Identification of Interplanetary Coronal Mass Ejections (ICMEs) Using Real-Time In Situ Data

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CCMC

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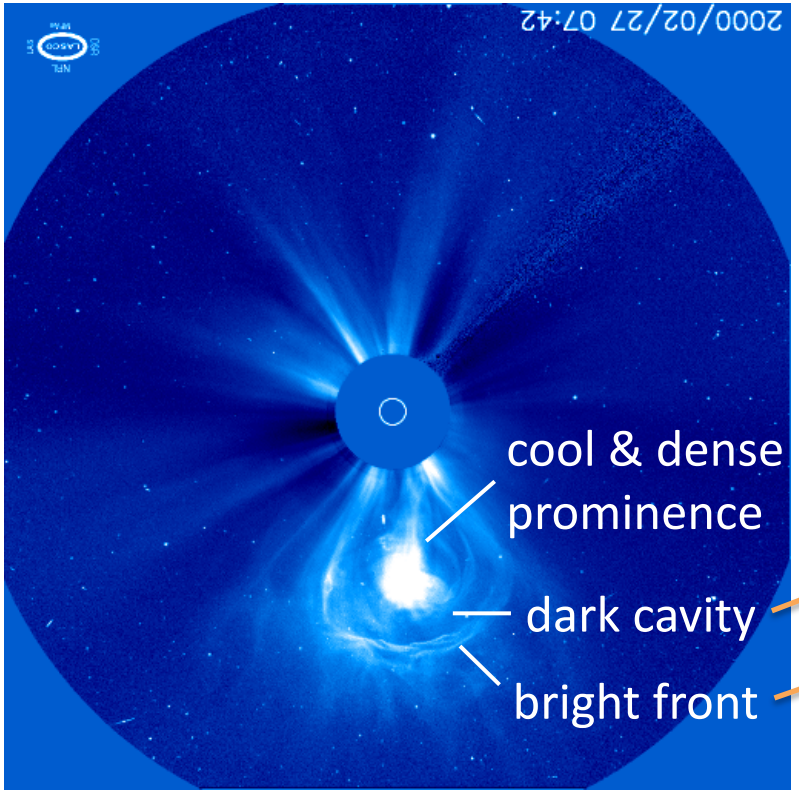
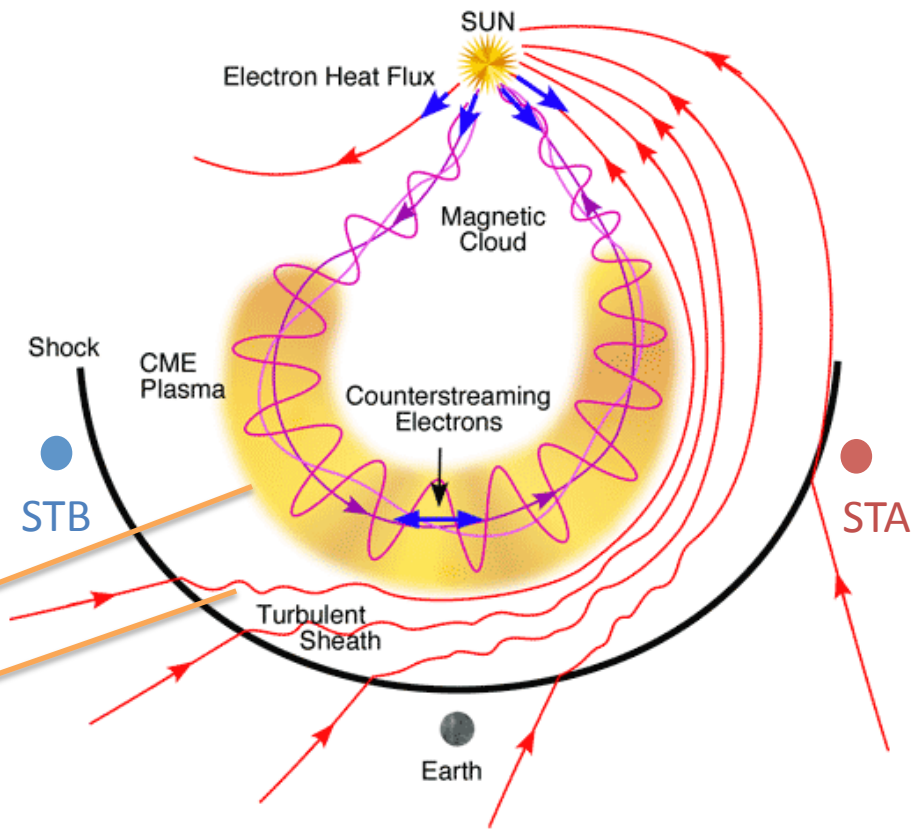
Outline

- CME vs. ICME
- ICME signatures & variability
- Small ICME-like transients
- SIR to distinguish
- Hybrid event
- Other notes

