Studies of Solar Wind Structures Using STEREO

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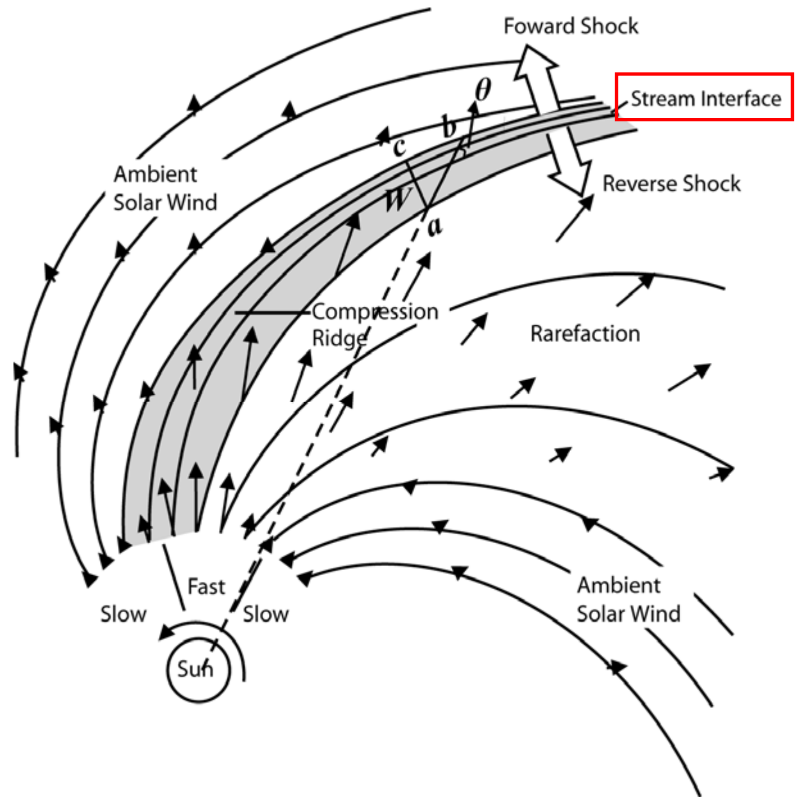
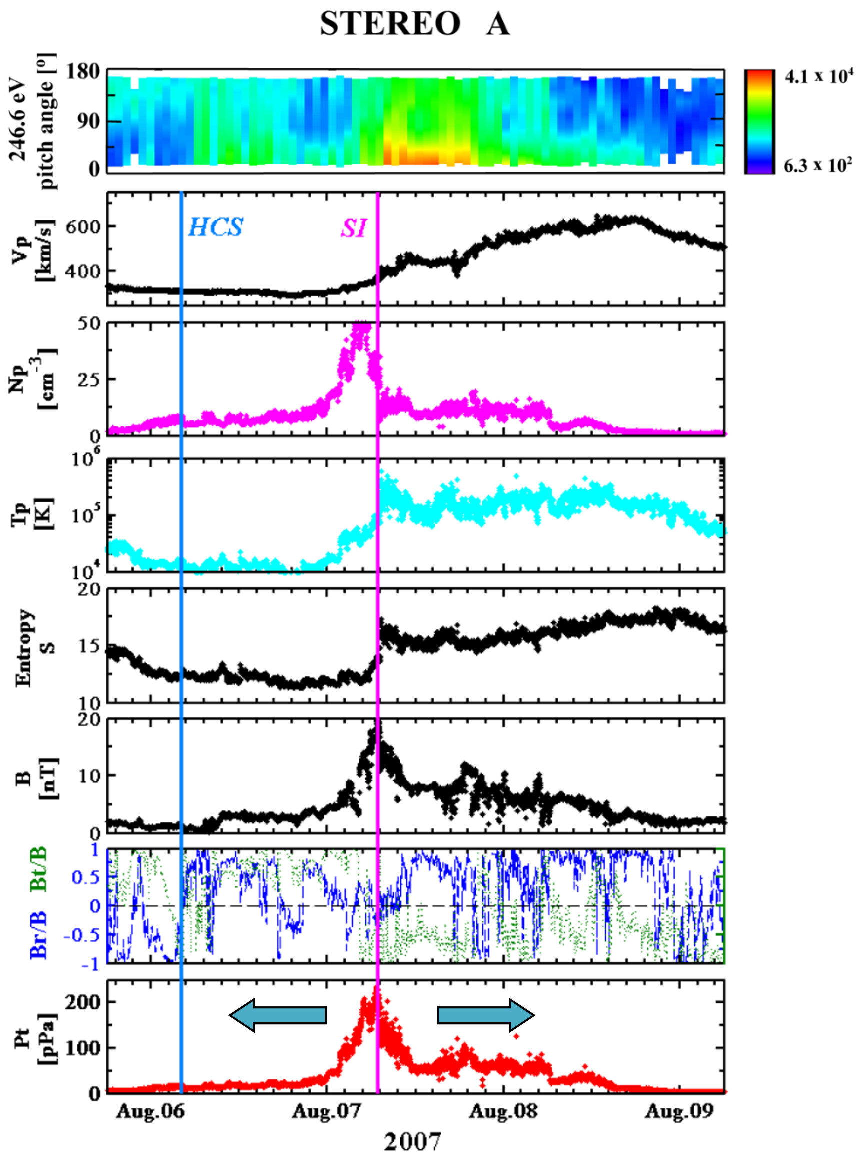
Stream Interaction Region (SIR)

