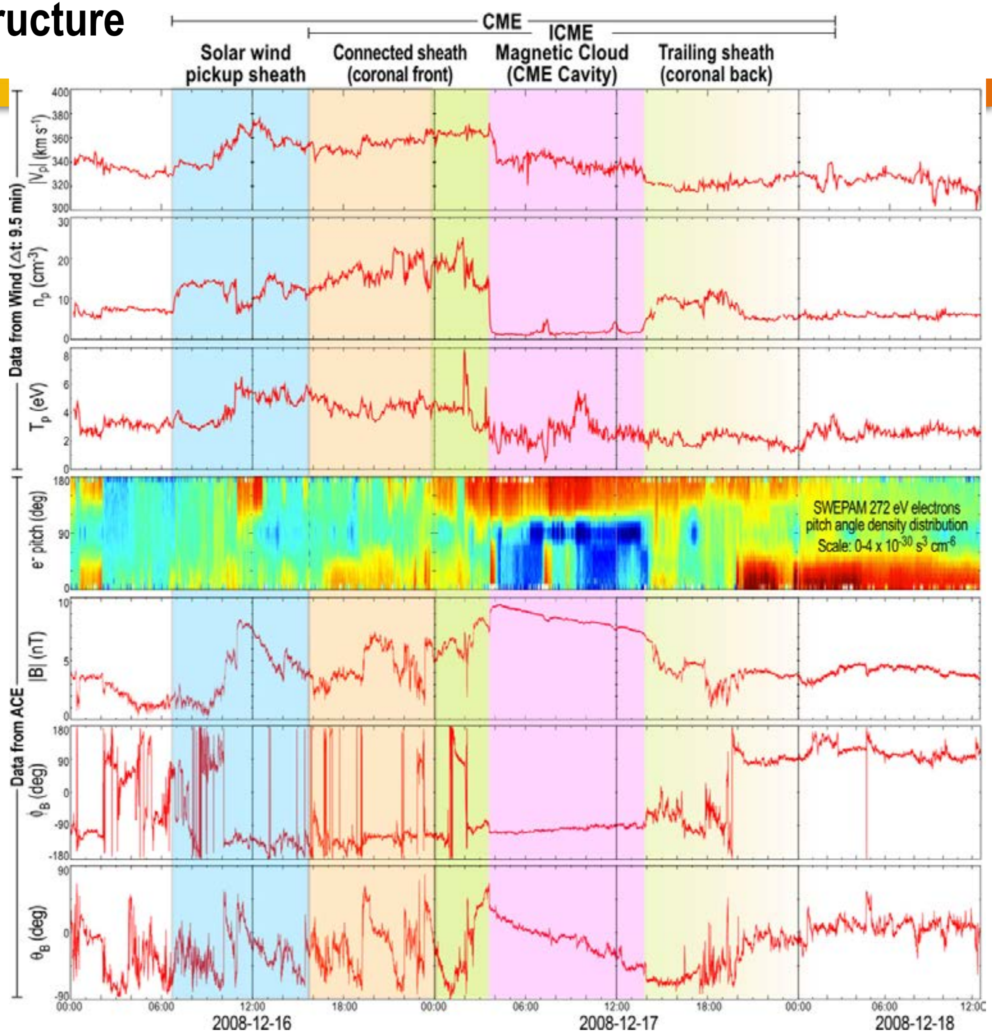
DeForest et al., 2013

- Individual parts of CMEs can be track om STEREO coronagraphs and heliospheric imagers.
- STEREO quadrature intervals are in very good for tracking events headed towards Earth.
- PUNCH coronagraph and heliospheric imagers will be in Earth orbit, but better resolve 3-D structure because these imagers will measure the polarization.

In Situ Measurements of Tracked CME Substructure

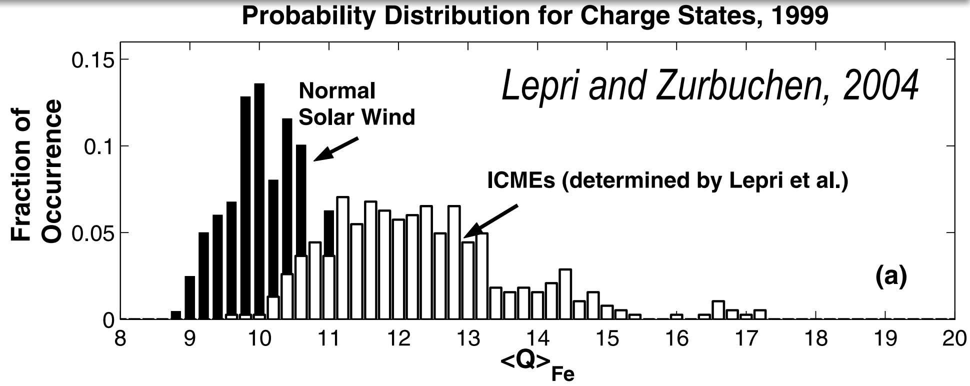


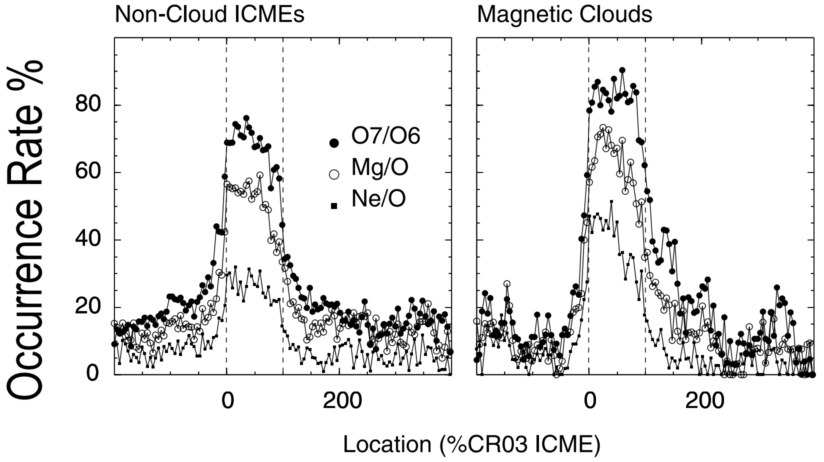
DeForest et al., 2013



Coronal Mass Ejection Heavy Ion Signatures

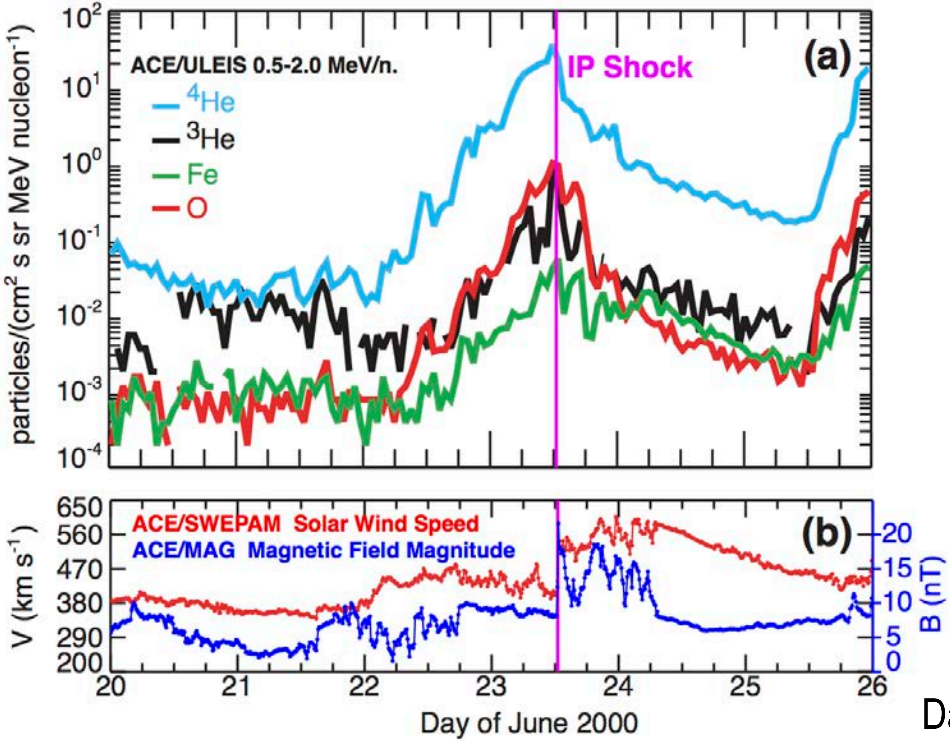
- The heavy ion composition for CMEs is different than for the background wind.
- Often there are more high charge states ions.
- Occasionally there are both really low and really high charge state ions.
- The elemental abundance ratios also are different in CMEs than in magnetic clouds.