CME

ICME



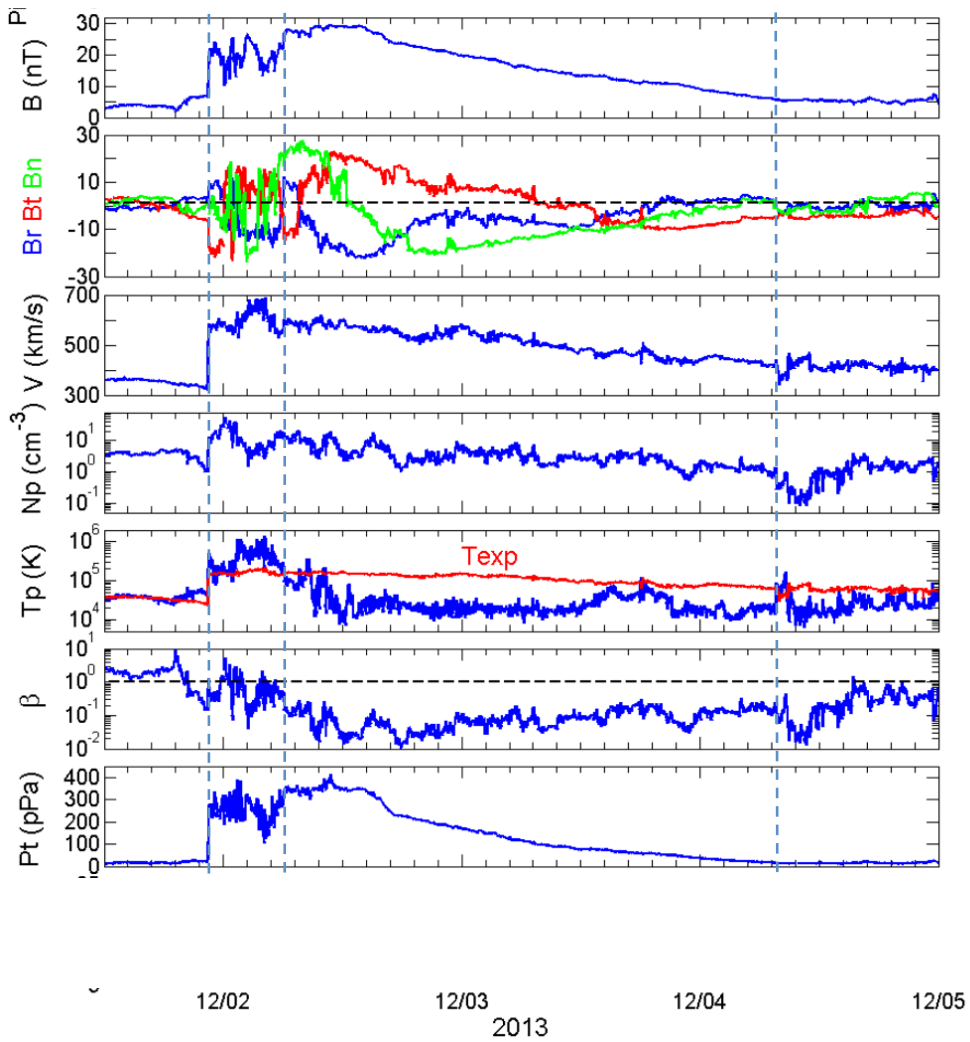


SOHO Large Angle and Spectrometric Coronagraph (LASCO) C3
3.7-32 Rs

Zurbuchen and Richardson (2006)

ICME Example

shock magnetic obstacle STA $\log_{10}f$



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	$T_p < 0.5T_{exp}$	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.* (2006)	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)
C	C2: Elevated oxygen charge states	$O^{7+}/O^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003)
C	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)
C	C4: Occurrence of He^{+}	$He^{+}/He^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
C	C5: Enhancements of Fe/O	$\frac{(Fe/O)_{CME}}{(Fe/O)_{photosphere}} > 5$	Ipavich *et al.* (1986)
C	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)
S	S2: Bidirectional ~MeV ions	2nd harmonic > 1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
S	S3: Cosmic ray depletions	Few % at ~ 1 GeV	Forbush (1937); Cane (2000)
S	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

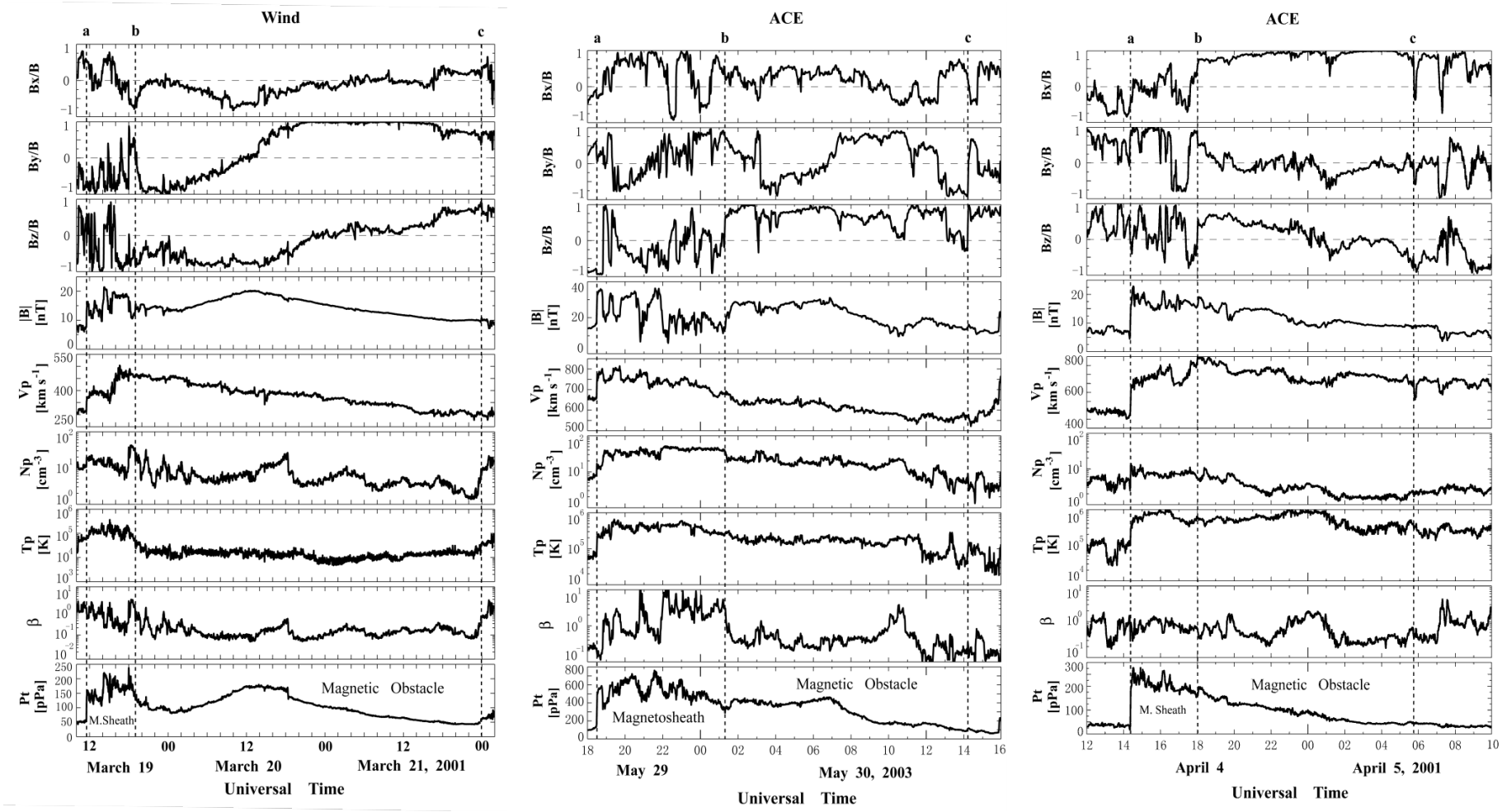
- ACE (DSCOVR coming soon) real-time data
  - Solar wind proton density, velocity, and temperature
  - Magnetic field vector
- STEREO beacon data
  - Only STEREO A is available now, about 11-12 days ahead (or 15-16 days behind) of Earth for corotating solar wind
- Add the following parameters to assist 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. (2006a)