- As the Sun rotates, fast and slow streams originating from different sources can collide and interact with each other, forming SIRs with a pressure ridge at the stream interface
- SIRs are predominate large-scale solar wind structures during 2007 – 2009
- If the flow pattern is roughly time-stationary, these compression regions form spirals in the solar equatorial plane that corotate with the Sun → **Corotating Interaction Regions (CIRs)**
- SIRs = CIRs (recur at least once) + transient & localized stream interactions
- The pressure waves associated with the collision steepen with radial distance, eventually form **shocks**, sometimes a pair of forward-reverse shocks



(after *Pizzo*, 1978)

SIR Identification



(*Jian et al*, 2009a)

* **Criteria (by inspection)**
  - ① Increase of V_p
  - ② A pile-up of P_t (sum of magnetic pressure and perpendicular plasma thermal pressure) with gradual declines at two sides
  - ③ Increase and then decrease of N_p
  - ④ Increase of T_p
  - ⑤ Compression of **B**, usually associated with **B** shear
  - ⑥ Change of entropy $\ln(T_p^{1.5}/N_p)$

* **Stream Interface (SI)**

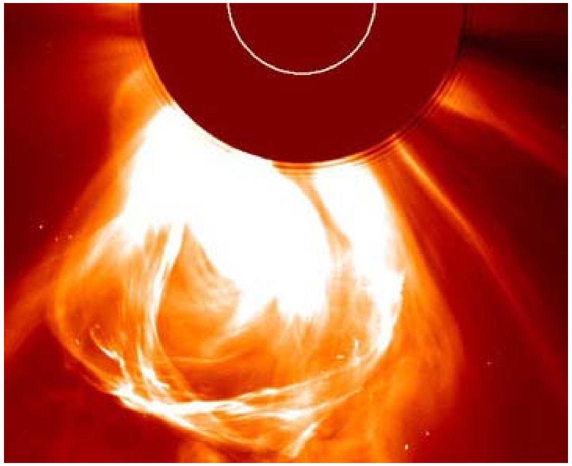
  at the peak of P_t, usually where V_p and T_p increase and N_p begins to drop after a N_p compression region

