Identifying ICMEs, SIRs and Other Large-Scale Solar Wind Structures

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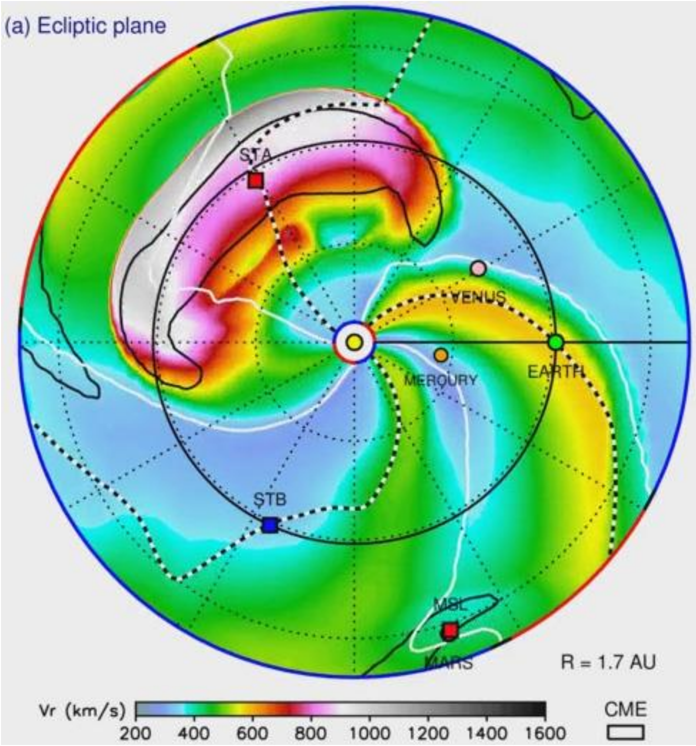
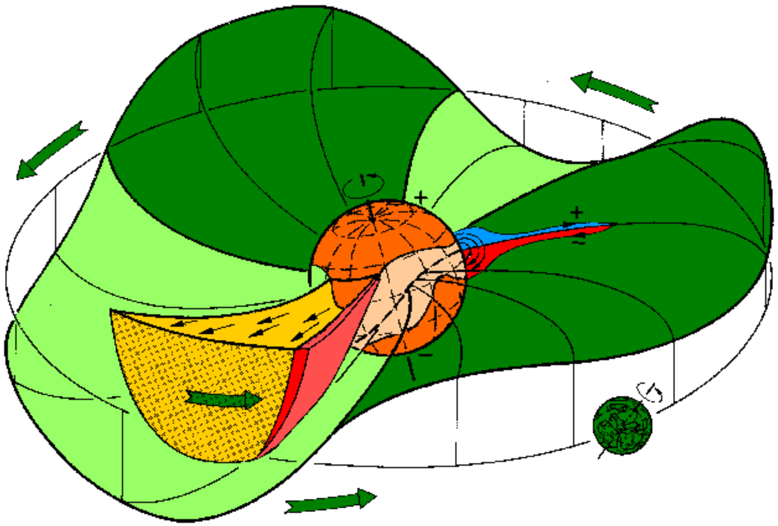
Types of Large-Scale Solar Wind Structures

- Heliospheric current sheet and plasma sheet
- Stream interaction region (SIR)
- Interplanetary coronal mass ejection (ICME)
- Hybrid event
- Driverless shocks
- Concluding remark

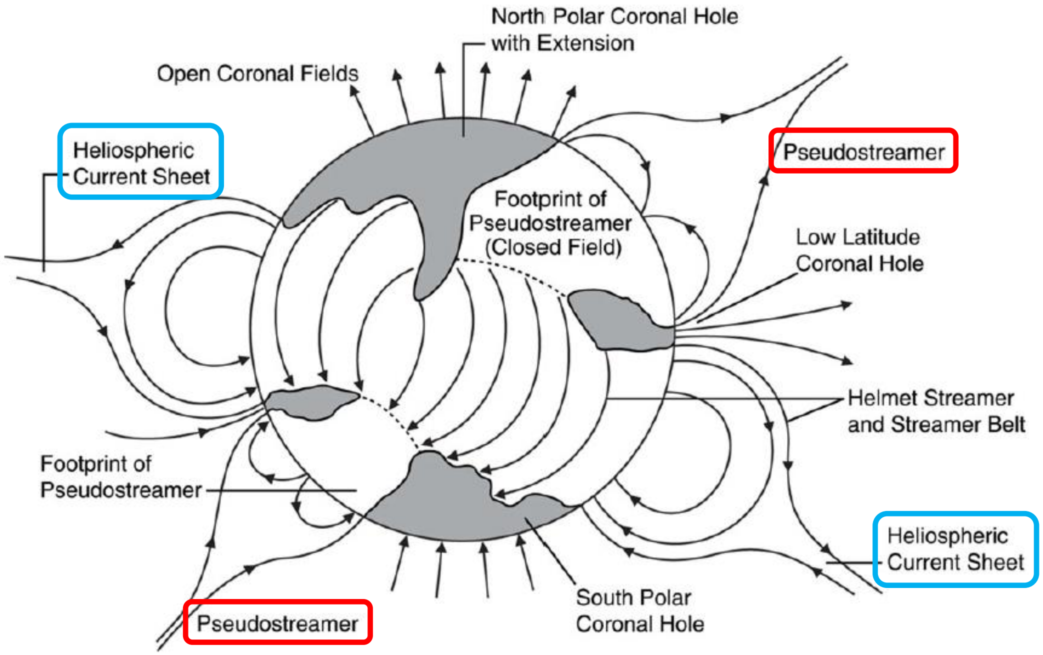
helioweather.net



Heliospheric Current Sheet (HCS) and Heliospheric Plasma Sheet (HPS)



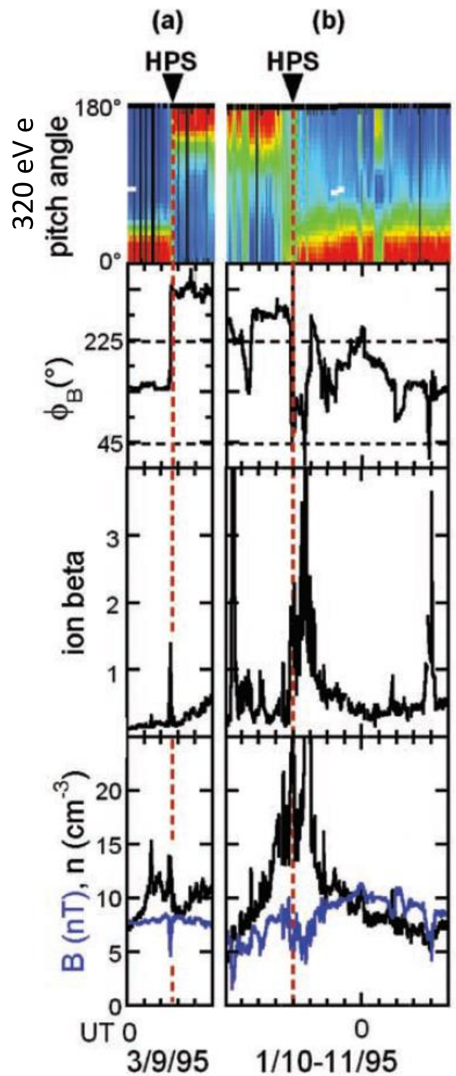
According to Alfvén (1977)



Luhmann et al. (2012)

- **HCS**: a change of long-term (>3 days) magnetic field polarity, indicated by the direction of magnetic field and suprathermal (100-300 eV) electron flux. It is also called as **magnetic sector boundary**
- **HPS** is a magnetic equatorial plane between sectors of opposite polarity, characterized by high density, low temperature, and slow wind
- The scale of HPS varies largely depending on the selection criteria

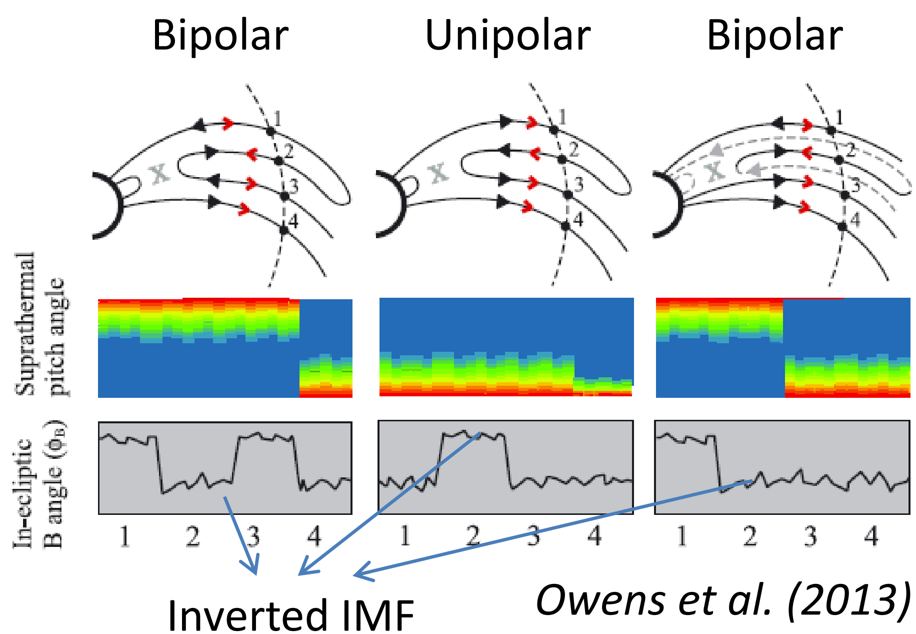
Detailed Structures at HCS



Crooker et al. (2004)