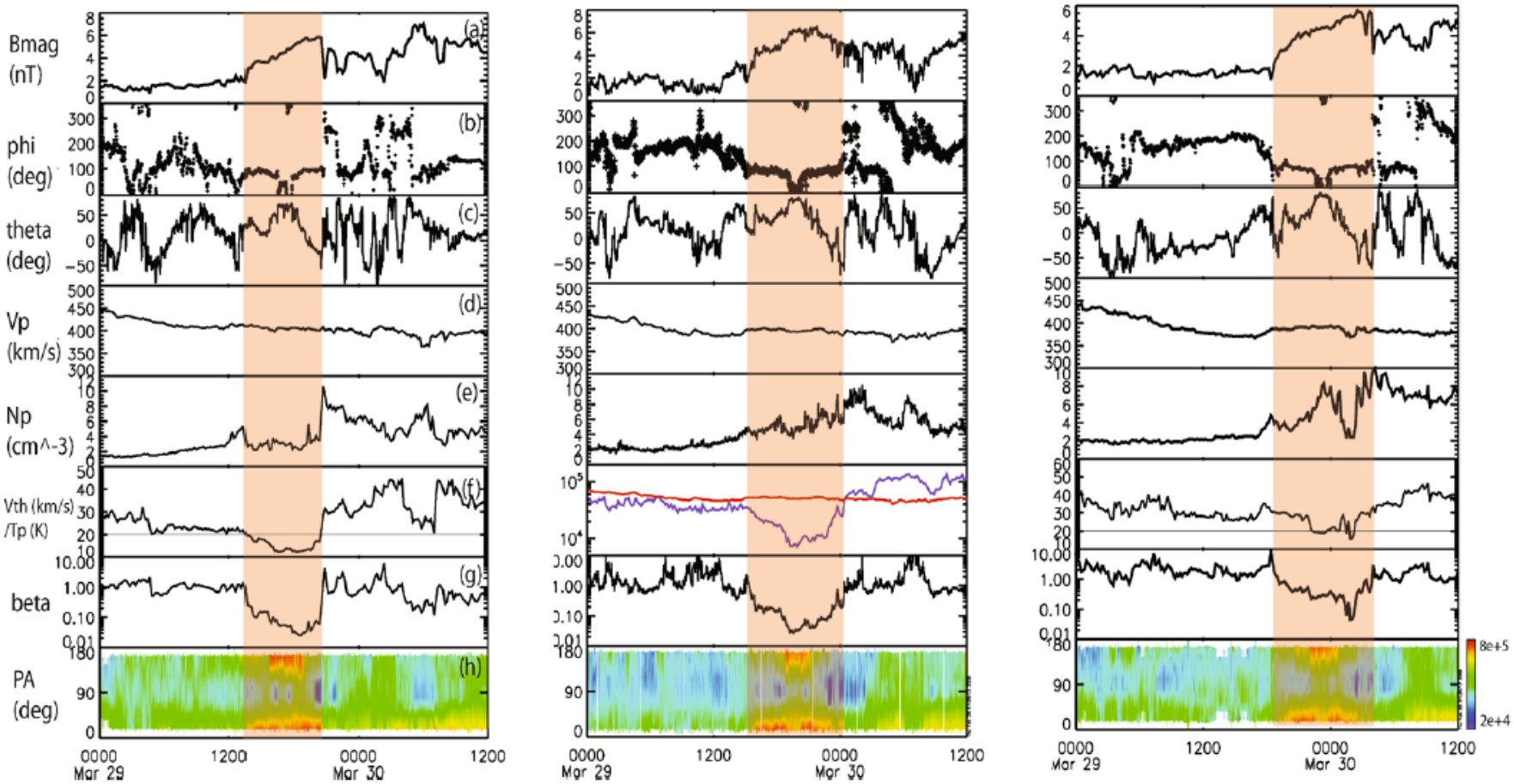
Group 3

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

Small ICME-Like Transients

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

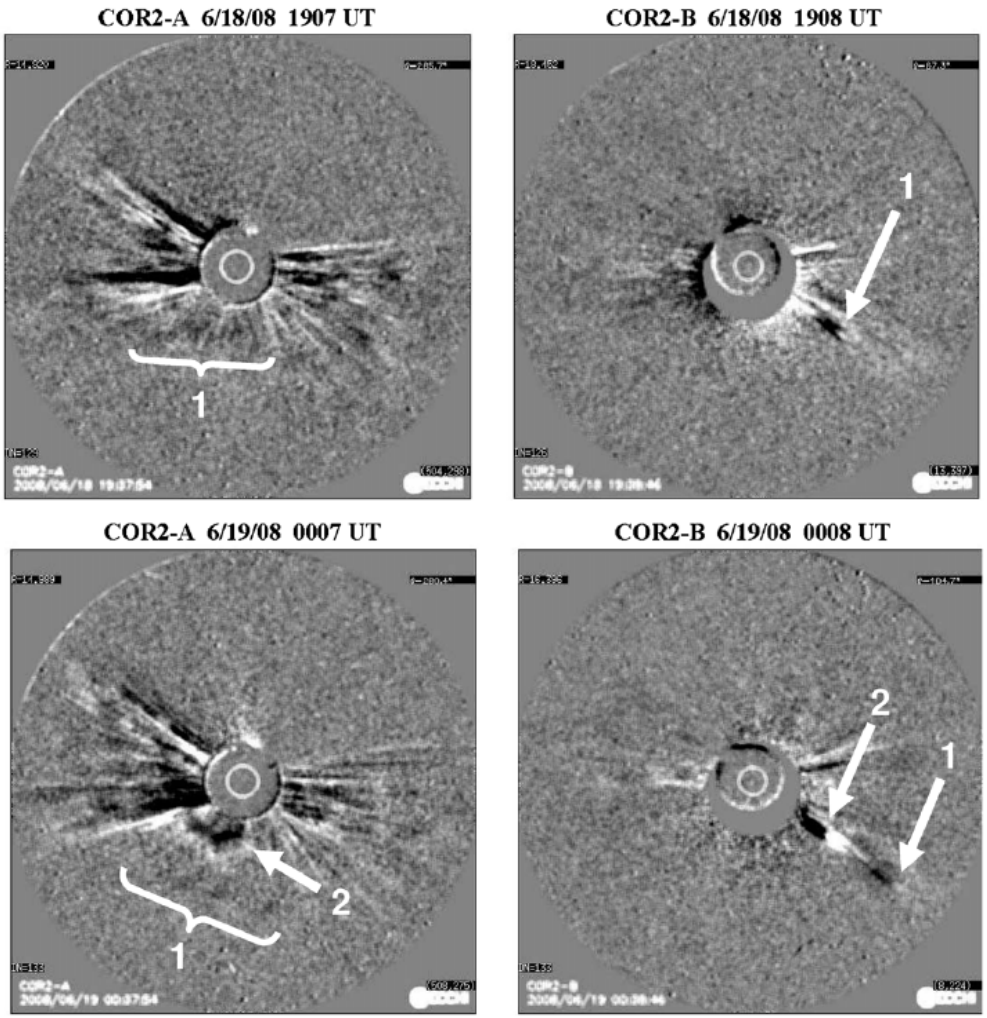
STEREO A **Wind** **STEREO B**



2007 2007 2007

Kilpua et al. (2009)

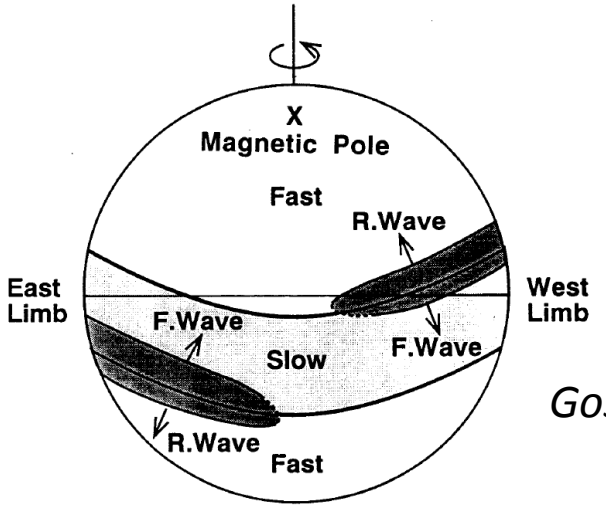