* **Heliospheric Current Sheet (HCS)**

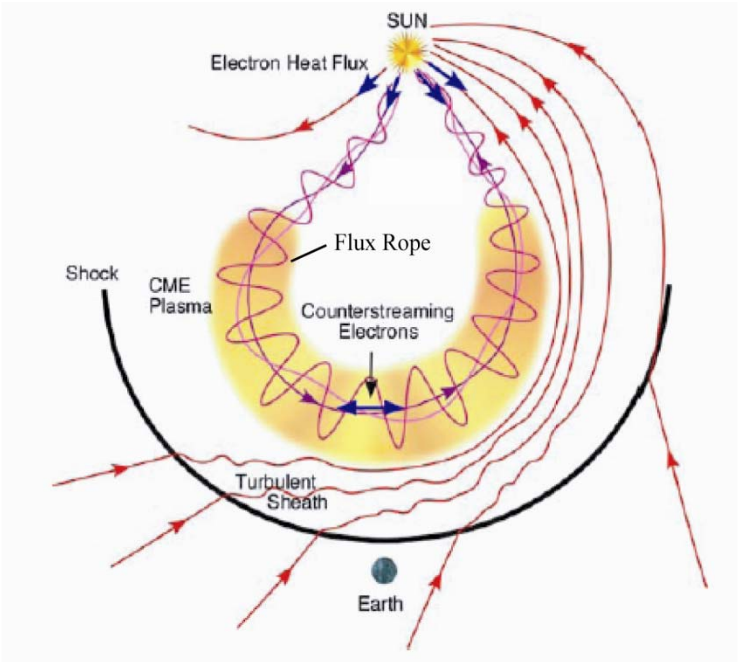
  identified by the change of the suprathermal electron pitch angle and magnetic field polarity

Interplanetary Coronal Mass Ejection (ICME)

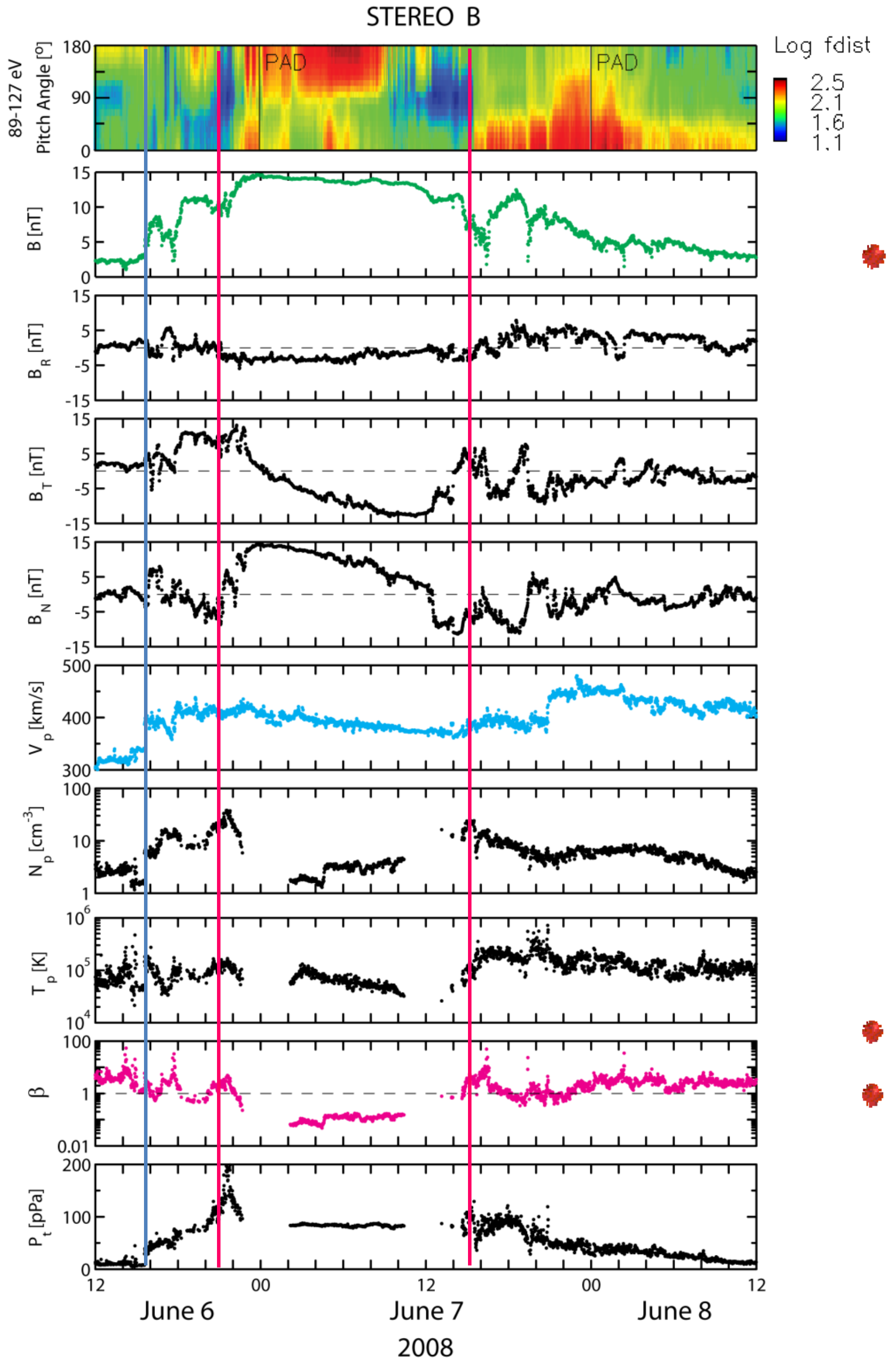
- CMEs have typical 3-part structure, but as they evolve and expand from the Sun, their signatures are not always seen by spacecraft
- During solar min, the solar and solar wind background are less structured than solar max, so the ICMEs should be affected less
- However, CMEs during solar min are weaker and slower themselves. Hence, some ICMEs are still hard to identify from STEREO during 2007 - 2009. With only a handful of events, such ambiguity in classification can affect statistics
- A specific subset of ICMEs are **Magnetic Clouds (MCs)**, characterized by enhanced magnetic field, smooth field rotations through a relatively large scale, and low β
- Overall spacecraft encounter flux ropes 30% of the time when hit by ICMEs from 4-year ISEE 3 observations (*Gosling*, 1990). We will examine the fractional rate near this solar min