The changes of magnetic field and electron flux directions do not always occur together

- → Suprathermal electron strahl
- → Magnetic field polarity



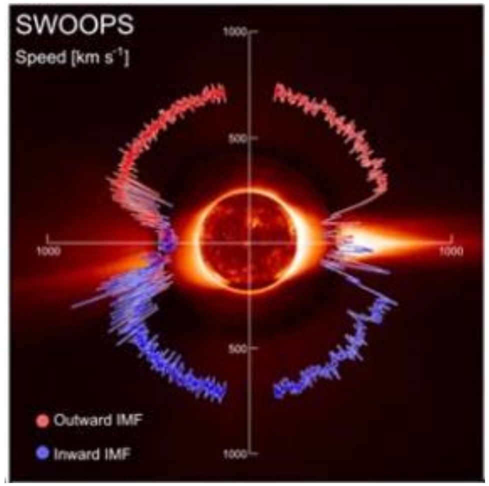
Owens et al. (2013)

Stream Interaction Region (SIR)

Ulysses

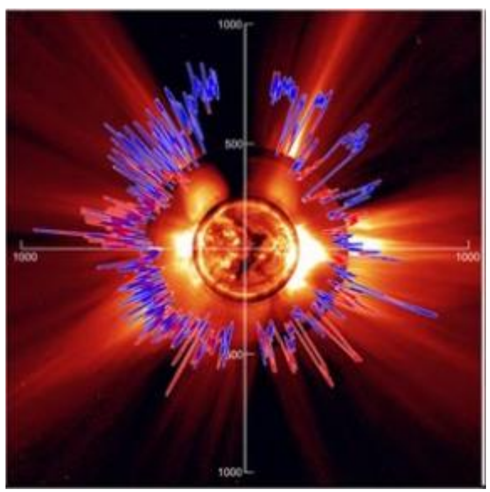
Declining Phase & Solar Minimum

1992-1998



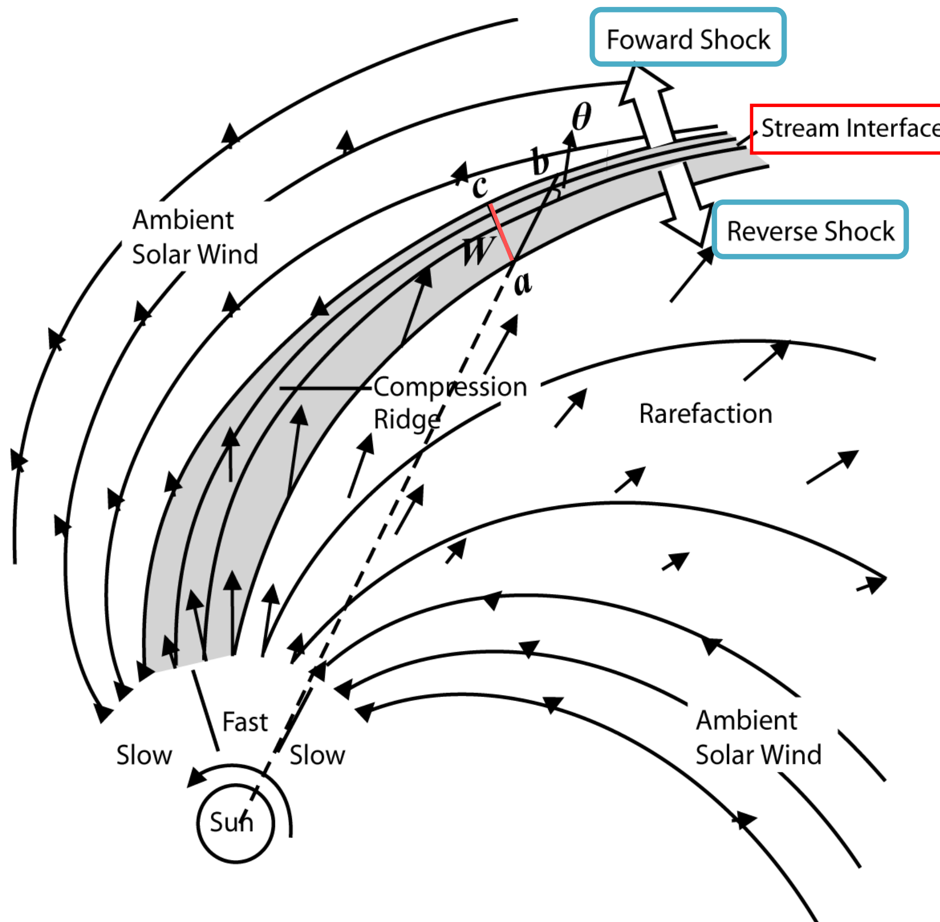
Rising Phase & Solar Maximum

1998-2004



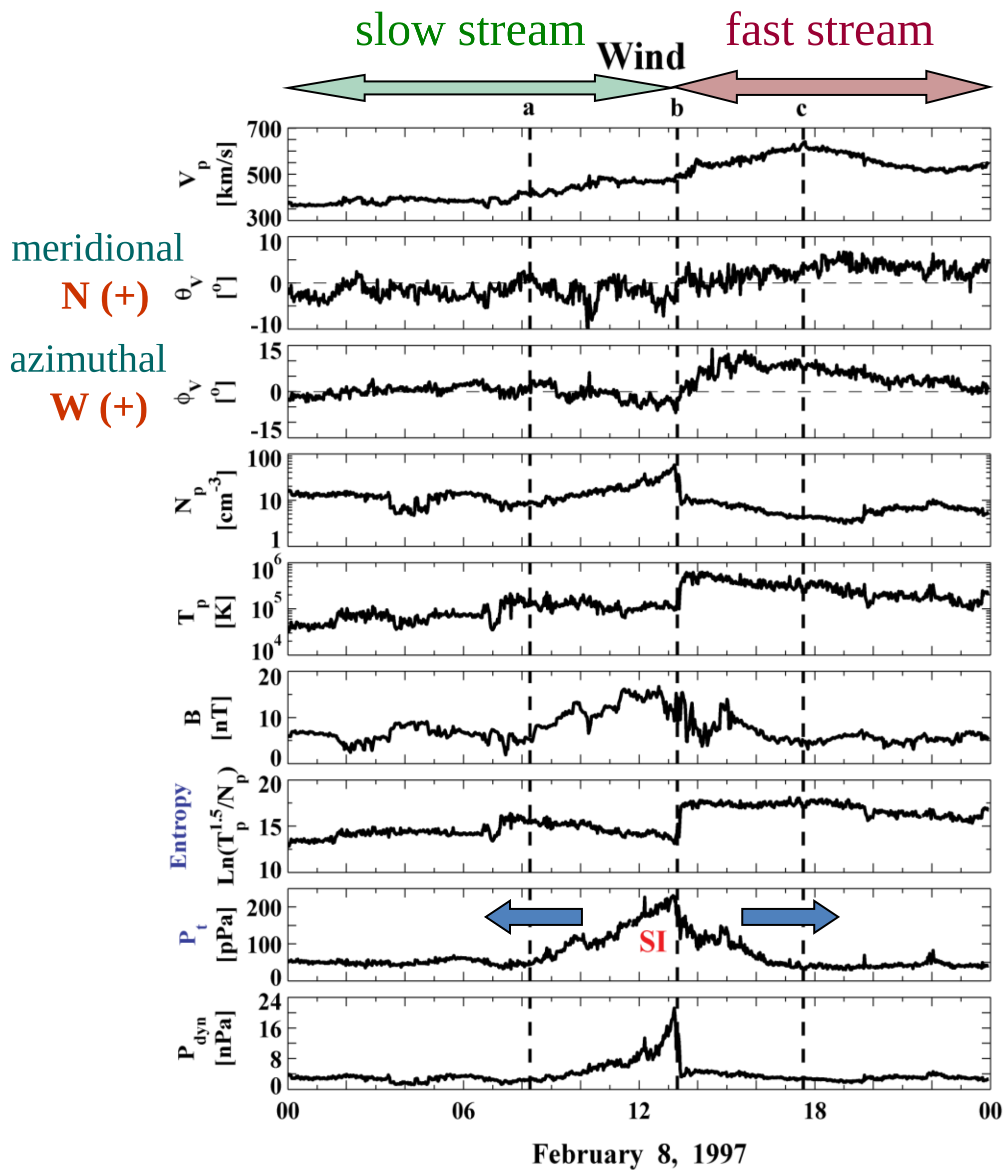
McComas et al. (2008)

- Corotating Interaction Regions (CIRs)
- Transient and Non-Recurrent SIRs



Jian et al. (2006a), after Pizzo (1978)

Identification of SIRs



Jian et al. (2006a)

- **Criteria**
  1) Increase of V_p (necessary)
  2) A pile-up of P_t with gradual decreases at two sides
  3) Increase and then decrease of N_p
  4) Increase of T_p
  5) Deflection of flow
  6) Compression of **B**, usually associated with **B** shear
  7) Change of entropy $\ln(T_p^{1.5}/N_p)$