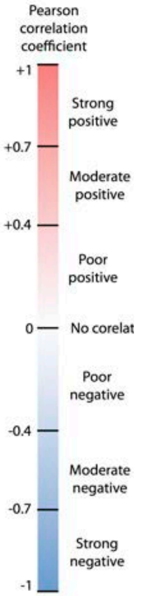
Richardson and Cane, 2004

Energetic Storm Particles are SEP Enhancements at Shocks



Dayeh et al. 2018

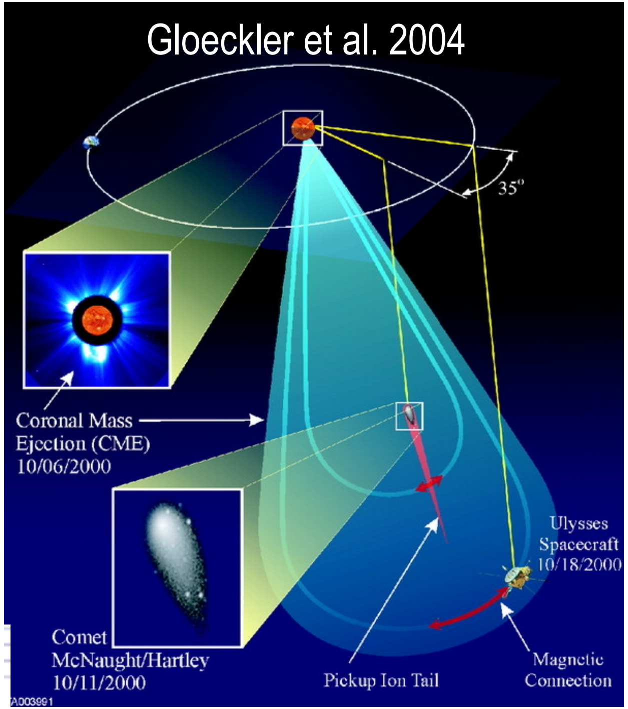
		ESP								
		γ_C	E_o^C	γ_O	E_o^O	γ_{Fe}	E_o^{Fe}	J_{max}^O	$^3He/^4He$	Fe/O
ESP	γ_C	1.00	-0.29	0.98	-0.34	0.69	-0.06	-0.48	0.39	0.29
	E_o^C	-0.29	1.00	-0.31	0.86	-0.44	0.55	0.05	-0.04	0.58
	γ_O	0.98	-0.31	1.00	-0.34	0.76	-0.07	-0.54	0.37	0.23
	E_o^O	-0.34	0.86	-0.34	1.00	-0.43	0.47	-0.01	-0.11	0.41
	γ_{Fe}	0.69	-0.44	0.76	-0.43	1.00	-0.10	-0.56	0.07	-0.15
	E_o^{Fe}	-0.06	0.55	-0.07	0.47	-0.10	1.00	-0.12	-0.03	0.26
	J_{max}^O	-0.48	0.05	-0.54	-0.01	-0.56	-0.12	1.00	-0.17	-0.15
	$^3He/^4He$	0.39	-0.04	0.37	-0.11	0.07	-0.03	-0.17	1.00	0.55
	Fe/O	0.29	0.58	0.23	0.41	-0.15	0.26	-0.15	0.55	1.00
Upstream and downstream of the IP shock	$Fe/O\|_U$	0.03	0.39	0.01	0.23	-0.12	0.15	0.00	0.42	0.53
	$Fe/O\|_D$	-0.10	0.76	-0.11	0.61	-0.21	0.21	-0.09	0.30	0.64
	$B\|_U$	0.08	0.08	0.04	-0.08	-0.10	-0.10	0.20	0.03	0.21
	$B\|_D$	-0.12	0.47	-0.18	0.31	-0.32	0.01	0.31	-0.08	0.22
	$B\|_D / B\|_U$	-0.26	0.60	-0.29	0.55	-0.29	0.12	0.13	-0.13	0.08
	$V\|_U$	-0.18	0.27	-0.16	0.27	-0.22	0.39	0.10	0.16	0.15
	$V\|_D$	-0.33	0.32	-0.35	0.32	-0.32	0.36	0.29	-0.02	0.07
	Δ_V	-0.33	0.19	-0.38	0.20	-0.26	0.11	0.37	-0.24	-0.08
	$n\|_U$	-0.03	0.41	-0.02	0.31	-0.15	-0.12	0.06	-0.03	0.23
	$n\|_D$	0.00	0.31	0.00	0.18	-0.08	-0.16	-0.01	-0.09	0.07
	$n\|_D / n\|_U$	0.03	-0.12	0.02	-0.10	0.10	-0.15	-0.09	-0.17	-0.22
	$T\|_U$	-0.13	-0.01	-0.14	0.01	-0.17	-0.05	0.17	-0.06	-0.01
	$T\|_D$	-0.31	0.21	-0.31	0.29	-0.23	0.29	0.23	-0.16	-0.07
	$T\|_D / T\|_U$	-0.24	0.20	-0.26	0.27	-0.14	0.27	0.02	-0.13	-0.03
	θ_{B_n}	0.02	0.01	0.02	-0.11	-0.04	-0.26	-0.07	0.01	0.02
	V_{shock}	-0.34	0.34	-0.40	0.28	-0.38	0.39	0.52	-0.16	0.07
ICME	P_{sheath}	-0.10	0.13	-0.11	0.20	-0.12	-0.13	0.02	-0.16	0.05
	T_{sheath}	-0.39	0.40	-0.41	0.40	-0.41	0.28	0.44	-0.17	-0.02
	n_{sheath}	0.10	-0.09	0.11	-0.12	0.09	-0.29	-0.08	-0.14	-0.07

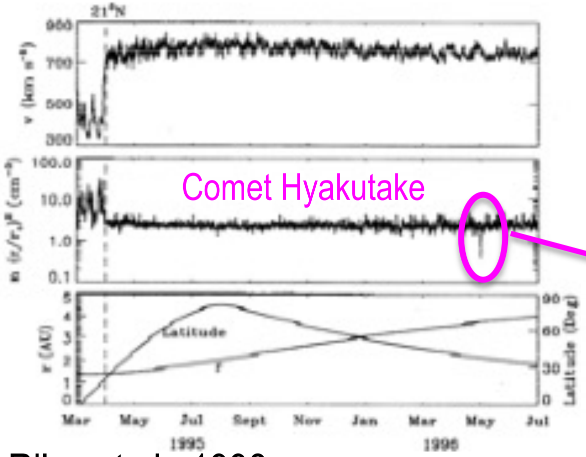


Shock Speed and ESP flux
Correlation 0.52
Highest Correlation: ESP Flux & Plasma Condition

Extended Comet Tails

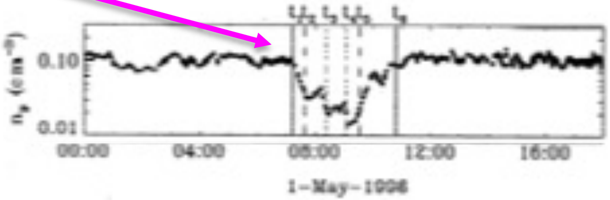
- PUNCH data could be used to find when other missions cross distant comet tails.
- Tail Lengths between 1 and 6.5 au long (Jones et al. 2018; 2022).
- Tail Crossing:
  - Enhanced amounts of single charged ions.
  - Very low plasma densities.
  - Field and flow rotations occur in a tail crossing.





Riley et al., 1998

- First thought to be a “density hole” (Riley et al, 1998).
- Several years later it was discovered to be a comet tail crossing (Gloeckler et al. 2000).



Summary

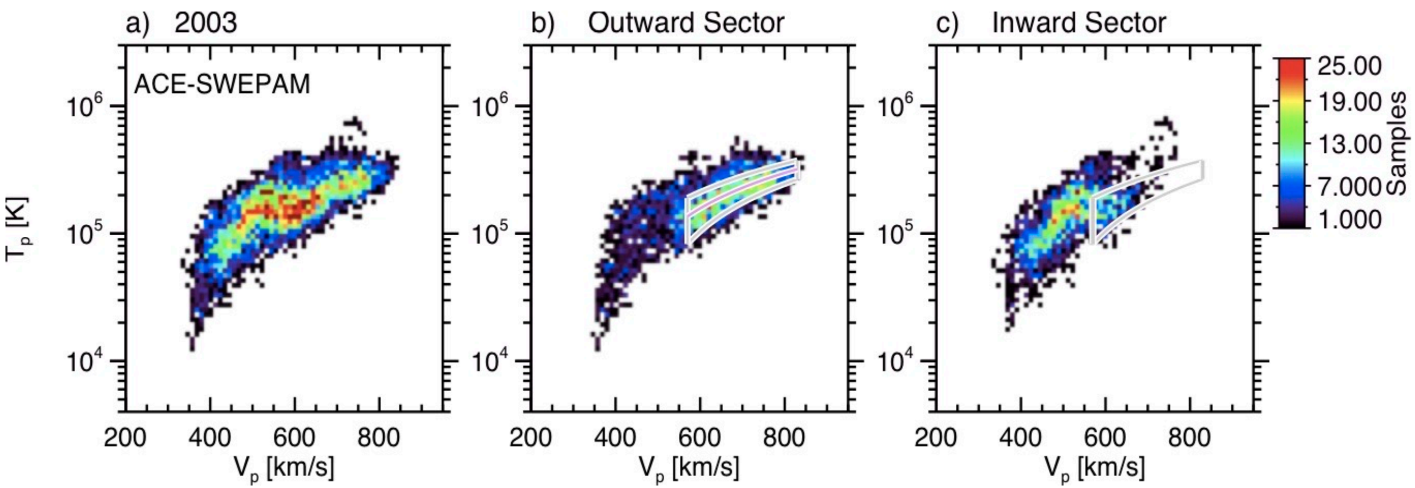
- We can leverage the Heliophysics System Observatory (HSO) to do a a wide variety of multi-spacecraft studies particularly during spacecraft alignments.