Origin of Small ICME-Like Transients



Sheeley et al. (2009)

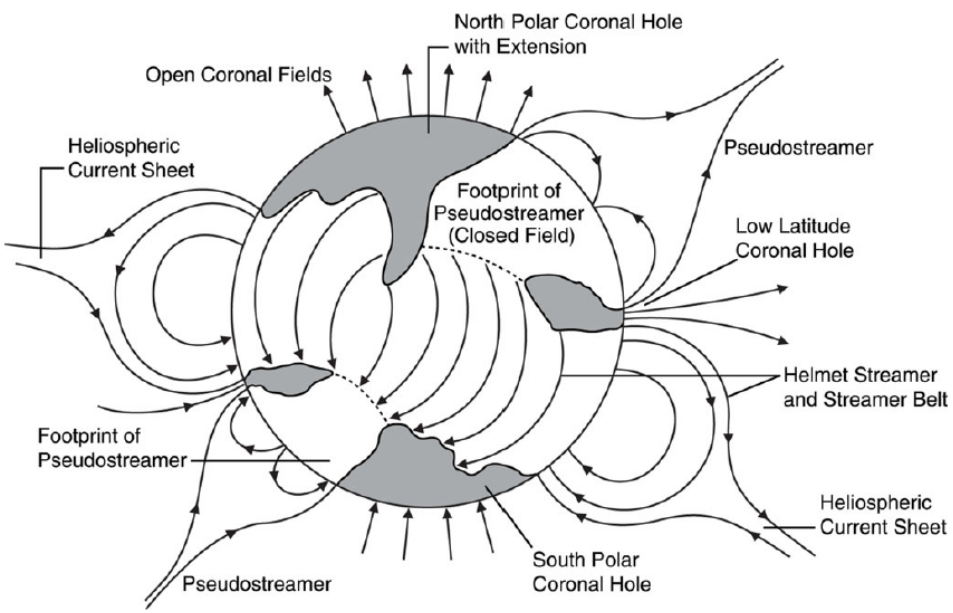
- **Origin**:
  - Small mass ejecta at the tip of helmet streamers
  - Blobs
  - Glances of large ICMEs too
- Left shows two blobs moving across COR2
- The blob series appear as a series of azimuthal waves in the face-on views