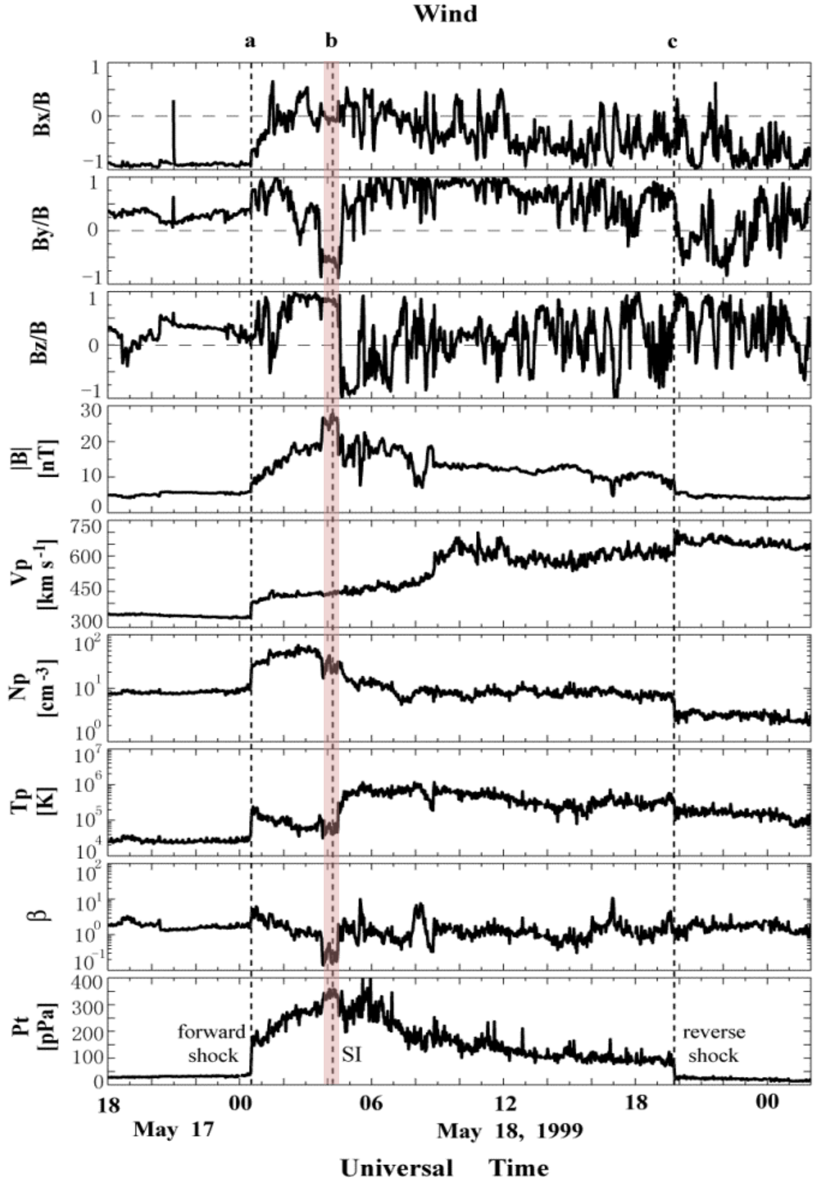
- **Stream interface (SI)**

  At the peak of P_t, sometime (~20% at 1 AU) it coincides with the location where V_p and T_p increase and N_p begins to drop after a N_p compression region

- **Relation with HCS**

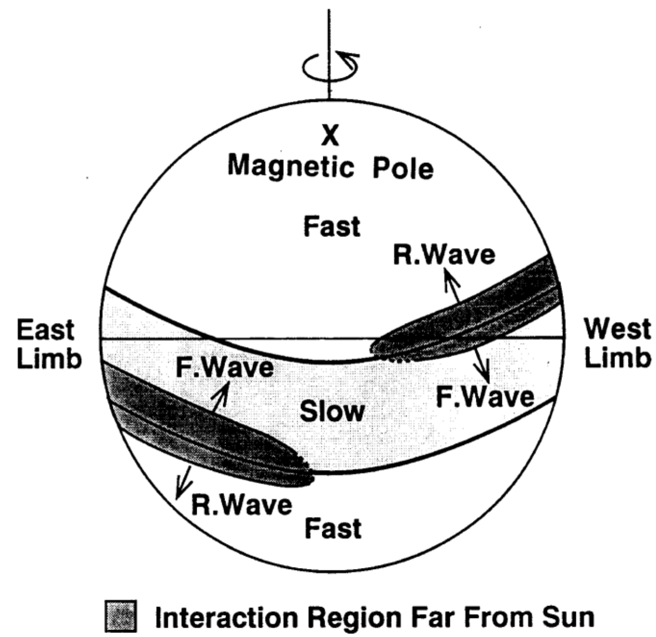
  ~60% of SIRs are associated with a HCS. SI often occurs after HCS

Shocks Driven by SIRs



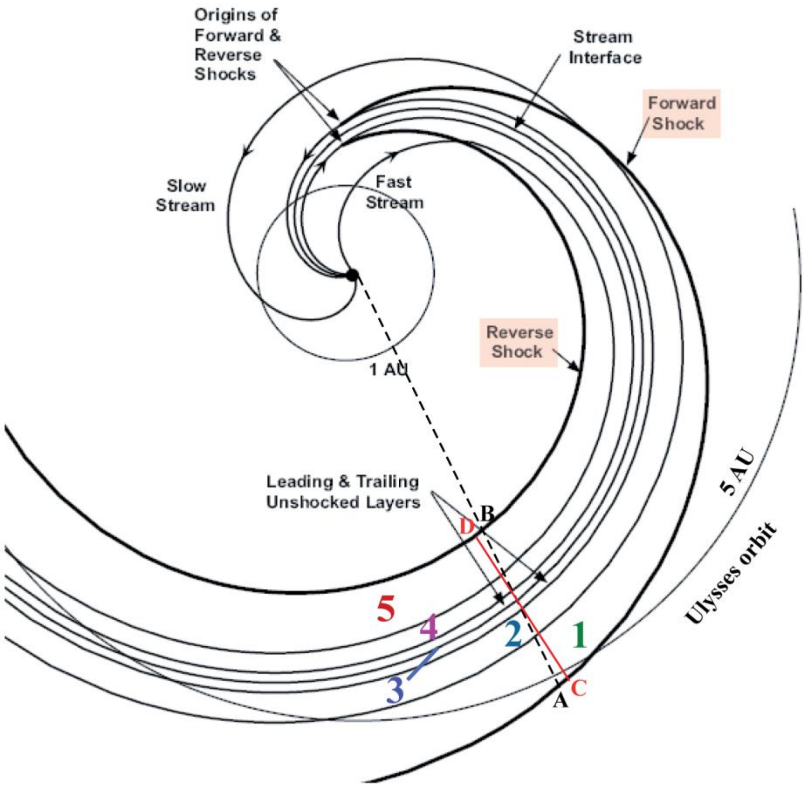
Jian et al. (2006a)

- At 1 AU, ~26% of SIRs drive shocks, rarely a pair of forward-reverse shocks
- The shock association rate increases with the radial evolution of SIRs
- At Jupiter's orbit (~5.4 AU), the shock rate is ~90% for SIRs (Jian et al., 2008)
- These shocks can contribute to energetic storm particles

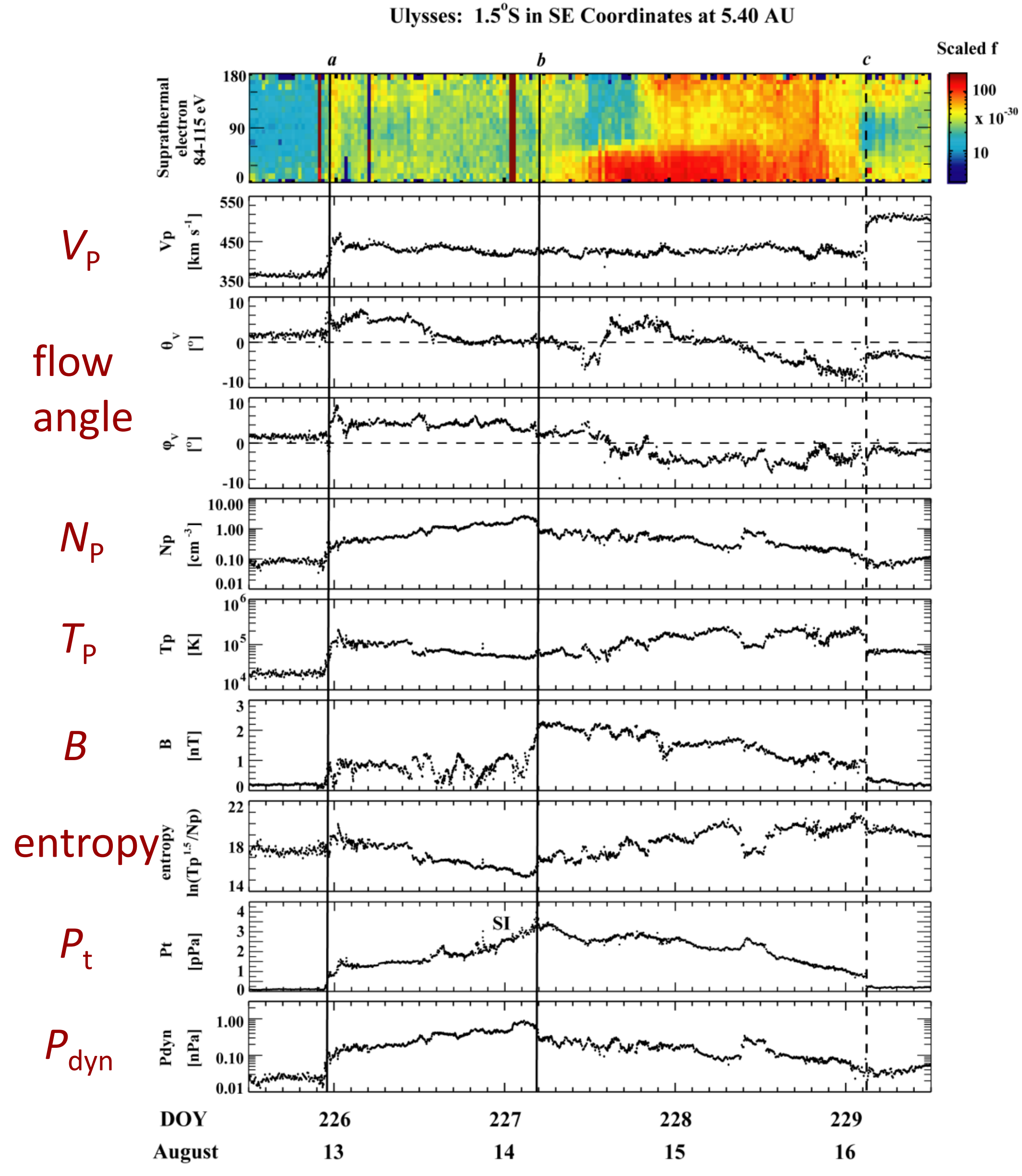


Gosling (1996)