SOHO



(*Zurbuchen and Richardson*, 2006)

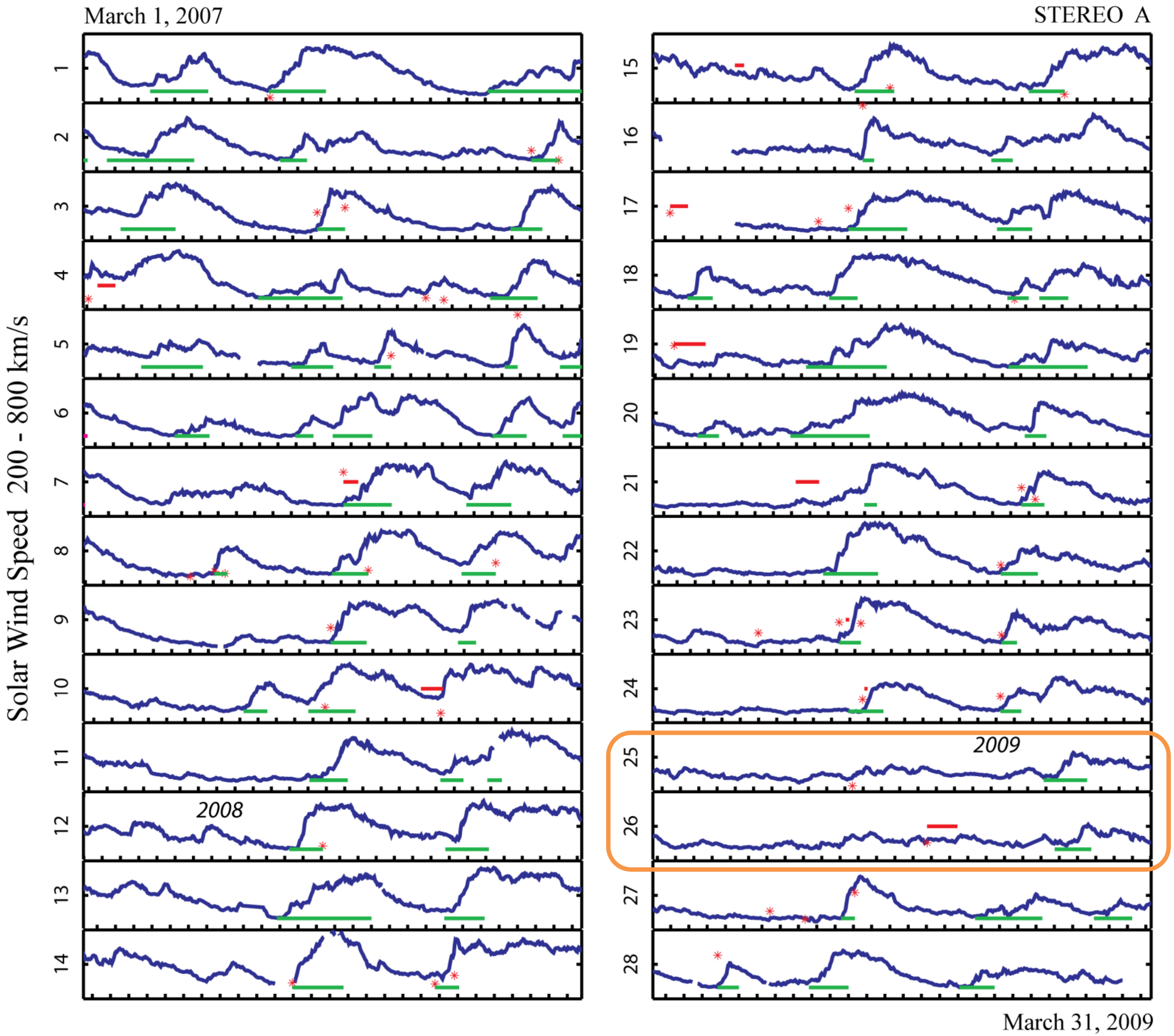


ICME Identification

- **Criteria (by inspection)**
  - ① a stronger than ambient **B**
  - ② a relatively quiet **B**
  - ③ relatively smooth **B** rotations
  - ④ low T_p
  - ⑤ low β
  - ⑥ bidirectional suprathermal electron fluxes
  - ⑦ P_t enhancement
  - ⑧ a declining V_p
  - ⑨ CME candidate from solar and heliospheric images

- Generally, at least **3** signatures
- None of the above criteria is necessary when any 3 signatures in the criteria list are prominent