In Situ-Remote Synergies:

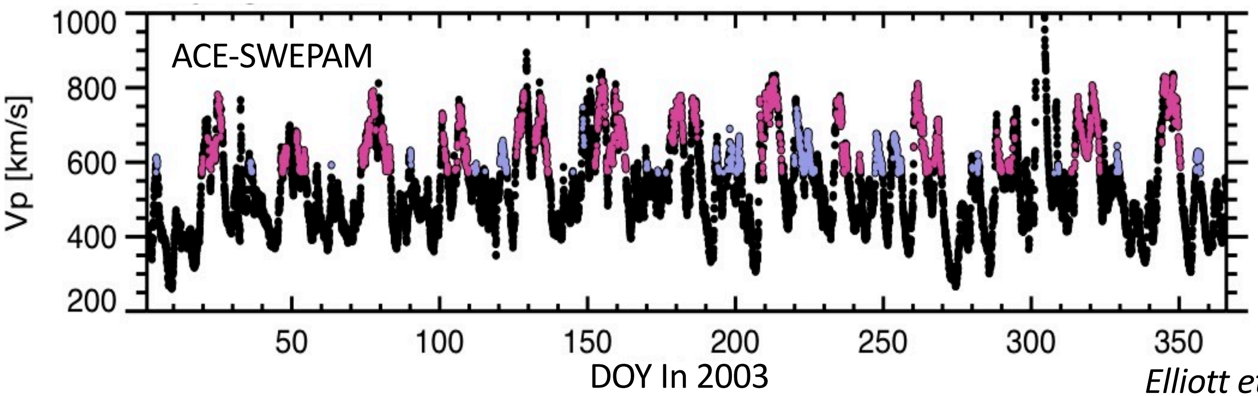
- Tracking of structures in coronal and heliospheric imaging to understand sources (slow wind, fast wind, moderately fast wind) and substructures of CMEs.
- Dynamic interactions en route that form shocks (Key missing space weather capability.)
- SEP enhancements at shocks
- Comet tails
- Testing a variety of space weather forecast capabilities using PUNCH observations.

BACKUP

Source Signatures in the T-V Relationship

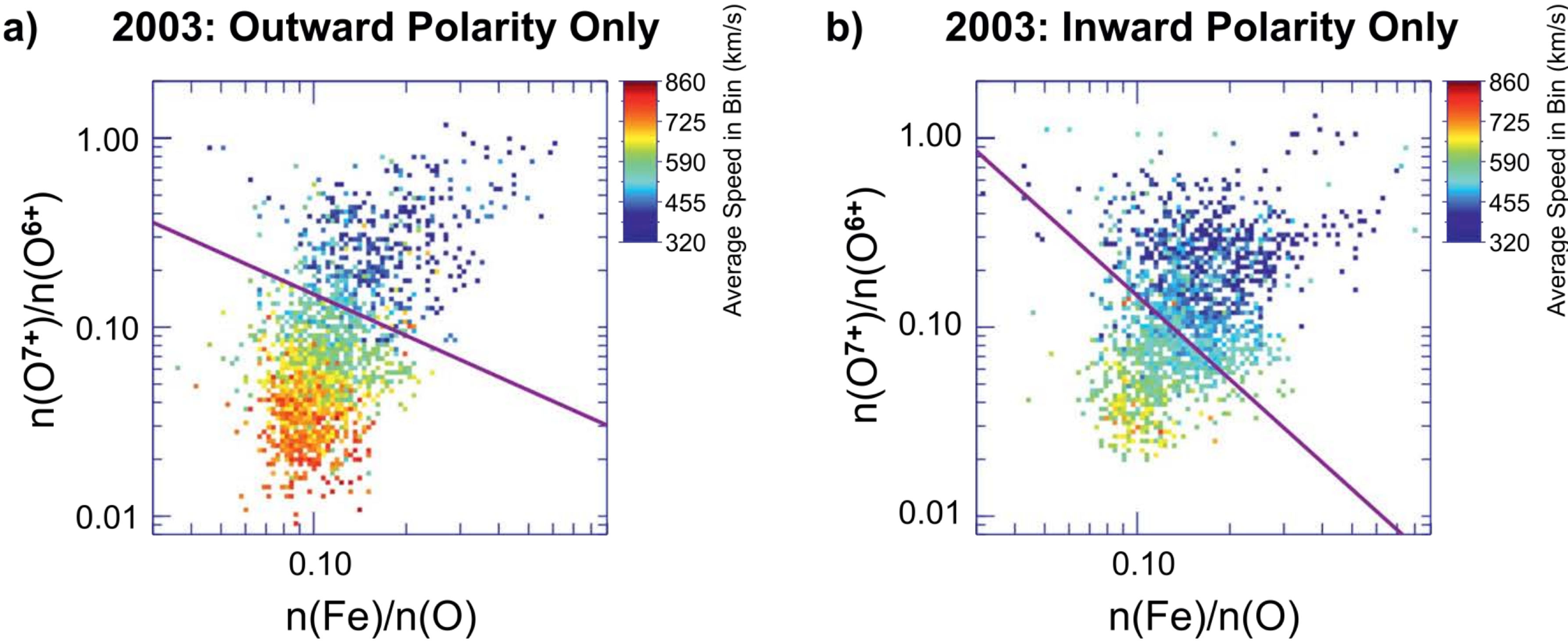


Elliott et al., 2012



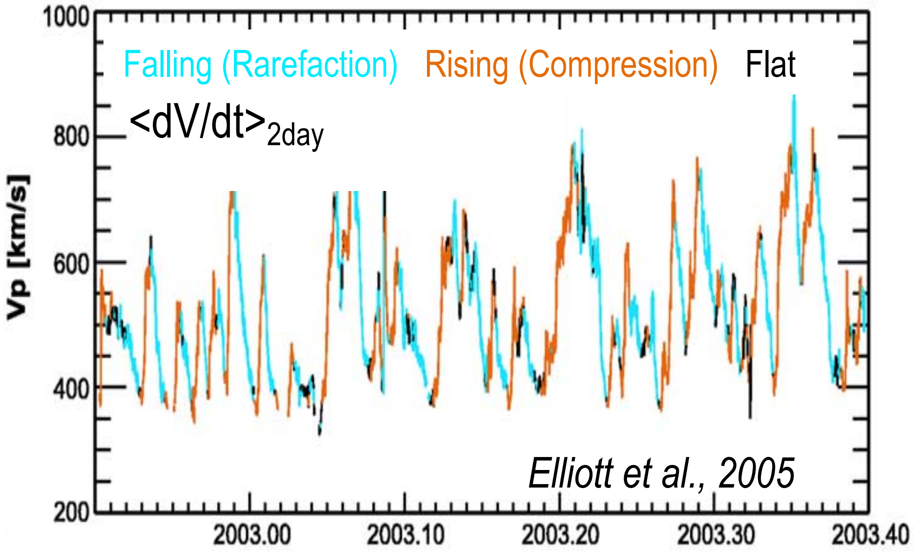
Elliott et al., 2012

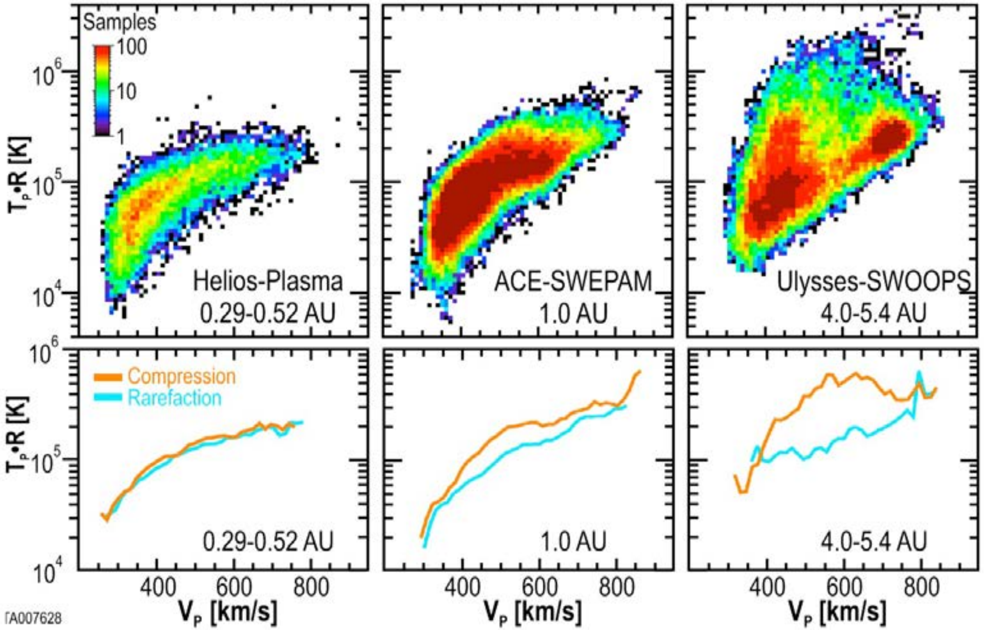
Composition of Polar Coronal Hole Extensions and Equatorial Holes