SIRs at 5.4 AU



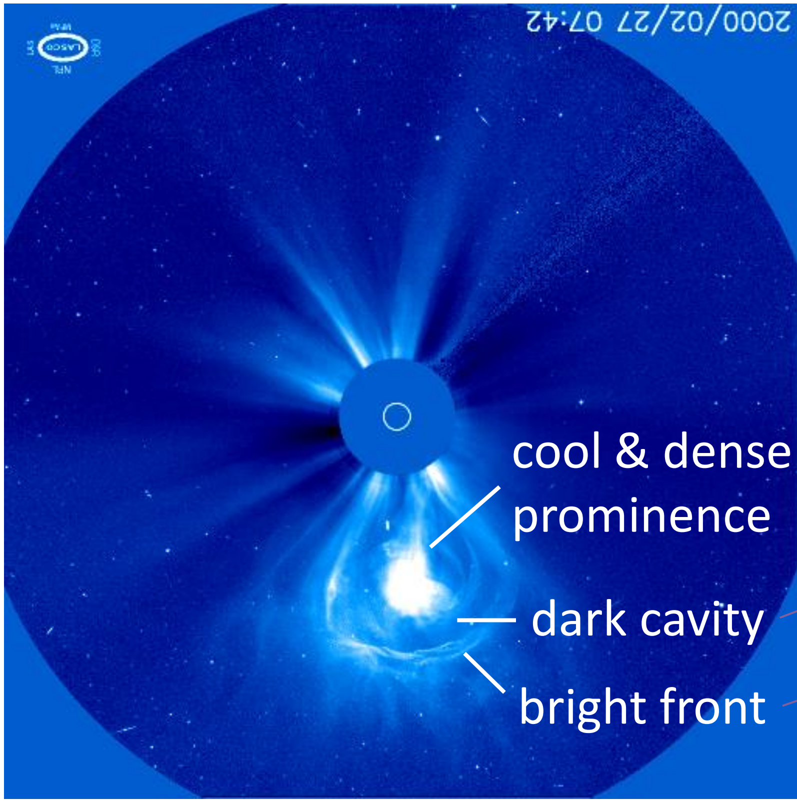
After Crooker et al. (1999)



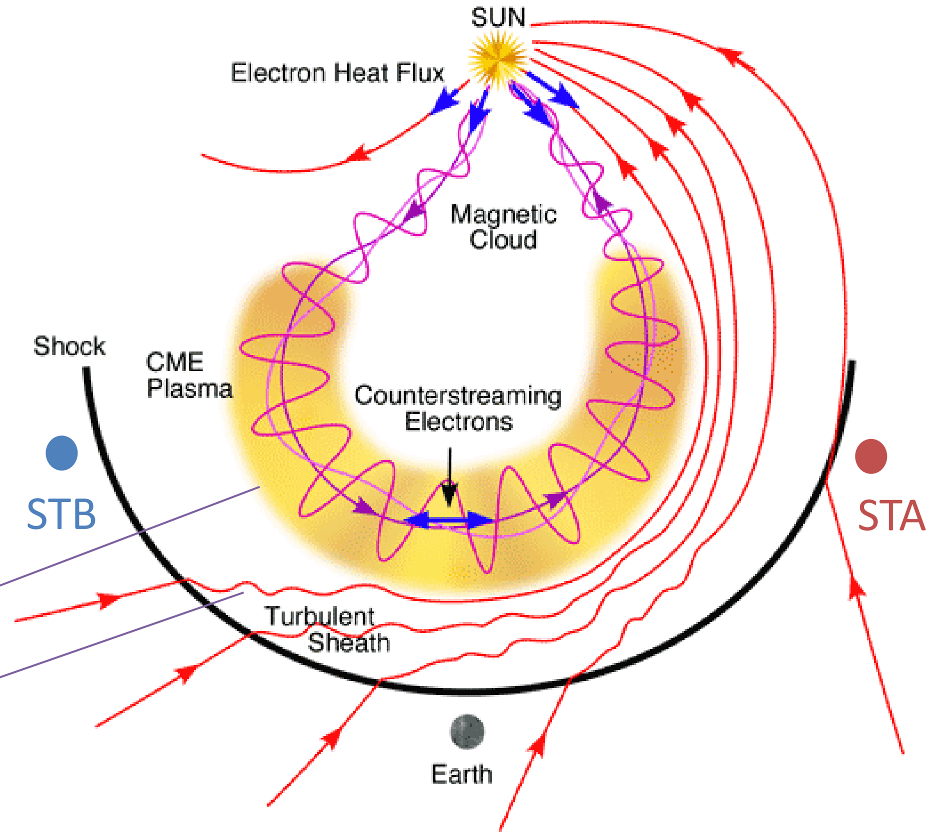
Jian et al. (2008)

CME

ICME

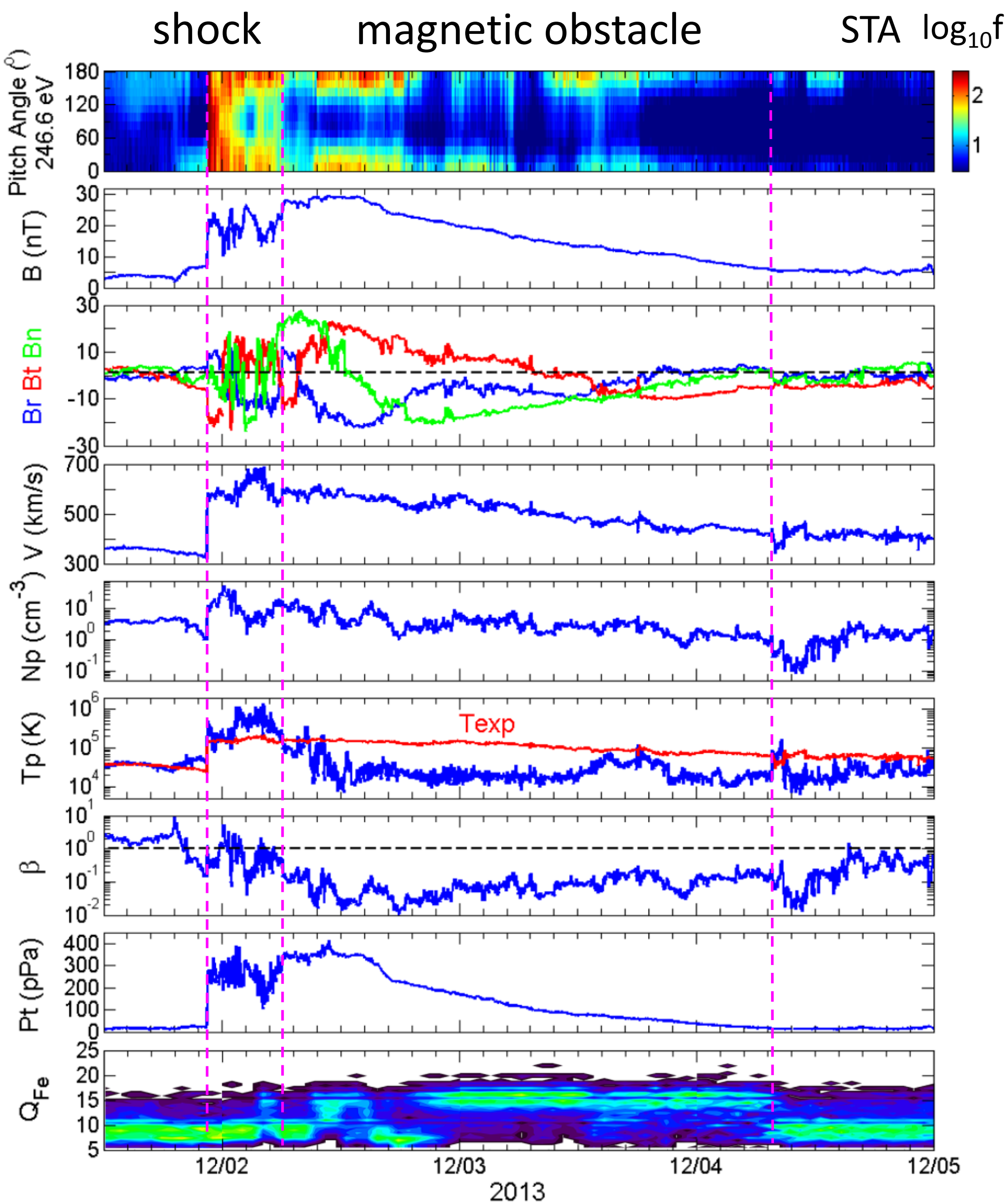


SOHO Large Angle and Spectrometric Coronagraph (LASCO) C3
3.7-32 Rs



Zurbuchen and Richardson (2006)