Solar Wind at STEREO A



28 Carrington Rotation Periods

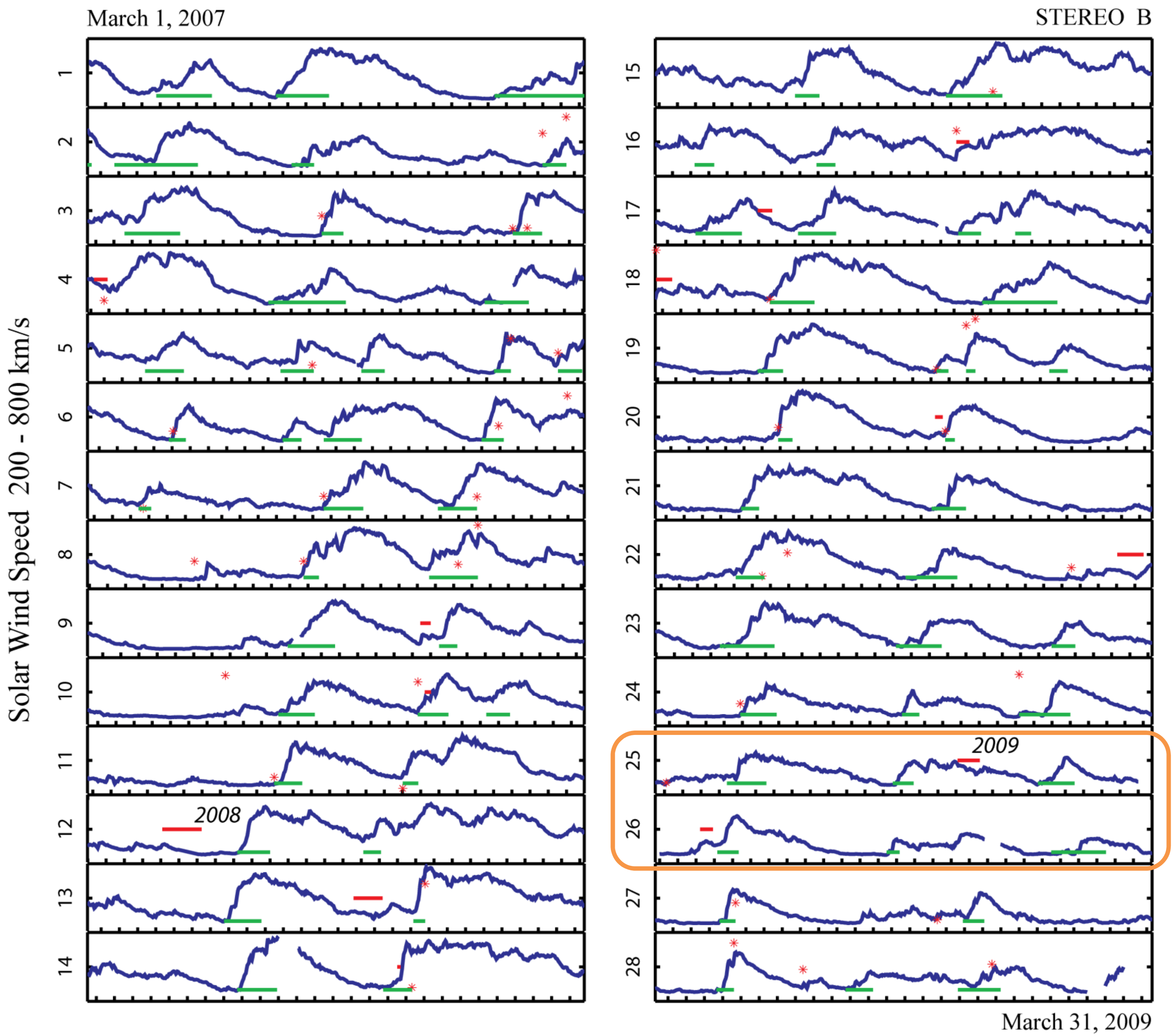
— SIR

— ICME

* Shock (height indicates Mach num 1-2.3)