Delano et al., 2021

Revealing Dynamic Interactions



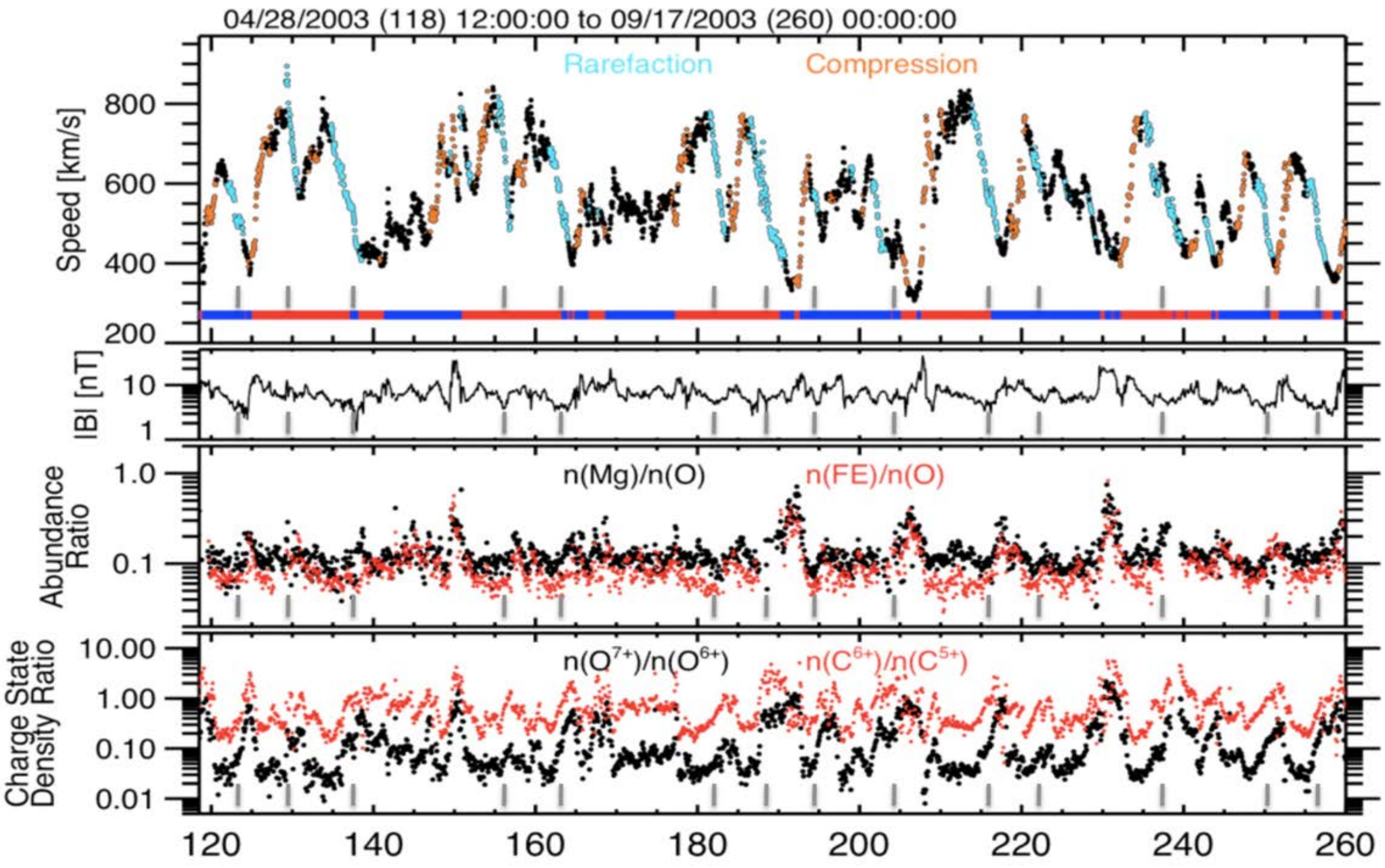


Elliott et al., 2012

We can use the steepness (dV/dt) of the rise and fall of the solar wind speed profile to identify compressions (rising) and rarefactions (falling).

This kind of sorting by steepness can be used to illustrate the radial evolution of the dynamic interactions.

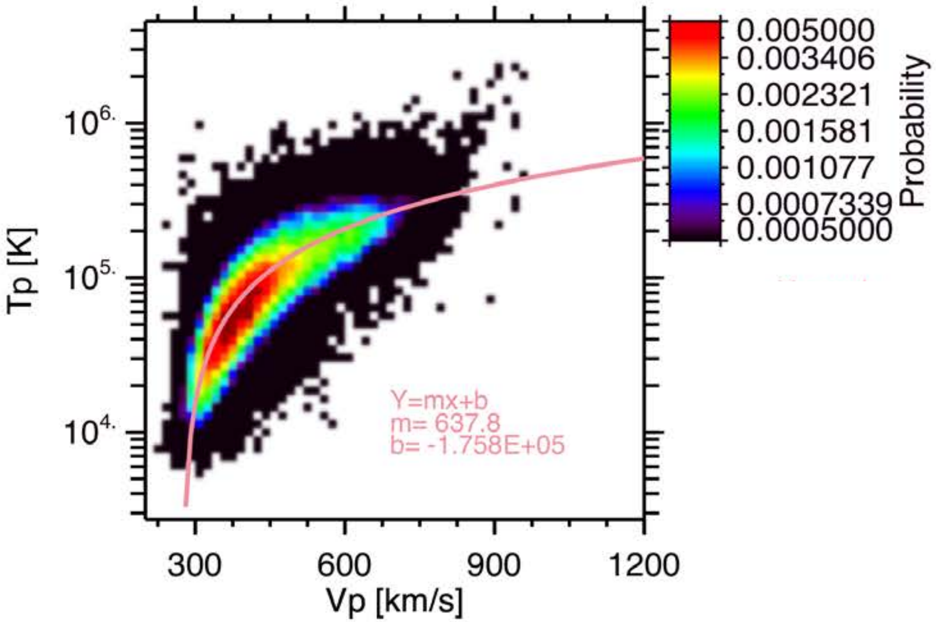
Composition Changes For Slow and Fast Wind