ICME Example



- **Magnetic cloud (MC)**: low β, large coherent internal magnetic field rotations over a relatively large angle (*Burlaga et al., 1981*)
- About 1/3 of ICMEs are magnetic clouds
- This fraction roughly decreases as the solar activity level increases
- All theories of CME initiation require either the presence or formation of a flux rope as an integral part of the eruption process

ICME Signatures – I

B: Magnetic field   P: Plasma dynamics

	Signature	Description	Selected references	
★	B1: B Rotation	$\gg 30°$, smooth	Klein and Burlaga (1982)	B
★	B2: B Enhancement	>10 nT	Hirshberg and Colburn (1969); Klein and Burlaga (1982)	B
★	B3: B Variance decrease		Pudovkin *et al.* (1979); Klein and Burlaga (1982)	B
★	B4: Discontinuity at ICME boundaries		Janoo *et al.* (1998)	B
★	B5: Field line draping around ICME		Gosling and McComas (1987); McComas *et al.* (1989)	B
to add β	B6: Magnetic clouds	(B1, B2 and $\beta = \frac{\sum nkT}{B^2/(2\mu_0)} < 1$)	Klein and Burlaga (1982); Lepping *et al.* (1990)	B
★	P1: Declining velocity profile/expansion	Monotonic decrease	Klein and Burlaga (1982); Russell and Shinde (2003)	P
	P2: Extreme density decrease	≤ 1 cm^{-3}	Richardson *et al.* (2000a)	P
to add T_{exp}	P3: Proton temperature decrease	$T_p < 0.5 T_{exp}$	Gosling *et al.* (1973); Richardson and Cane (1995)	P
	P4: Electron temperature decrease	$T_e < 6 \times 10^4$ K	Montgomery *et al.* (1974)	P
	P5: Electron Temperature increase	$T_e \gg T_p$	Sittler and Burlaga (1998); Richardson *et al.* (1997)	P
★	P6: Upstream forward shock/"Bow Wave"	Rankine-Hugoniot relations	Parker (1961)	P
to add P_t	P7: Pt Enhancement		Jian *et al.* (2006b)	P

Zurbuchen and Richardson (2006)

ICME Signatures – II

C: Plasma composition

W: Plasma waves

S: Suprathermal particles

	Signature	Description	Selected references
C	C1: Enhanced α/proton ratio	$He^{2+}/H^{+} > 8\%$	Hirshberg *et al.* (1972); Borrini *et al.* (1982a)
	C2: Elevated oxygen charge states	$O^{7+}/O^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003)
	C3: Unusually high Fe charge states	$\langle Q \rangle_{Fe} > 12$; $Q_{Fe}^{\geq 15+} > 0.01$	Bame *et al.* (1979); Lepri *et al.* (2001); Lepri and Zurbuchen (2004)
	C4: Occurrence of He^{+}	$He^{+}/He^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
	C5: Enhancements of Fe/O	$\frac{(Fe/O)_{CME}}{(Fe/O)_{photosphere}} > 5$	Ipavich *et al.* (1986)
	C6: Unusually high $^{3}He/^{4}He$	$\frac{(^{3}He/^{4}He)_{CME}}{(^{3}He/^{4}He)_{photosphere}} > 2$	Ho *et al.* (2000)
	W1: Ion acoustic waves		Fainberg *et al.* (1996); Lin *et al.* (1999)
S	S1: Bidirectional strahl electrons		Gosling *et al.* (1987)
	S2: Bidirectional ∼MeV ions	2nd harmonic > 1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
	S3: Cosmic ray depletions	Few % at ∼ 1GeV	Forbush (1937); Cane (2000)
	S4: Bidirectional cosmic rays	2nd harmonic > 1st harmonic	Richardson *et al.* (2000b)

Zurbuchen and Richardson (2006)

Integrated Space Weather Analysis (iSWA) System

http://iswa.gsfc.nasa.gov/iswa/iSWA.html

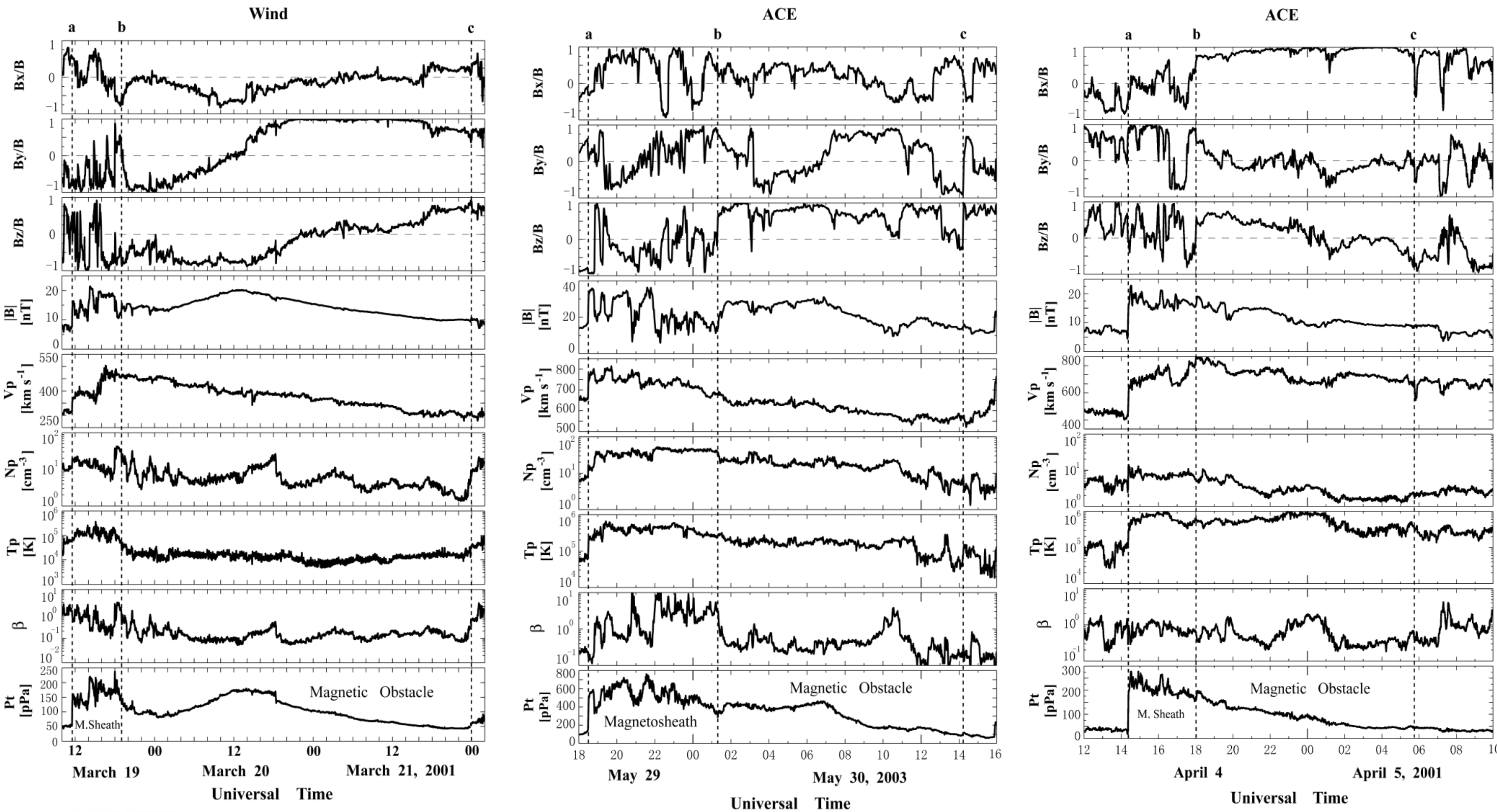
- Real-time data from the Deep Space Climate Observatory (DSCOVR)
  - Solar wind proton density, velocity, and temperature
  - Magnetic field vector
- Beacon data from the Solar Terrestrial Relations Observatory (STEREO)
  - Only STEREO A is available now, about 10 days ahead (or 17 days behind) of Earth for corotating solar wind
- Add the following parameters to assist identification, assuming $N_\alpha=0.04N_p$, $T_\alpha=4T_p$, $N_e=N_p+2N_\alpha$, $T_e=T_p$

$$\beta = \frac{\sum_{i=p,\alpha,e}(N_i k T_i)}{\frac{B^2}{2\mu_0}} \qquad P_t = \sum_{i=p,\alpha,e}(N_i k T_i) + \frac{B^2}{2\mu_0}$$

$$T_{ex}(\times 10^3 K) = \begin{cases} (0.031V - 5.1)^2, & if\ V < 500\ km/s \\ 0.51V - 142, & if\ V \geq 500\ km/s \end{cases}$$

Lopez (1987)