One Large-Scale Solar Wind Structure to Distinguish: Stream Interaction Region (SIR)

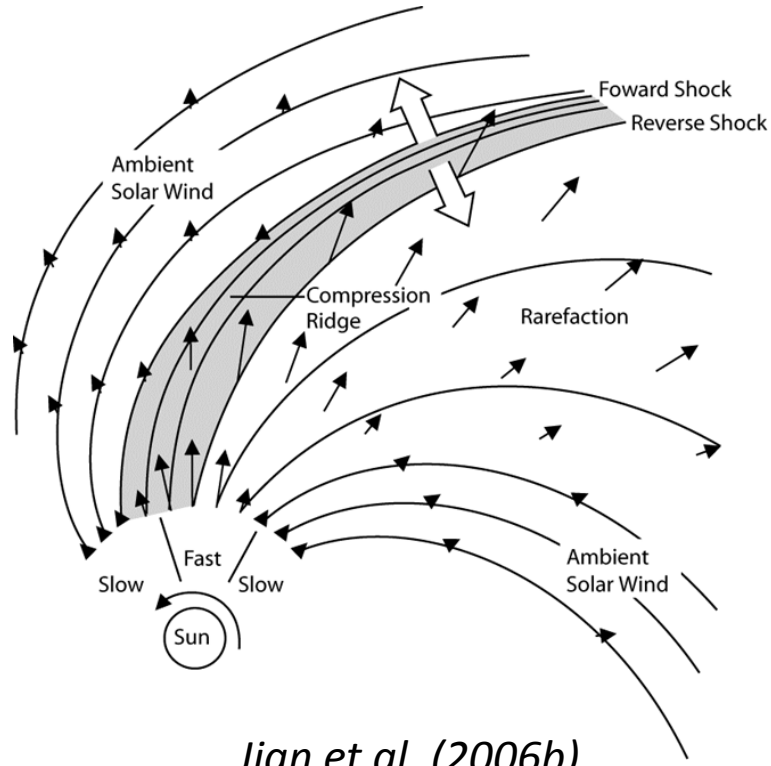


Gosling (1996)

~ 80% of SIRs are **corotating interaction regions (CIRs)**

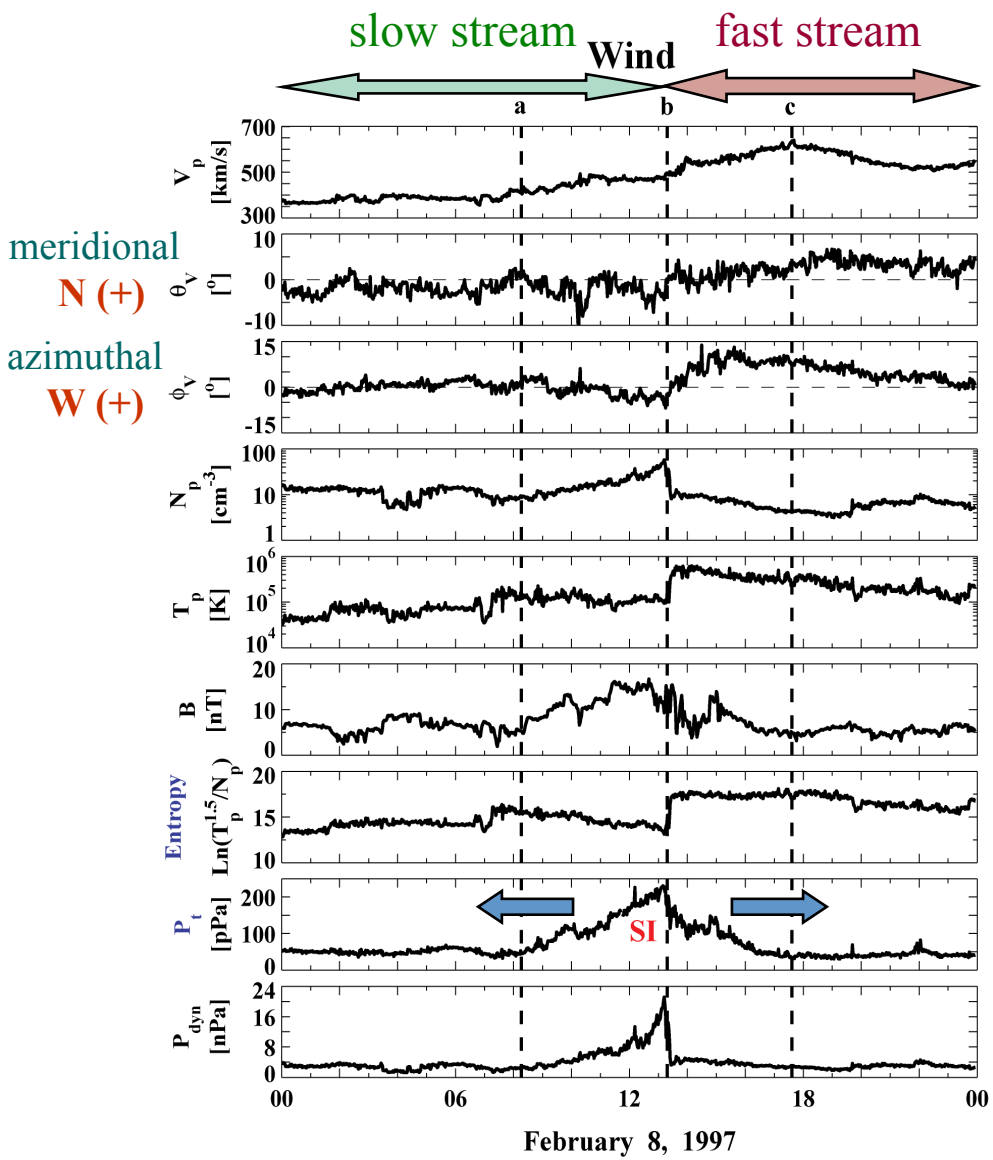


Luhmann et al. (2012)