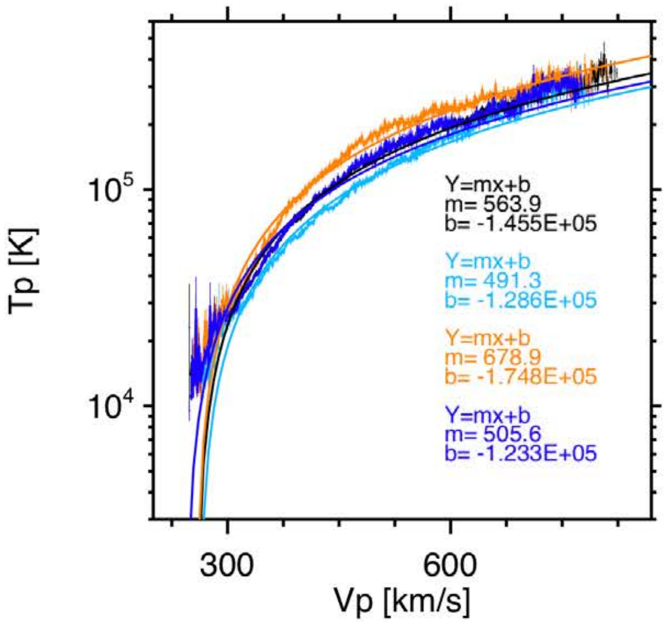


T-V Relationship

ICMEs Removed

01/01/1963 00:00 06/03/2019 07:00

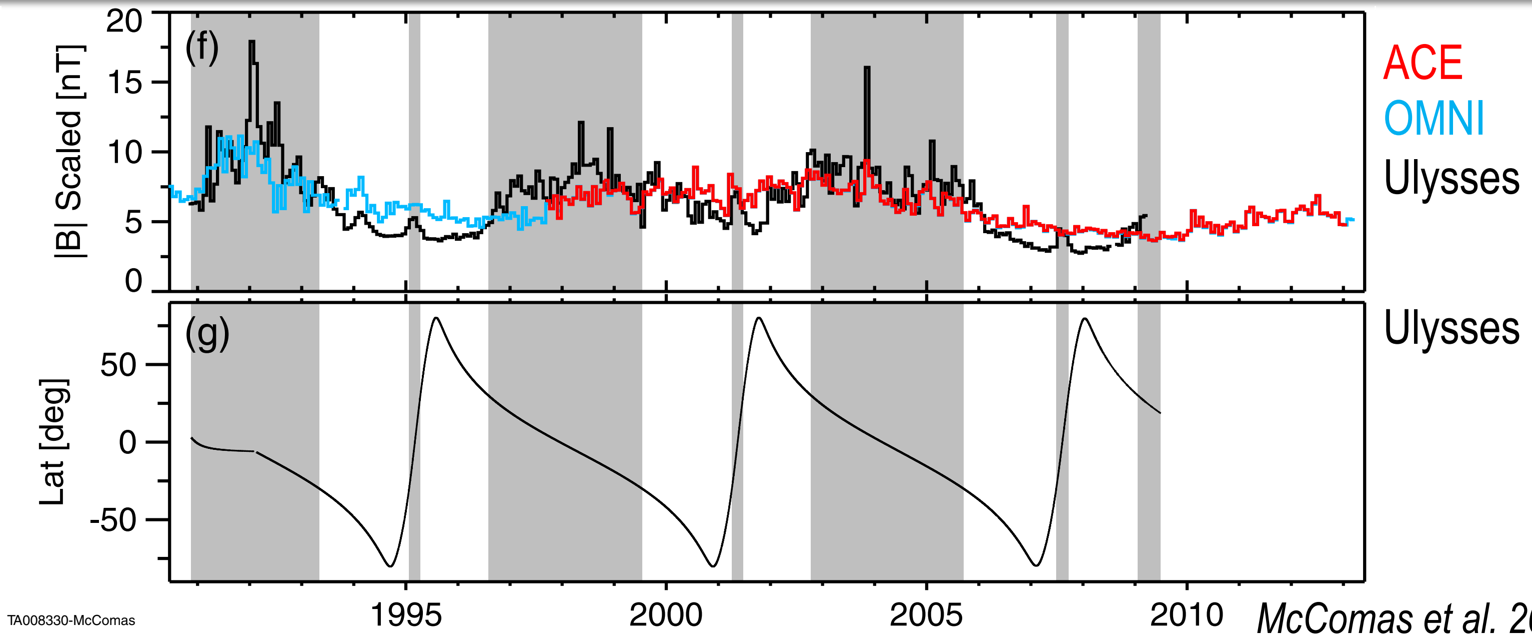




- **Linear** relationship between T and V.
- Sorting by the 2-day average of $\langle dV/dt \rangle_{2day}$ improves the ability to reproduce T and V.

- Rising profiles (orange) $\langle dV/dt \rangle_{2day}$ > 7000km/s/year
- Falling profiles (light blue) $\langle dV/dt \rangle_{2day}$ < - 7000km/s/year
- Flat profiles (dark blue) $|\langle dV/dt \rangle_{2day}| \leqq$ 7000km/s/year
- All the data (black)

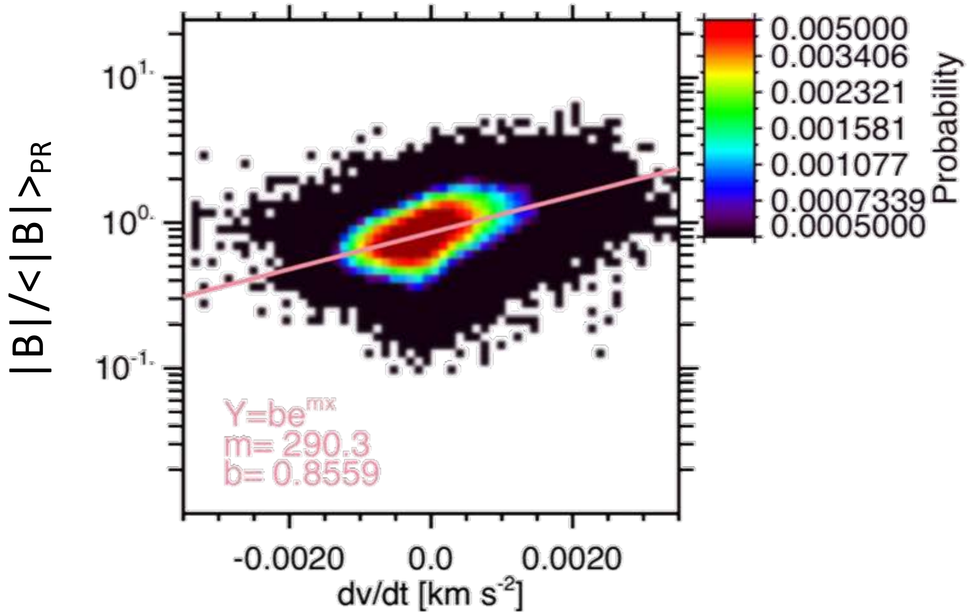
Long Term Trends in IMF |B| Independent of Location

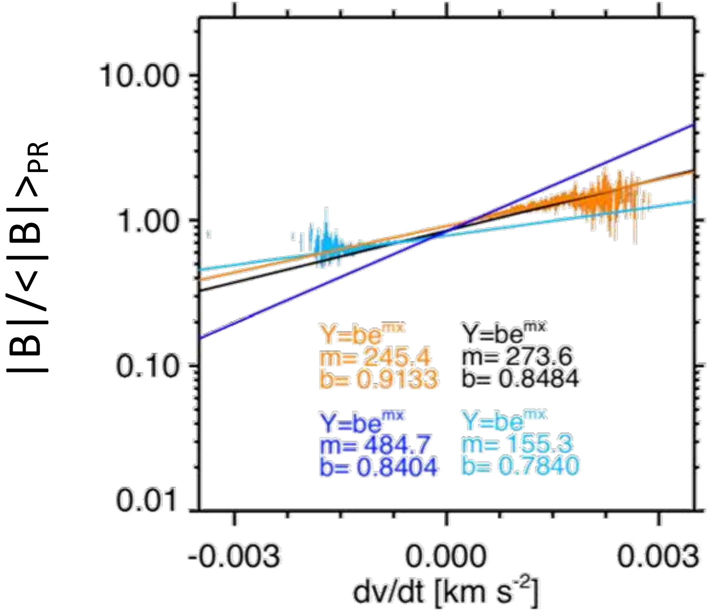


McComas et al. 2013

- The magnitude of the field |B| has some long term trends that track the long term trends for the Sun.
- These means there are long term baseline trends in |B| that affect the baseline field strength.
- Other variations in |B| observed in situ reflect the field from an individual structure and a dynamic interactions.

Estimate the |B|Using the Steepness in the Speed-Time Profile $|B|/\langle|B|\rangle_{PR}$ vs. <dV/dt>

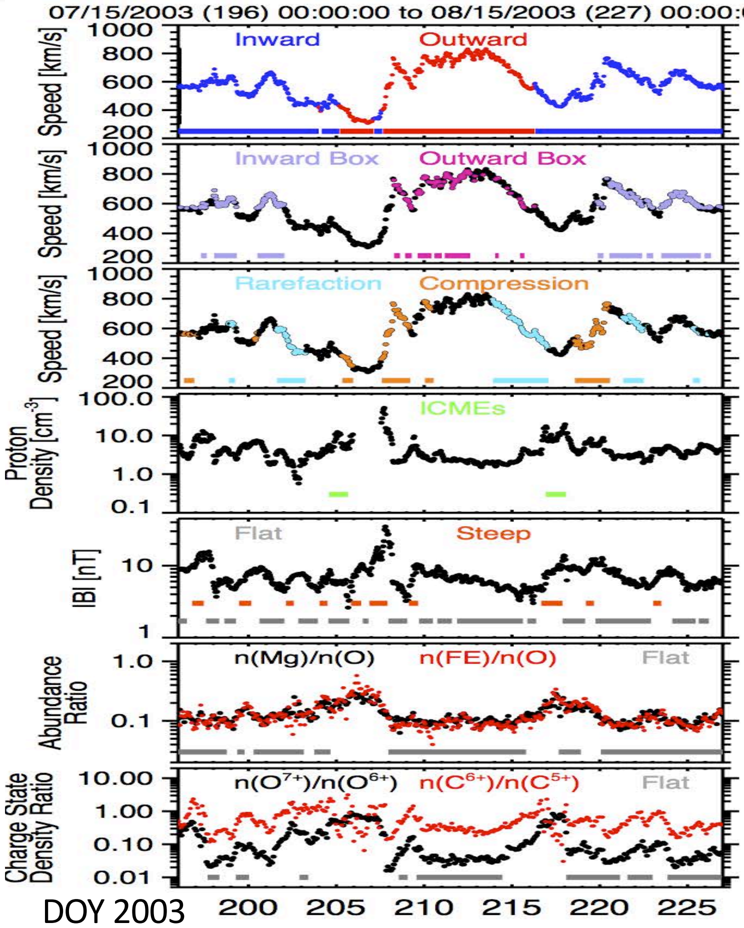




- Normalize interplanetary magnetic field strength (|B|) by the average value over the prior solar rotation to remove most of the very long term trends (solar cycle and greater) present in |B|.
- $|B|/\langle|B|\rangle_{\text{prior rot}}$ is plotted vs $\langle dV/dt\rangle_{\text{2day}}$ since we know that |B| typically peaks when in the middle of the rise in speed.