Variability of ICMEs



Group 1

Containing well-defined flux rope (magnetic cloud) with central maximum in P_t

Group 2

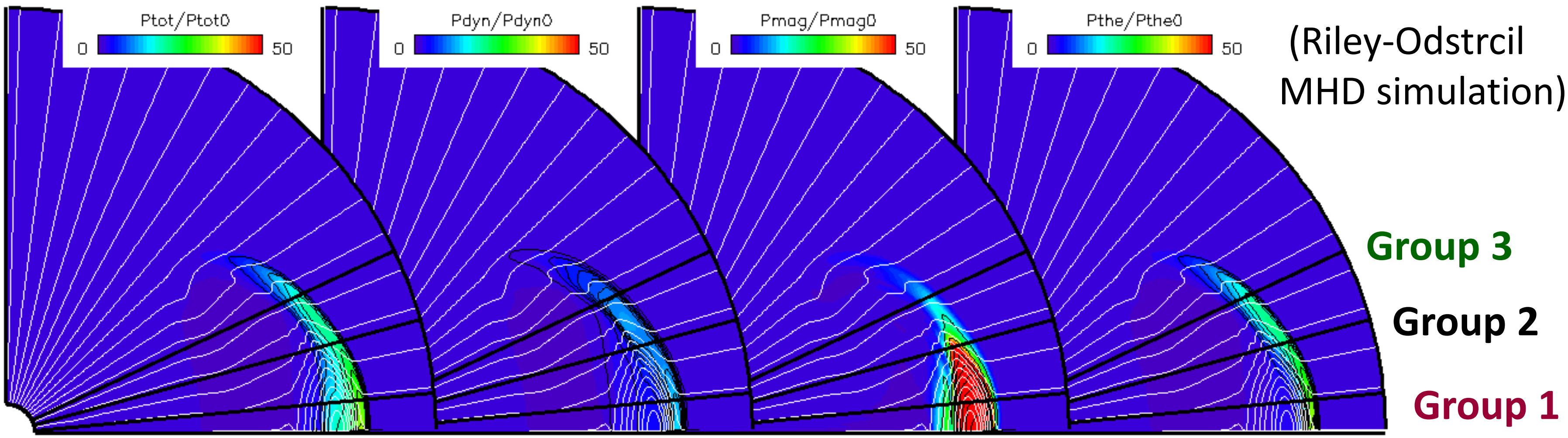
Containing magnetic obstacle with central P_t "plateau"

Jian et al. (2006b)

Group 3

Poorly-defined magnetic obstacle with monotonic P_t decrease after the leading shock and/or sheath

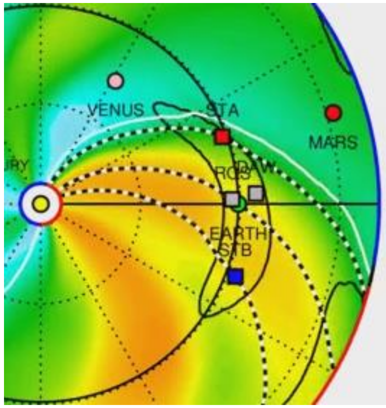
Interpretation of Three Groups of ICMEs

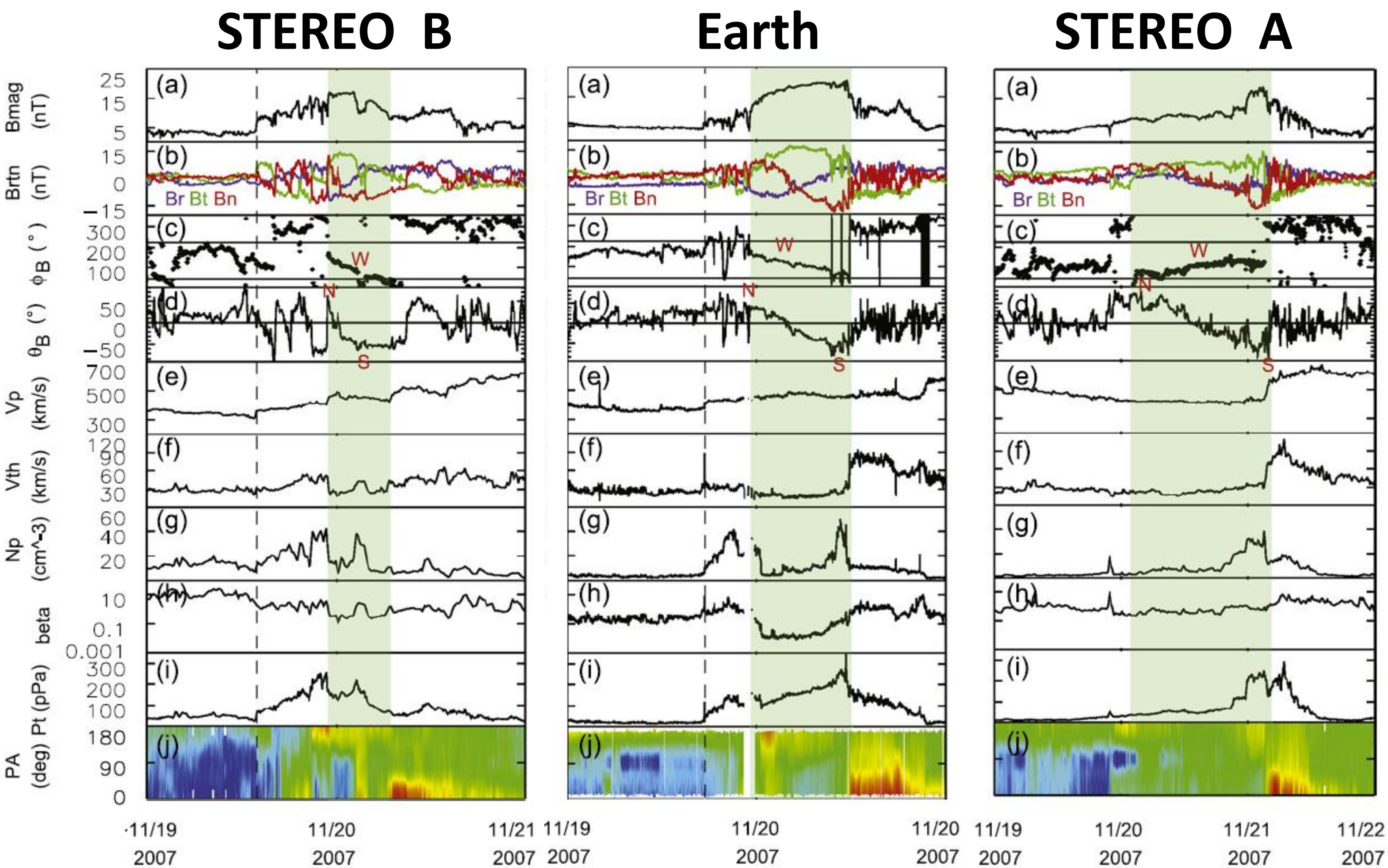


- The three groups of ICMEs classified using the Pt temporal profiles, possibly associated with different approach distances to the central flux rope

Multipoint Observations of ICMEs

40° apart



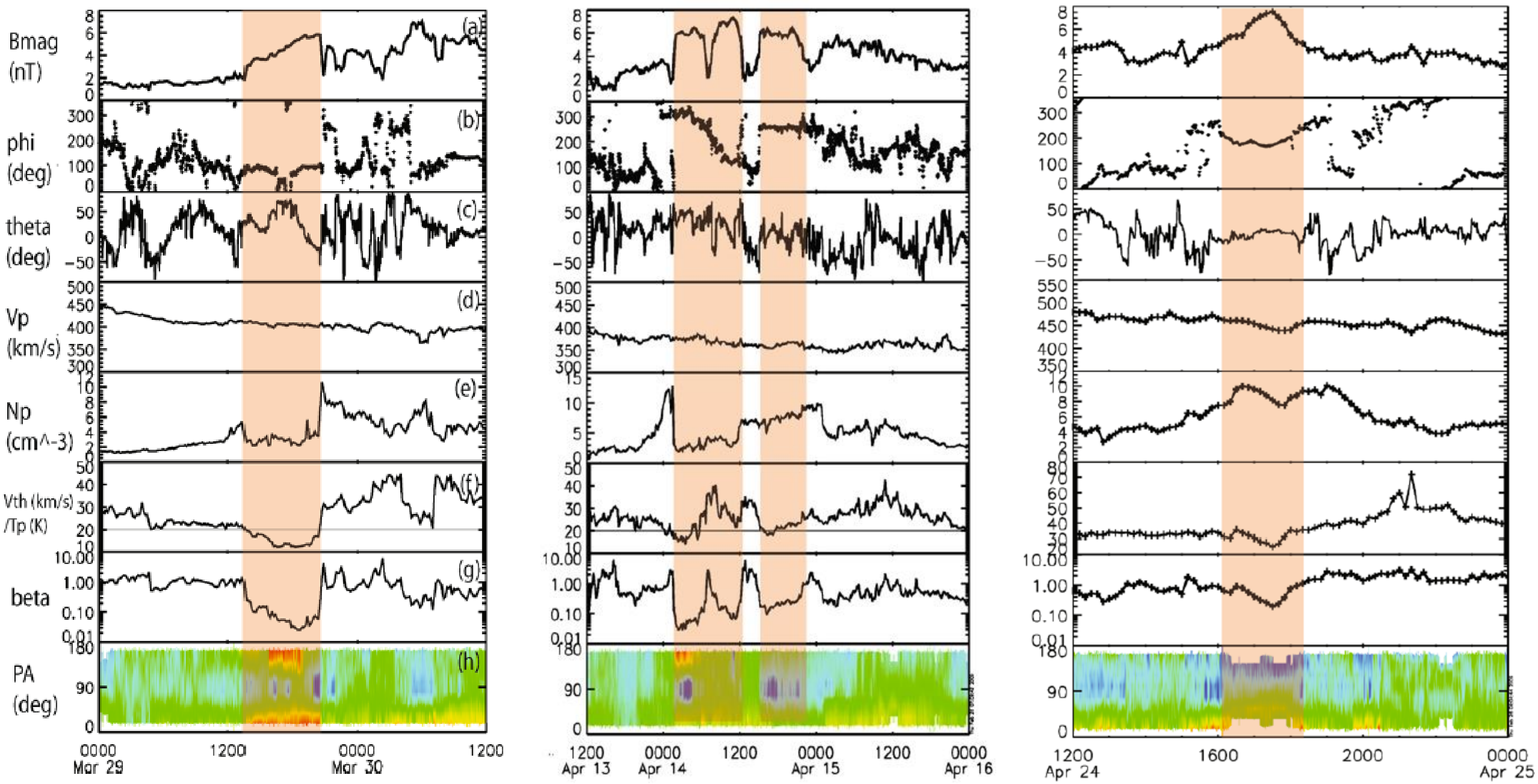


Kilpua et al. (2011)