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

Identification of SIRs



Jian et al. (2006b)

* **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 $\ln(T_p^{1.5}/N_p)$

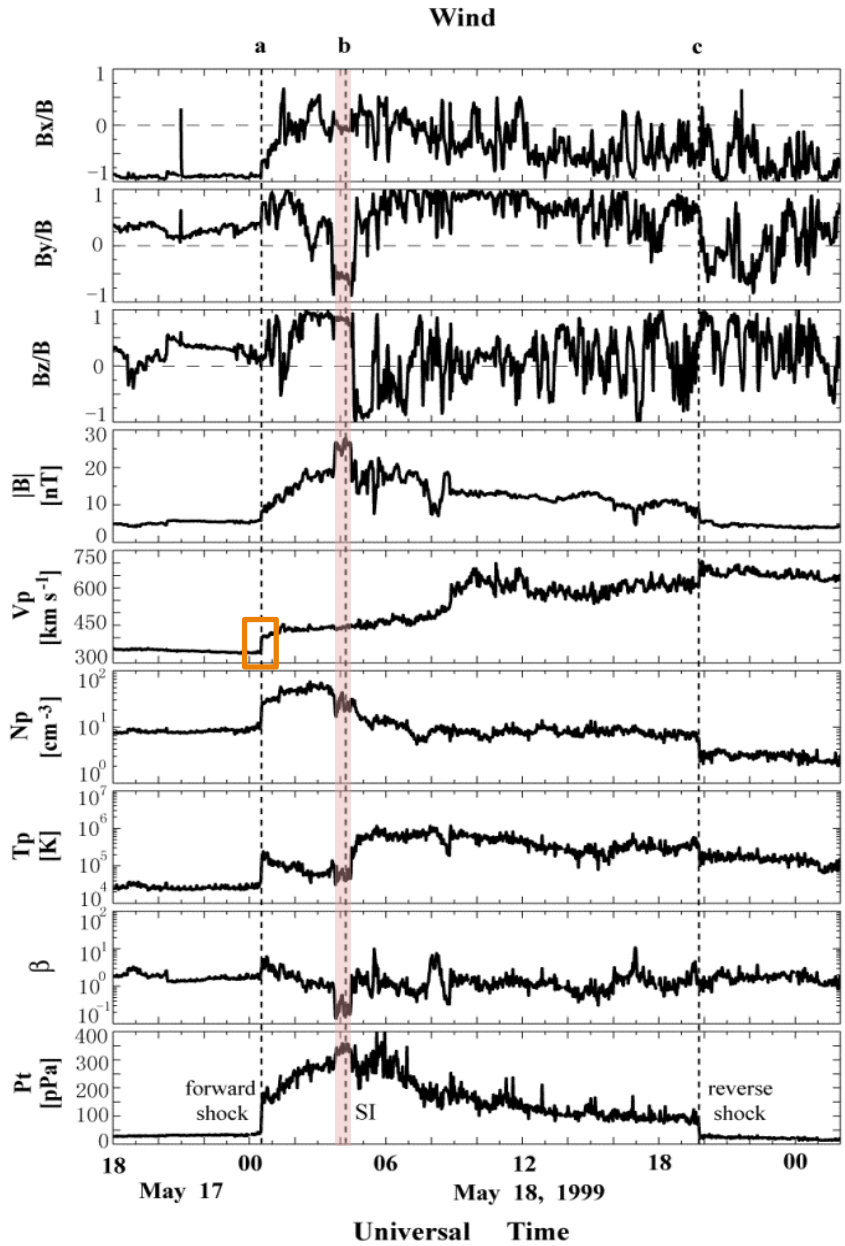
* **Stream interface (SI)**

  at the peak of P_t, sometime it coincides with the location where V_p and T_p increase and N_p begins to drop after a N_p compression region