Separating Dynamic Interactions and Source Properties

- We can examine magnetic connections, solar wind sources, and dynamic interactions by combining data sets.



Magnetic Connection

Core/Boundary of Hole

Dynamic Interactions

Dynamic Interactions & Source

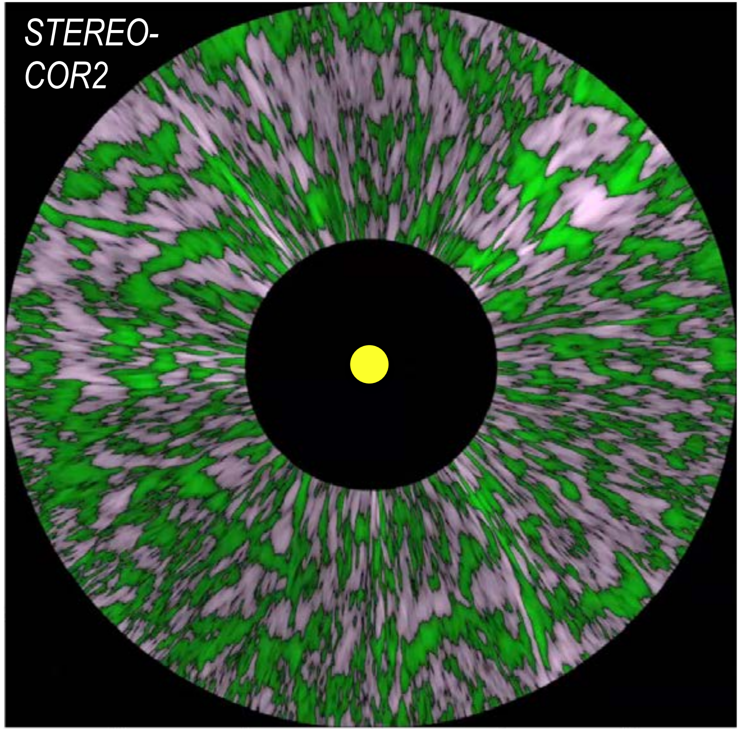
Dynamic Interactions

Chromosphere

Coronal Electron Temperature

General Tracking of the Solar Wind

Visible-Light Variations in the Outer Corona



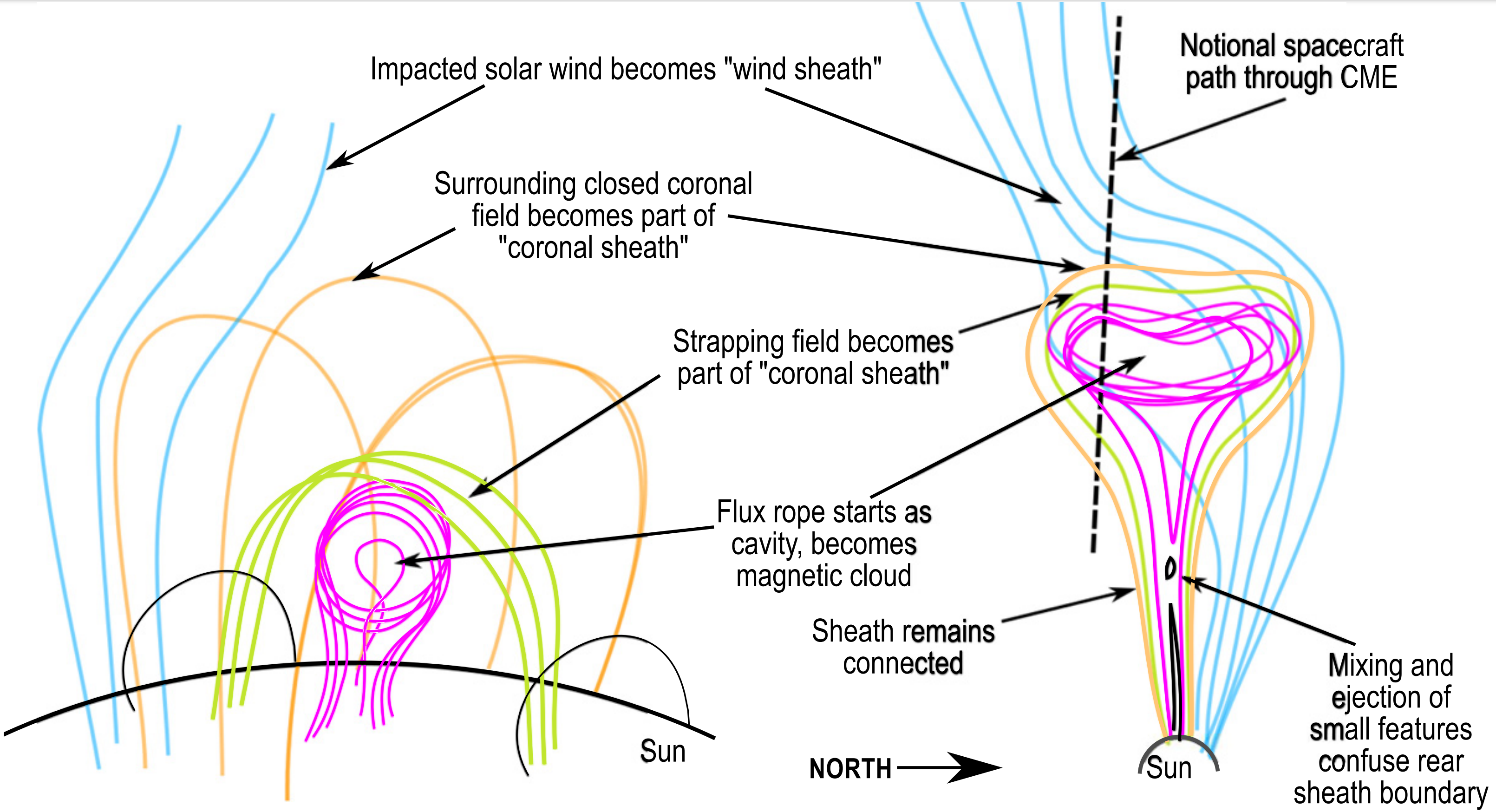
DeForest et al. 2018

- The PUNCH spacecraft will be in Earth orbit, but include polarization information in the corona and heliosphere which allows the 3-S structure to be resolved and density to be estimated.

- PUNCH team is testing a variety of tracking methods which are rapidly evolving.

- With the polarization and the new tracking techniques it may be possible to track the background wind and examine the radial evolution of the dynamic interactions.