Small ICME-Like Transients

1) lasting a few hours 2) B increase 3) often seen in the slow wind

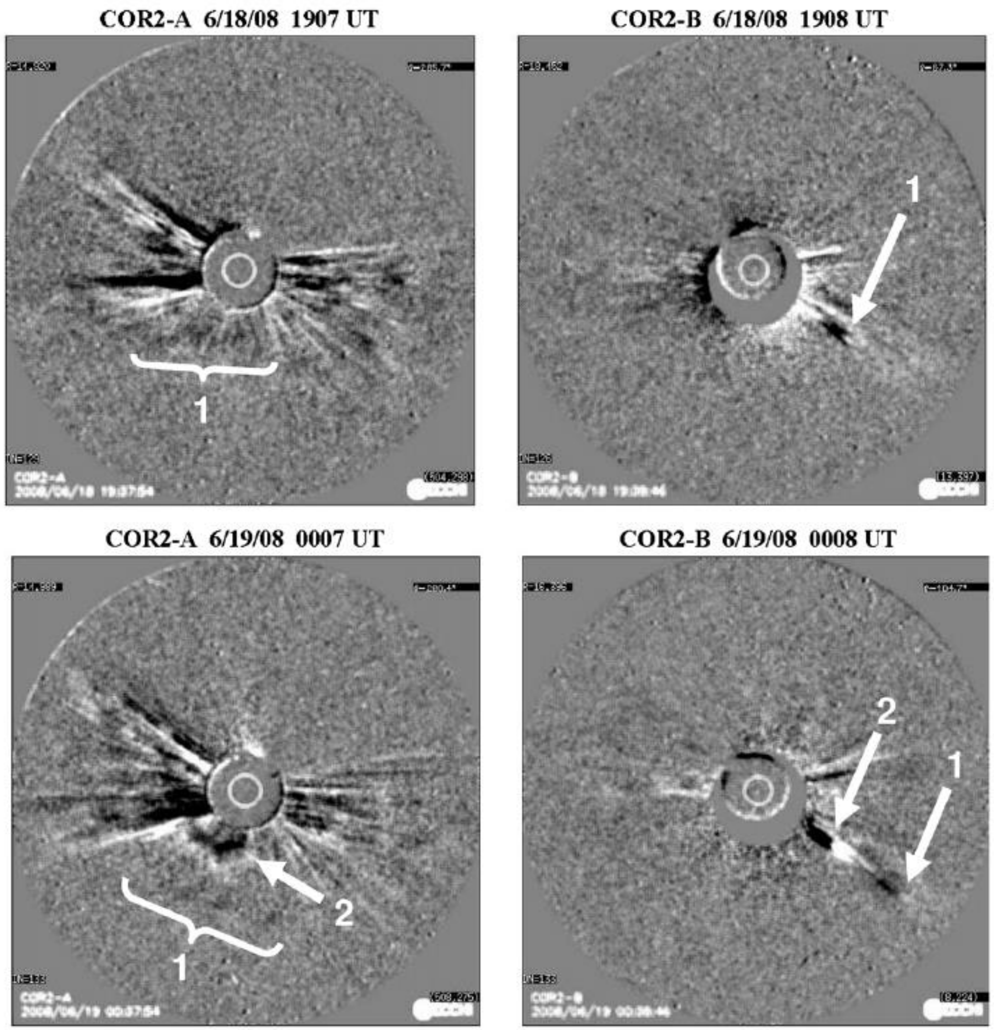
STEREO A **STEREO A** **STEREO A**



2007 2007 2007

Kilpua et al. (2009)

Origin of Small ICME-Like Transients



Sheeley et al. (2009)

- **Origin**:
  - Small mass ejecta at the tip of helmet streamers
  - Blobs
  - Glances of large ICMEs
- Left shows two blobs moving across COR2
- The blob series appear as a series of azimuthal waves in the face-on views

Hybrid Event

- ~10% of ICMEs and 6% of SIRs are in the hybrid events, where multiple ICMEs interact or ICME and SIR interact
- They can cause stronger geomagnetic activity

One very rare example among hundreds of ICMEs has the interplanetary counterpart of **prominence** (region *c*–*d*)

V_P

flow angle
(meridional, azimuthal)

N_P

T_P

N_α

T_α

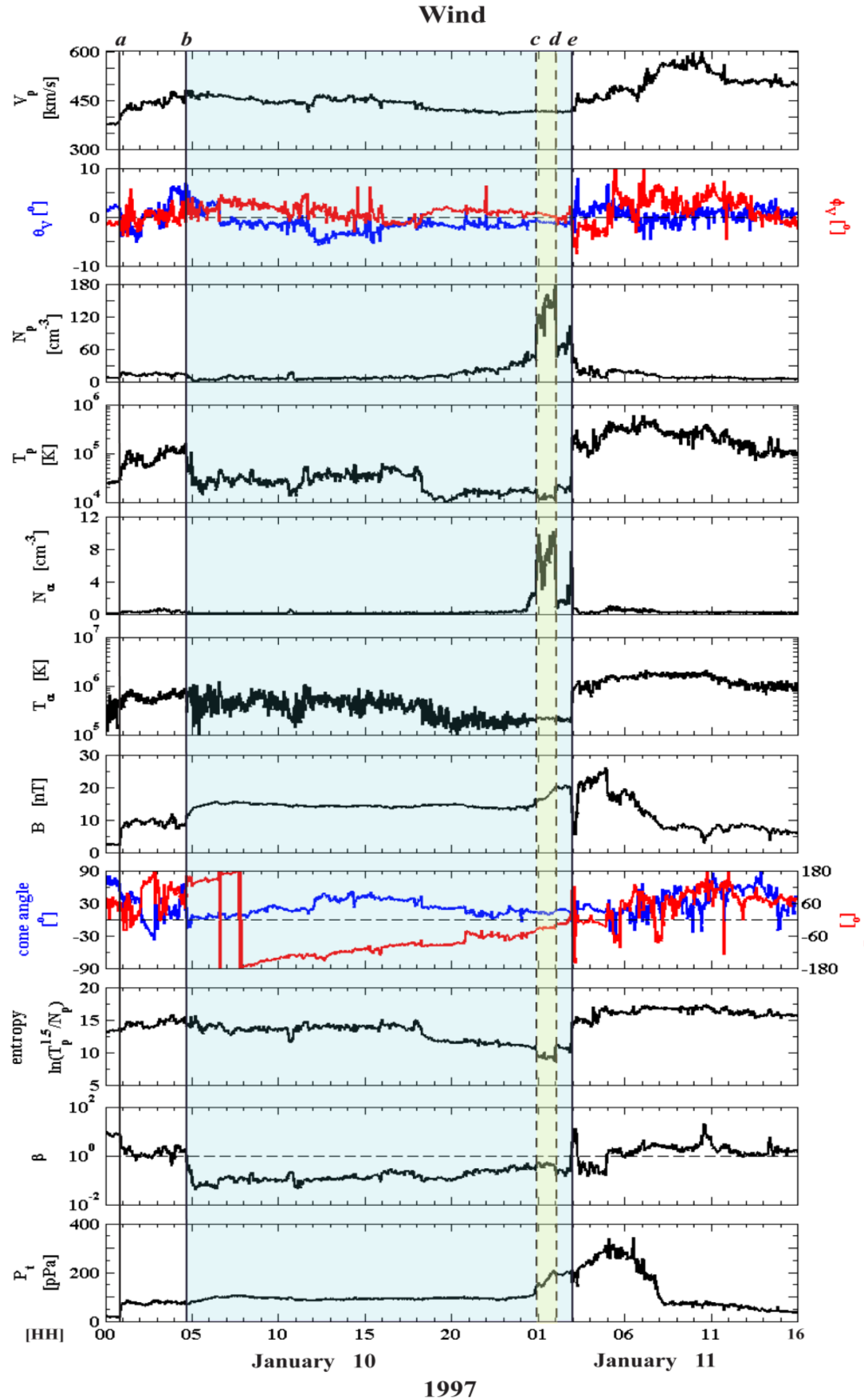
B

cone angle arcsin(B_r/B)
clock angle arctan(B_t/B_n)