* **Magnetic sector boundary**

  identified by the long-term changes of the magnetic field polarity

About 30% of SIRs drive shocks, sometimes a pair of forward-reverse shocks

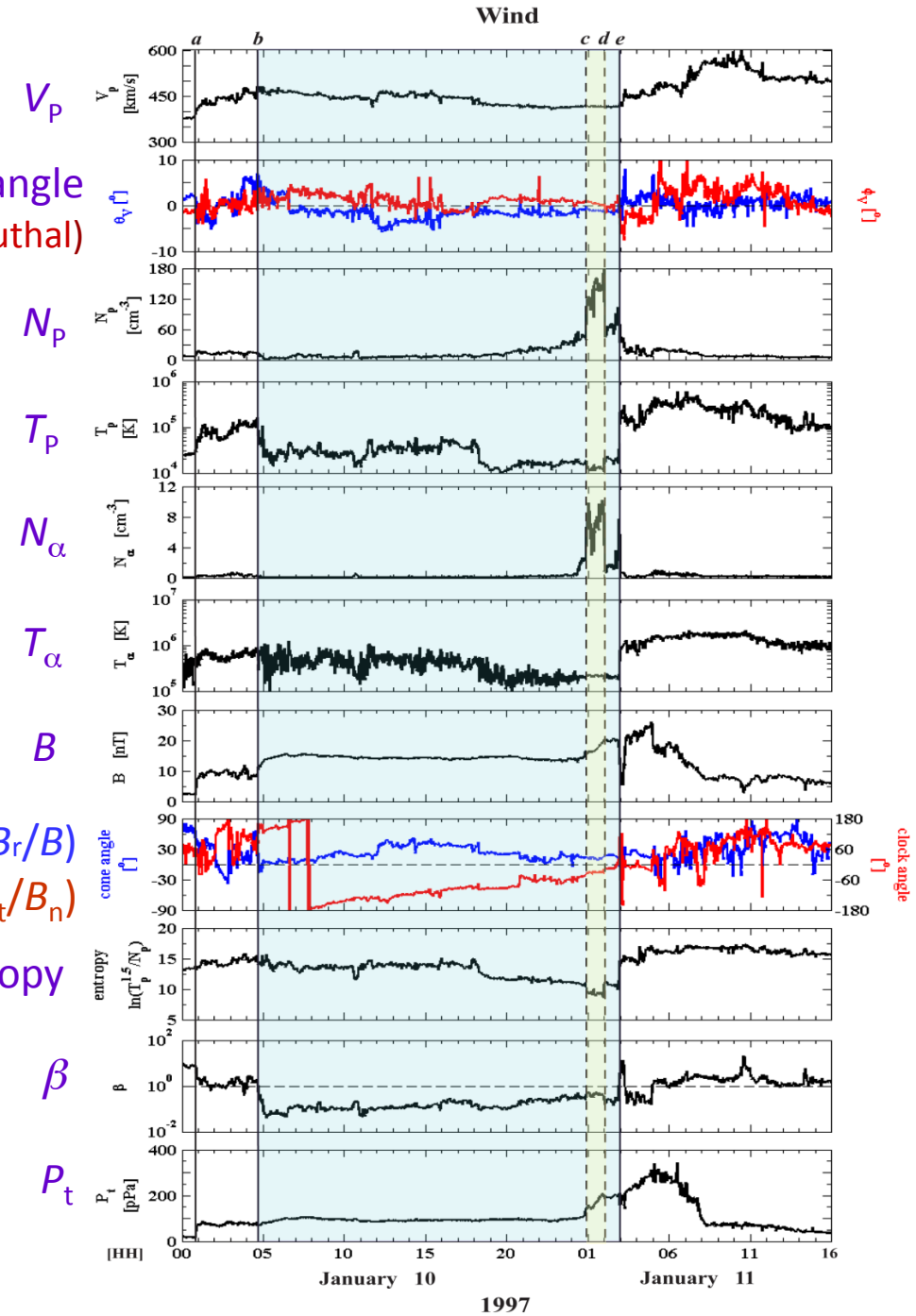


Jian et al. (2006b)

Hybrid Event

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

Unusual composition and charge state in c-d (Burlaga et al., 1998)