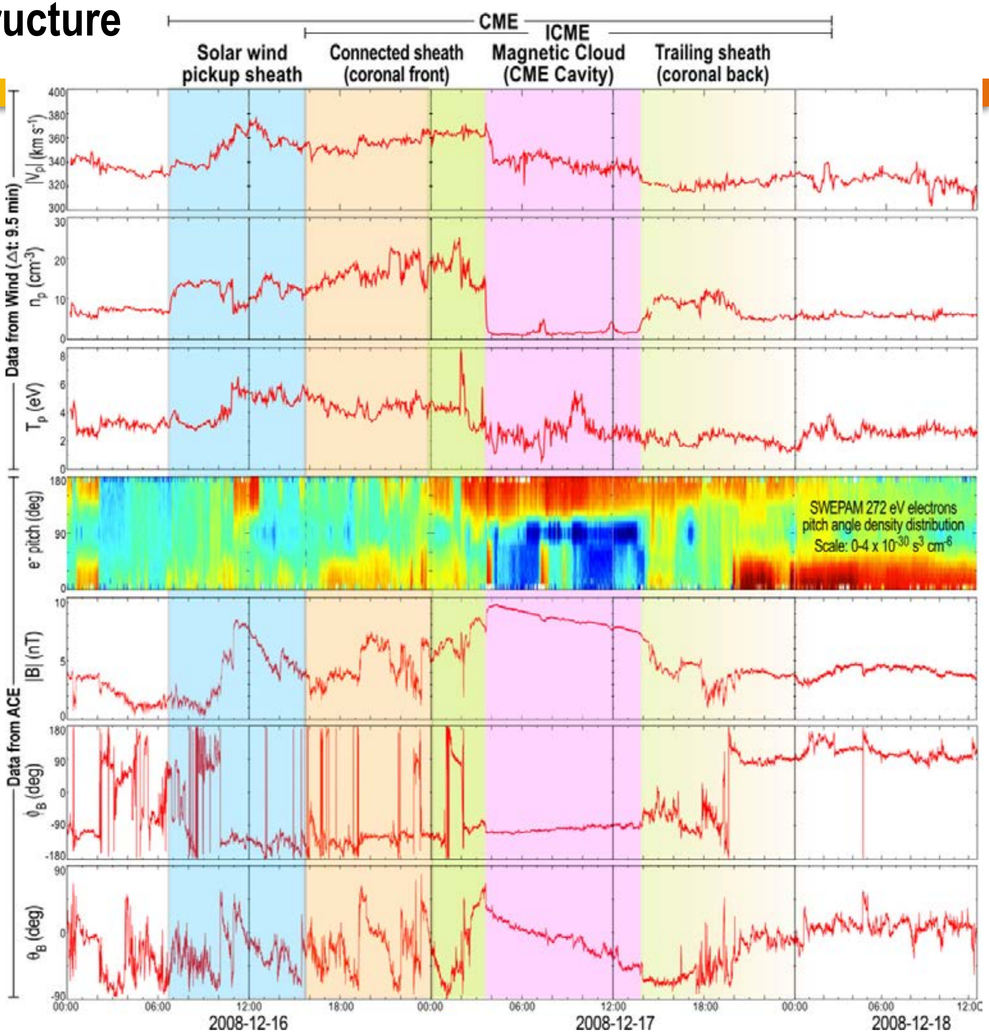
Diagram of Parts of CME Structures



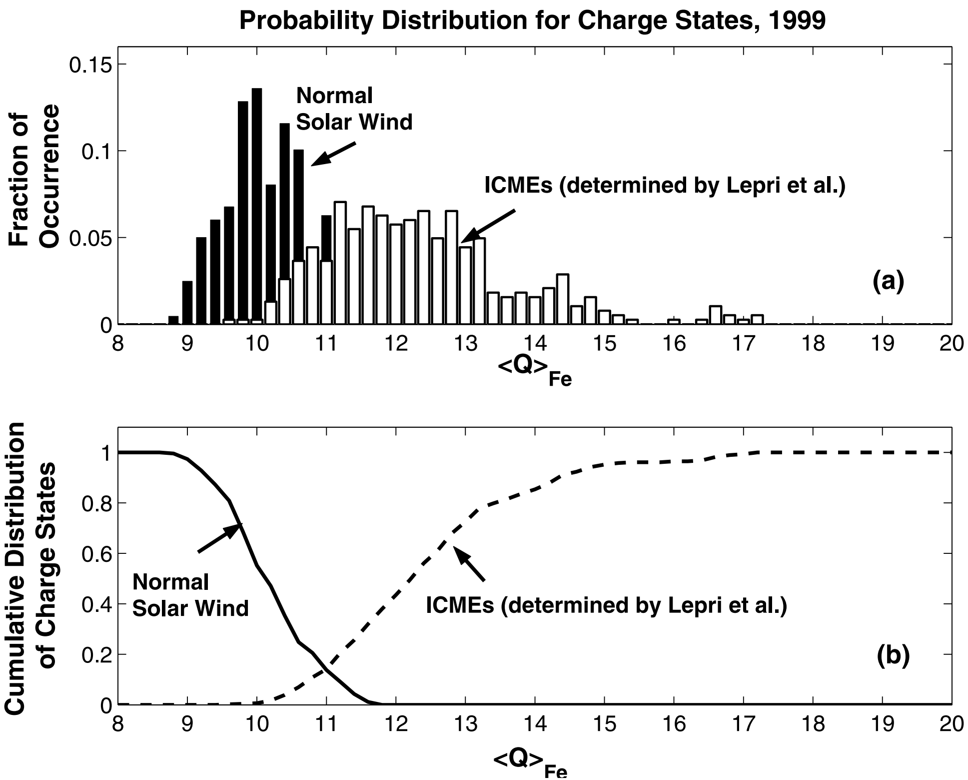
DeForest et al., 2013

In Situ Measurements of Tracked CME Substructure

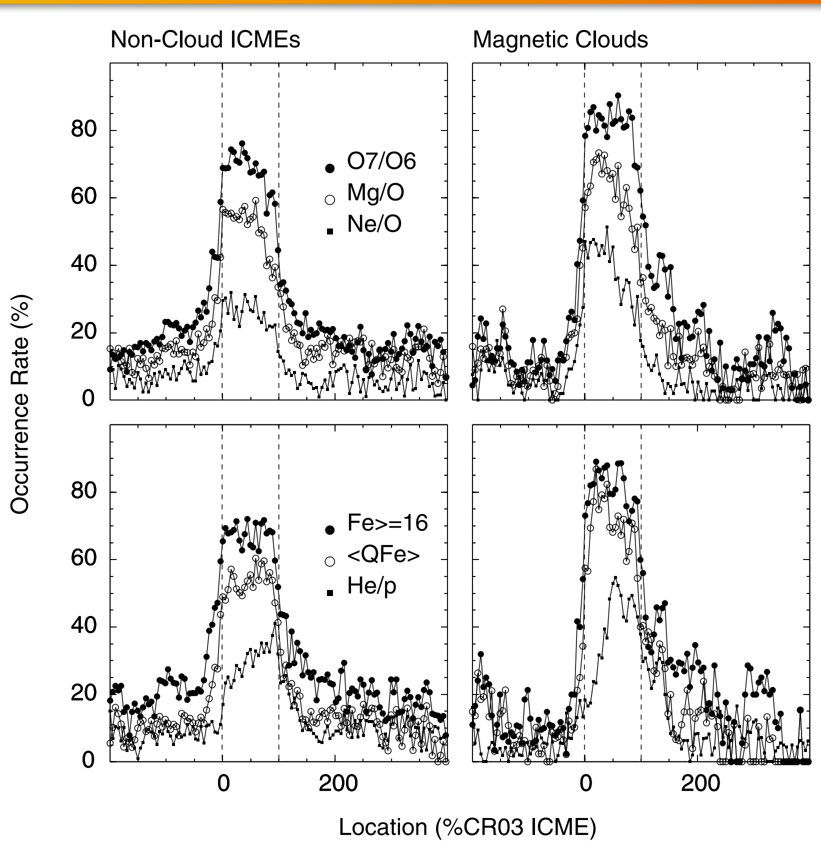
- Color scheme the same as the prior diagram.
- DeForest et al. were able to track 2 different parts of the leading sheath, a trailing sheath and the magnetic cloud using STEREO.
- The CME tracking in PUNCH should also allow for better tracking of the CMEs back to the Sun and enable comparisons with in situ observations at IMAP, Solar Probe and Solar Orbiter.
- Solar Orbiter-HIS and IMAP-CODICE both measure heavy ion composition.