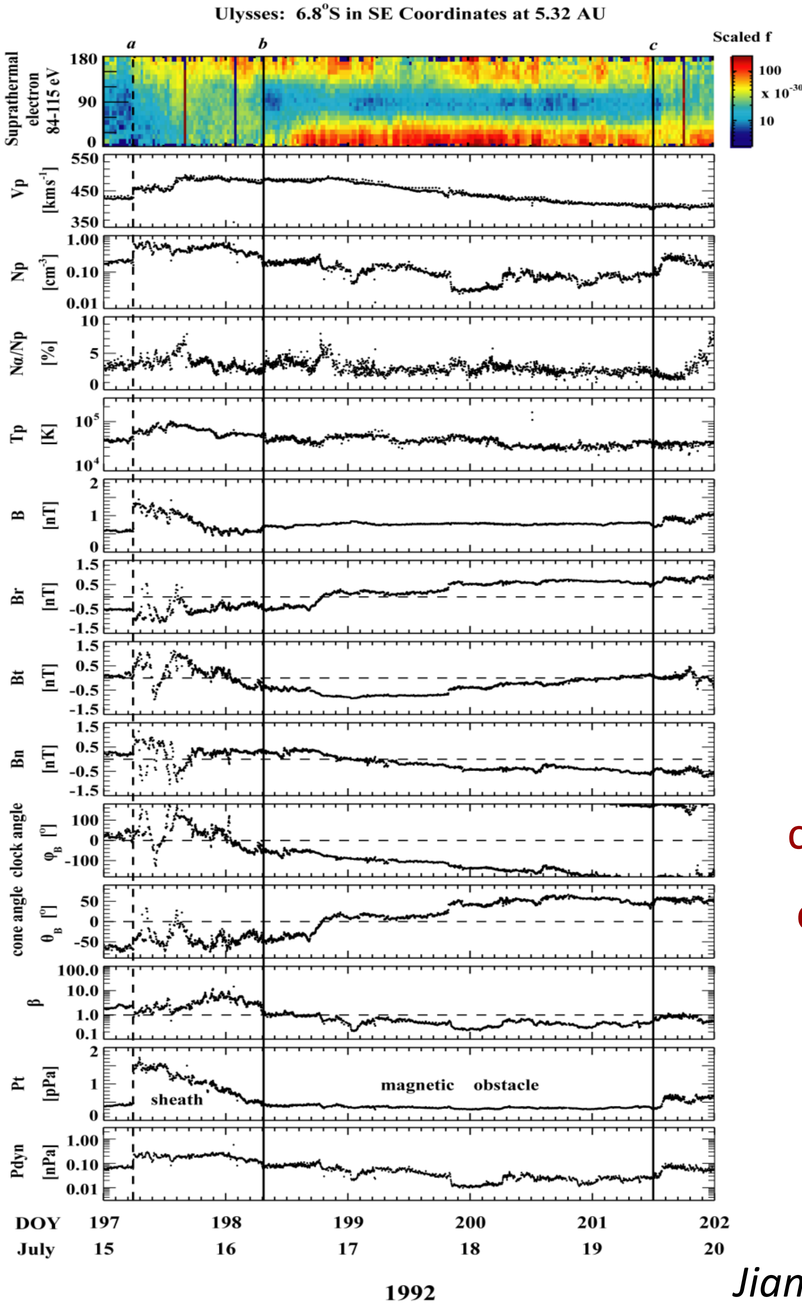
entropy

β

P_t



ICMEs at 5.3 AU



suprathermal electron

V_P

N_P

N_α/N_P

T_P

B

B_r

B_t

B_n

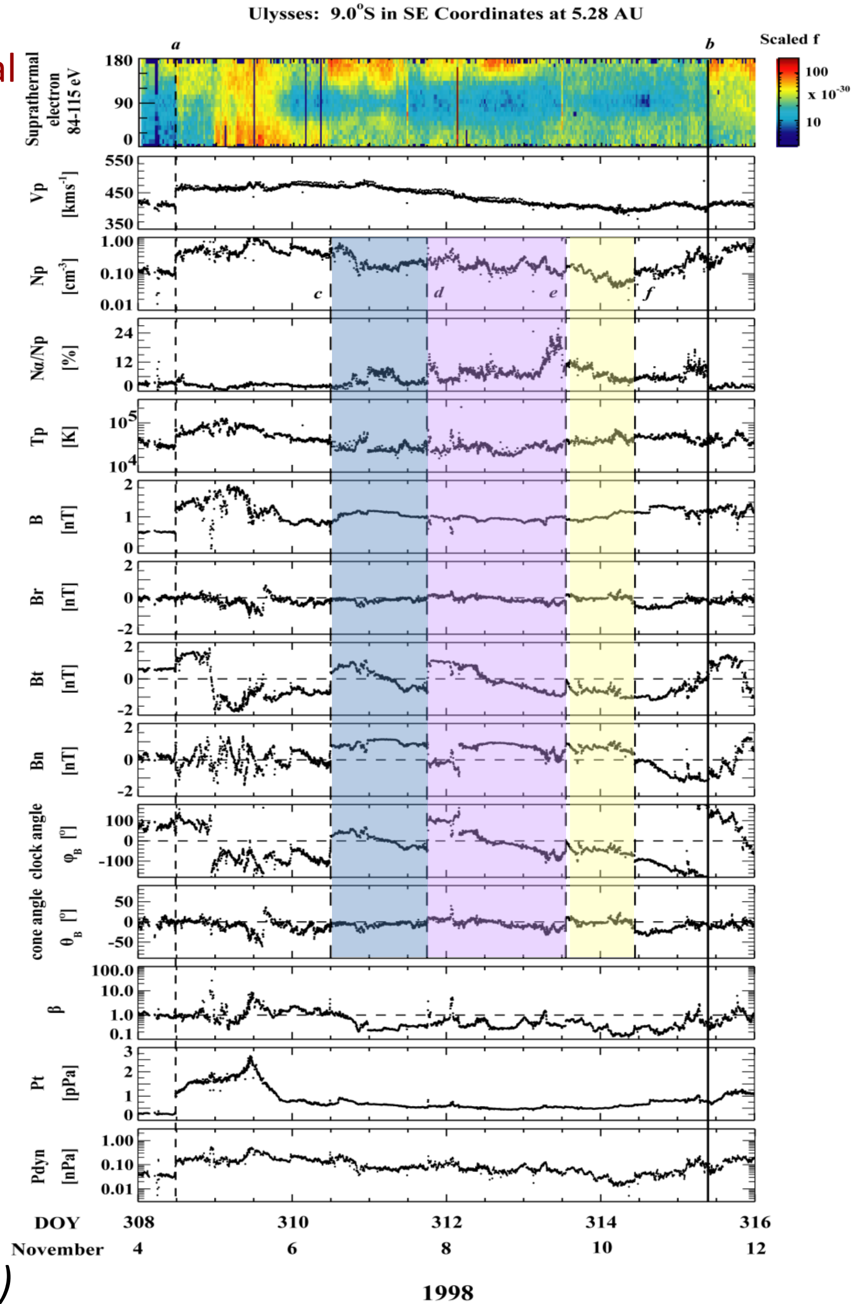
clock angle

cone angle

β

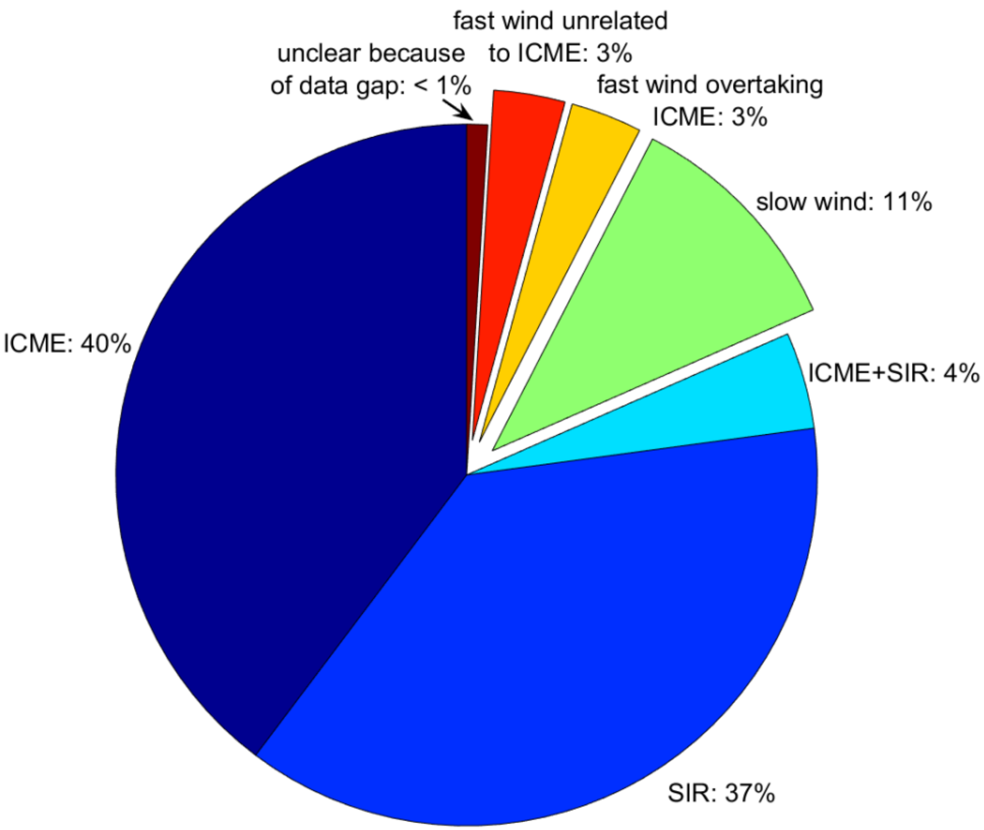
P_t

P_{dyn}



Jian et al. (2008)

Driverless Shocks



Jian et al. (2013)

- About 10-20% of shocks observed at 1 AU are found to be driverless
- They could be attributed to
  - low-latitude coronal holes deflecting nearby CMEs away from the Sun-Earth line
  - CMEs becoming unrecognizable at 1 AU

Concluding Remarks

- ✓ There are multiple types of large-scale structures in the solar wind: heliospheric current sheet (HCS), stream interaction region (SIR), interplanetary CME (ICME), and shock

- ✓ These structures are closely related

- ✓ They can impact the magnetosphere and/or ionosphere of Earth and other planets. Shocks is a major type of sources to energize particles

- ✓ Besides the aforementioned criteria, to identify solar wind structures in real time
  - ✓ always check the solar observations taken about 2-5 days ago till present
  - ✓ Check the solar wind at Earth about 27 days ago at Earth or at STEREO A about 10 days ago (at present). If the latitudes of STEREO A and Earth do not differ much, and if the Sun is relatively quiet, we would expect similar solar wind at Earth