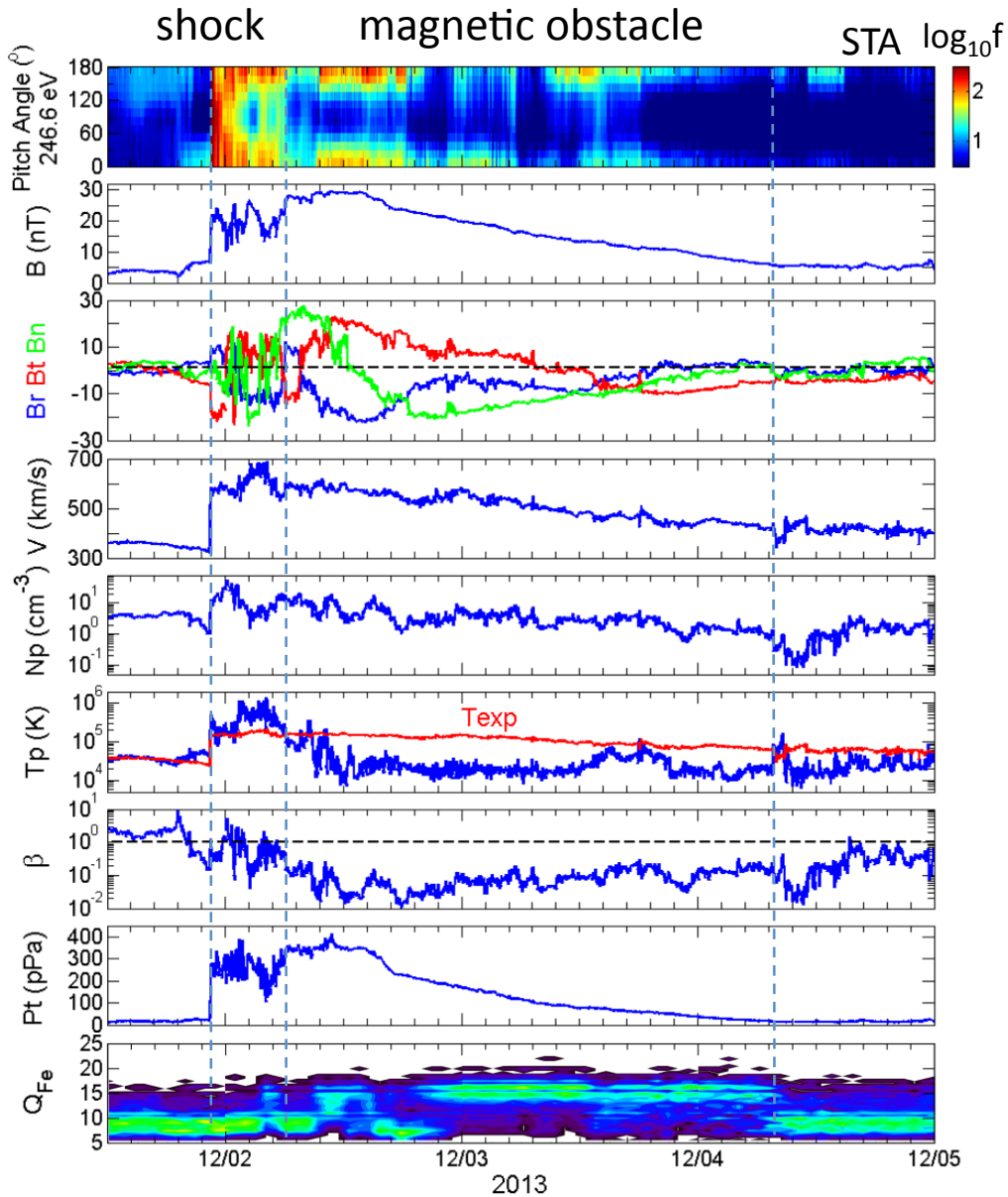


Other Notes

- ✓ Both ICMEs and SIRs can drive shocks. The ICME-driven shocks are generally associated with more significant parameter changes
- ✓ Check if the Sun is quiet or active (with eruptions) using the solar observations taken about 2-5 days ago
- ✓ Check the solar wind at Earth about 27 days ago at Earth or at STEREO A about 16 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
- ✓ About 10% of ICMEs and 6% of SIRs are in the hybrid events, where multiple ICMEs interact or ICME and SIR interact. Such events often cause stronger geomagnetic activity

Backup

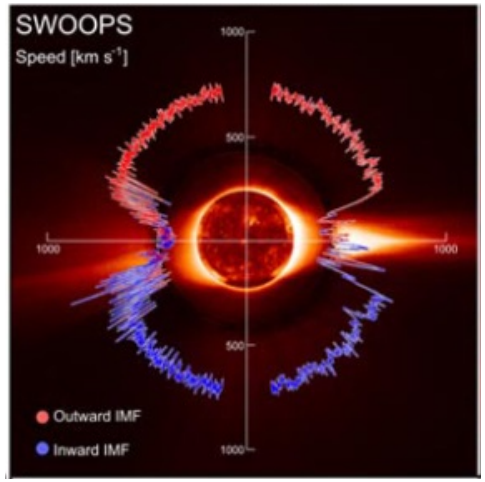
ICME Example



One Large-Scale Solar Wind Structure to Distinguish: Stream Interaction Region (SIR)

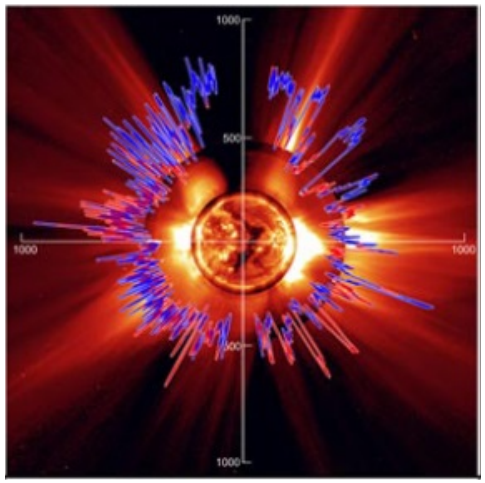
Declining Phase & Solar Minimum

1992-1998



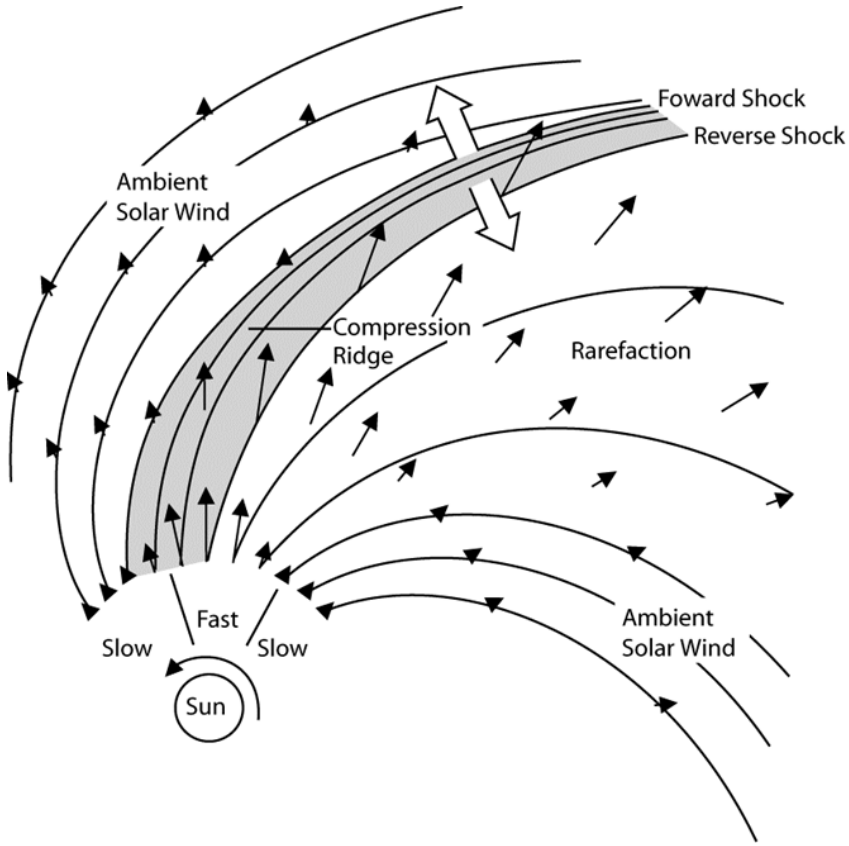
Rising Phase & Solar Maximum

1998-2004



Ulysses

About 80% of SIRs are **corotating interaction regions (CIRs)**



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