Coronal Mass Ejection Heavy Ion Signatures



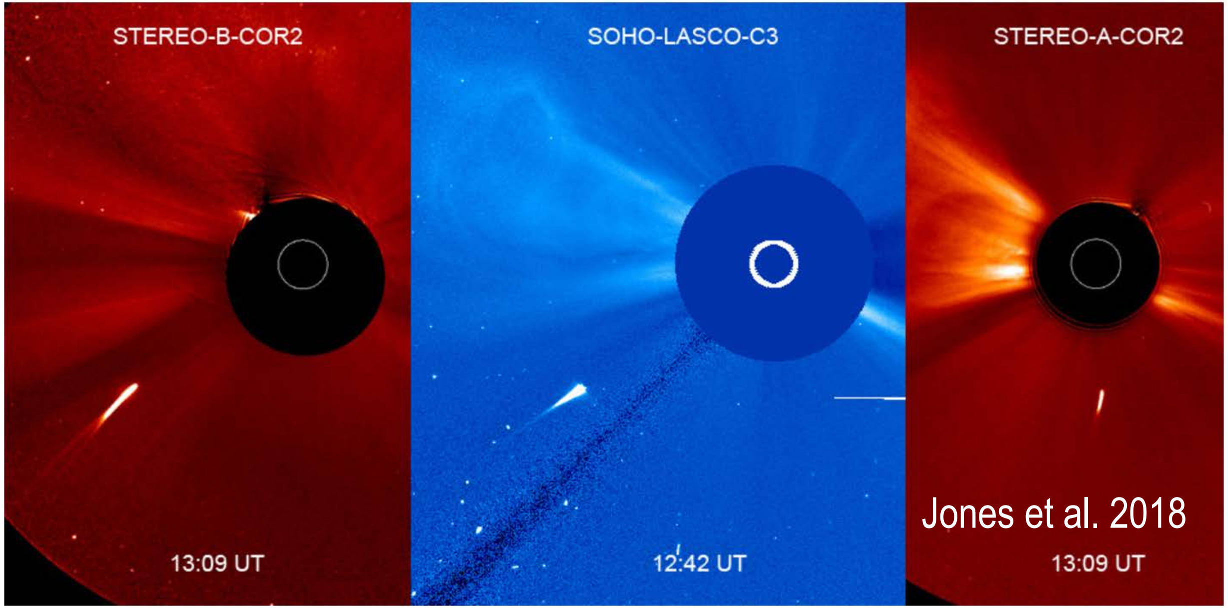
Lepri and Zurbuchen, 2004

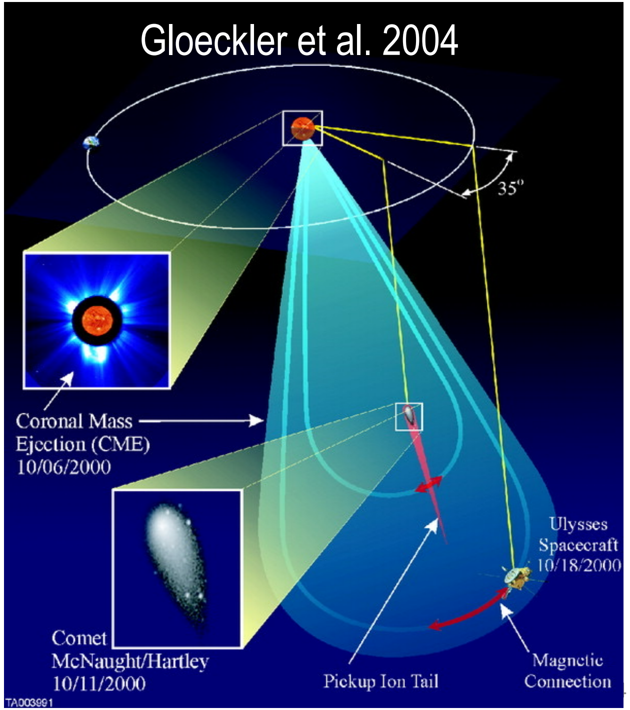


Richardson and Cane, 2004

Extended Comet Tails

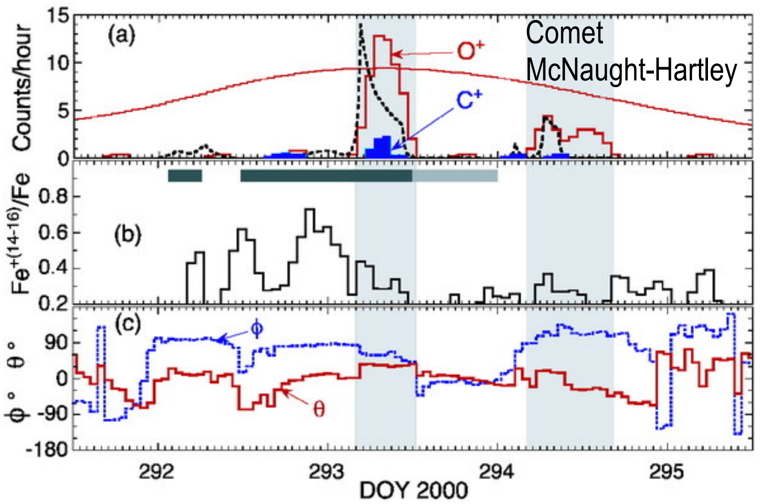
- Can PUNCH observe extended comet tails?
- Based on in situ data some tails have been found to between 1 and 6.5 au long (Jones et al. 2018; 2022).
- PUNCH data could be used to find when other missions cross distant comet tails.



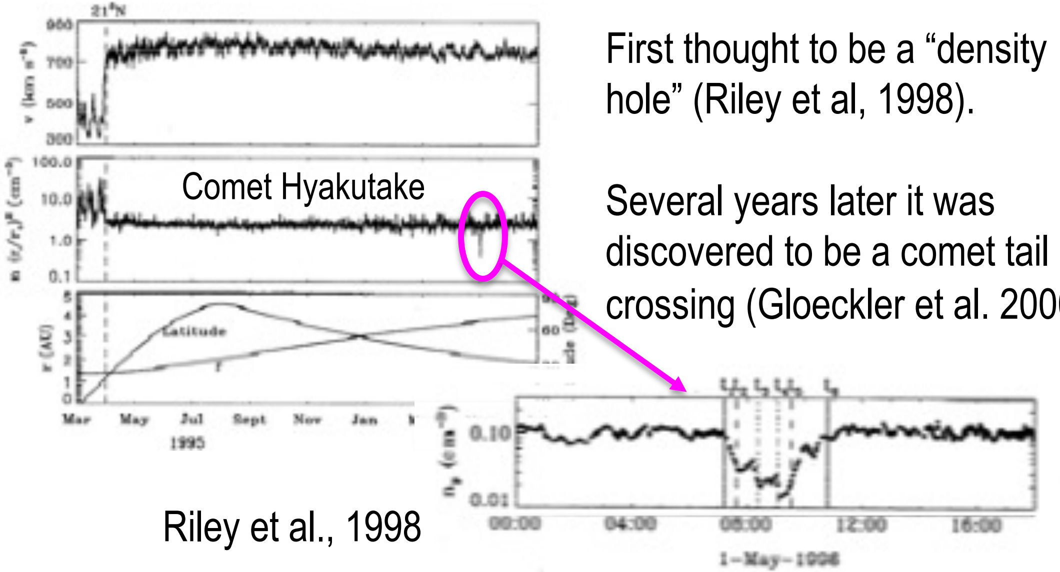


In situ Signatures of a Comet Tail Crossing

- Single charged heavy ions in the solar wind are signature of comet tails.
- Sometimes low plasma densities occur in comet tail crossings.
- Sometimes field and flow rotations occur in a tail crossing.



Gloeckler et al. 2004



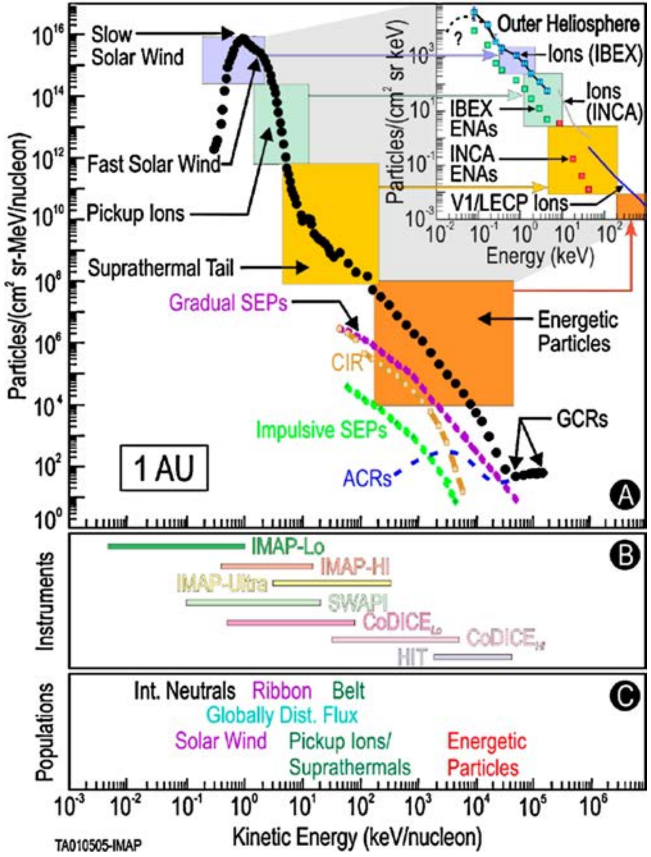
Riley et al., 1998

First thought to be a "density hole" (Riley et al, 1998).

Several years later it was discovered to be a comet tail crossing (Gloeckler et al. 2000).

IMAP

- SWAPI – solar wind
- CODICE-Lo - solar wind composition
- CODICE-Hi – suprathermal composition
- MAG Magnetometer
- SWE – solar wind electrons,
- HIT - SEPs



McComas et al., 2018

Ideas

- PUNCH with STEREO COR-2 any coronagraphs
  - Cross-calibration
  - Side-View improve tomography
- ESA- Vigil Launch 2029; too far in future?
- EUV
- SO and PSP in quadrature (imagers)
- Magnetic fields: Faraday Rotation GONG data (Jackson solar physic 2023)

Notes

- CME Challenge Version 2
  - Fixed polarization brightness
  - Several viewing angles between Halo and 90 deg
  - Adding a 4pi viewer (can download fits files, but they are large)
- Projections
- Wcs solar soft idl
- Astropy

- all sky heliospheric imager fortran code
  - Package to convert coordinates.

- At least 14 days prior of data without CMEs; 1 image every hour

- Background test with WSA, rotation without CMEs. In development. (Check with Elena at APL on model runs)

- Can the SOC add F- corona (polarized 7%?) into the simulated data?

- Moire patterns? Grid pattern of the model Gameria polar grid gets distorted in line of sight grid.

- Anna M.: Equal space equal delta tau steps or do equal delta distance along the line of sight steps?.