70 SIRs
10 ICMEs
46 Shocks

Solar Wind at STEREO B



28 Carrington Rotation Periods

— SIR

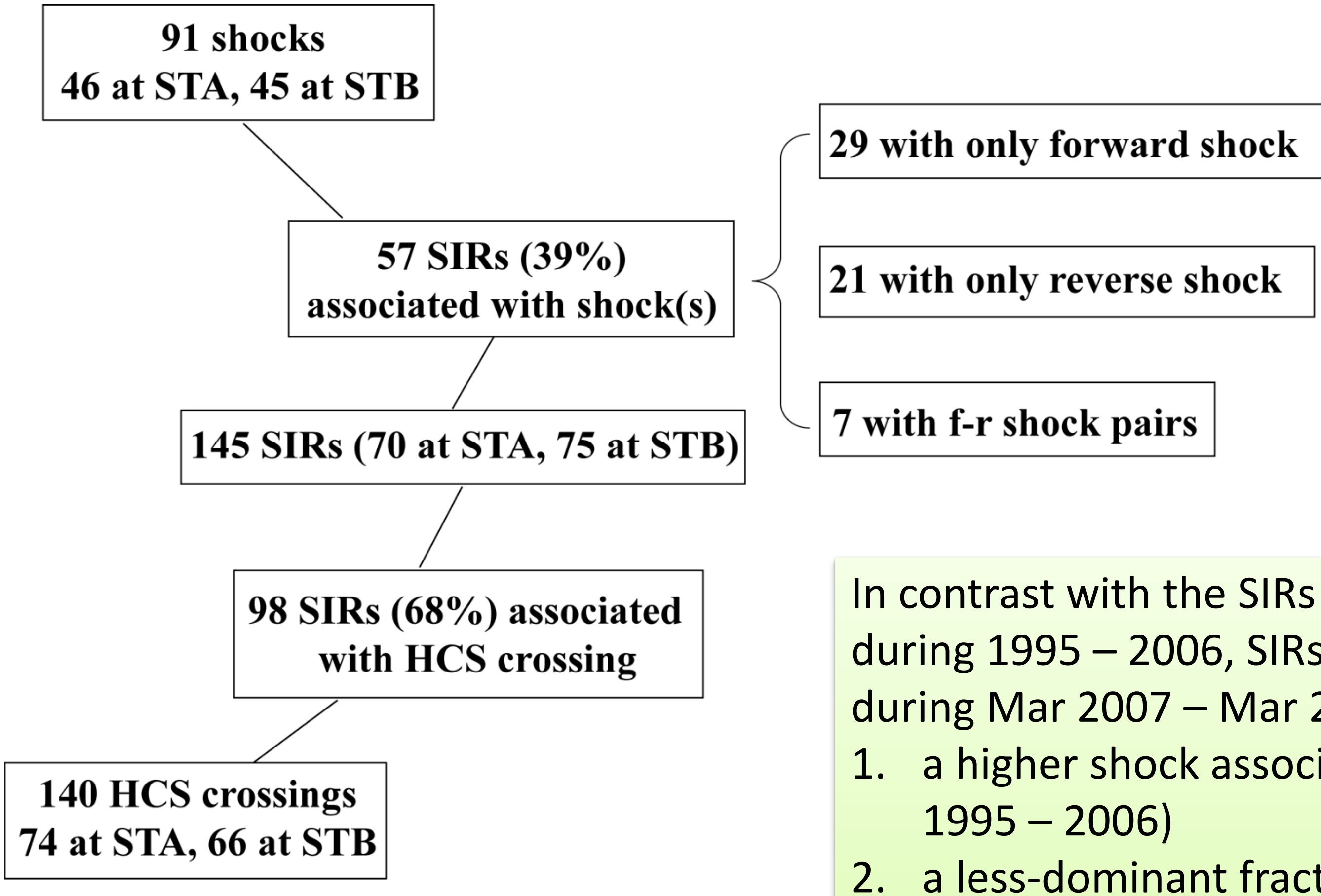
— ICMEs

* Shock

75 SIRs
13 ICMEs
45 Shocks

SIRs Observed by STEREO

March 2007 – March 2009

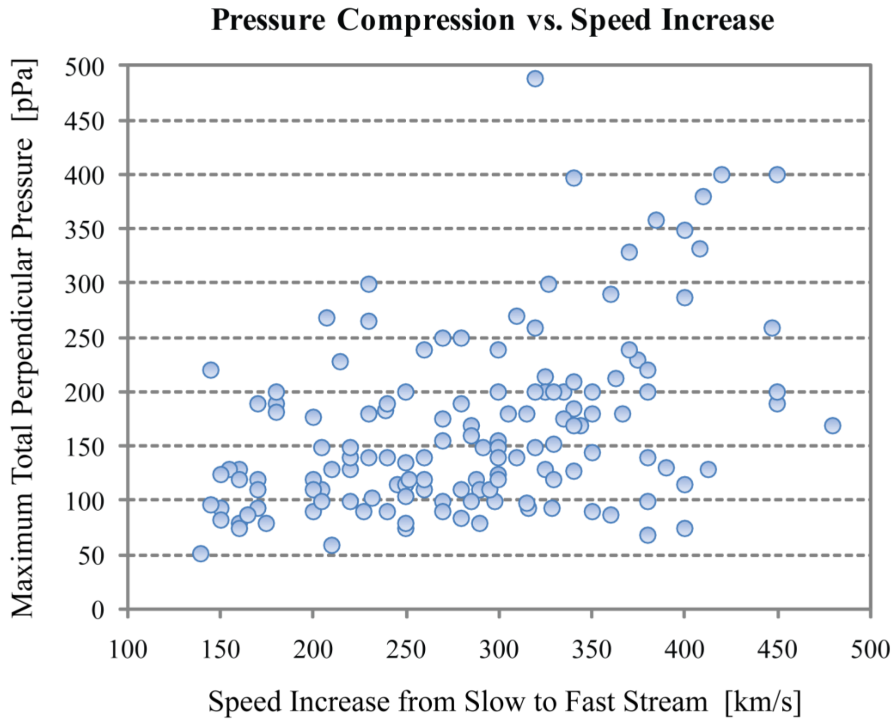


The difference occurred in late 2008 – early 2009

In contrast with the SIRs observed by Wind/ACE during 1995 – 2006, SIRs observed by STEREO during Mar 2007 – Mar 2009 have

1. a higher shock association rate (26% for 1995 – 2006)
2. a less-dominant fraction of forward shocks
3. a higher association rate with HCS crossing (58% for 1995 – 2006)
4. a much higher CIR fraction (89% vs. 59%)

Properties of Stream Interaction Regions



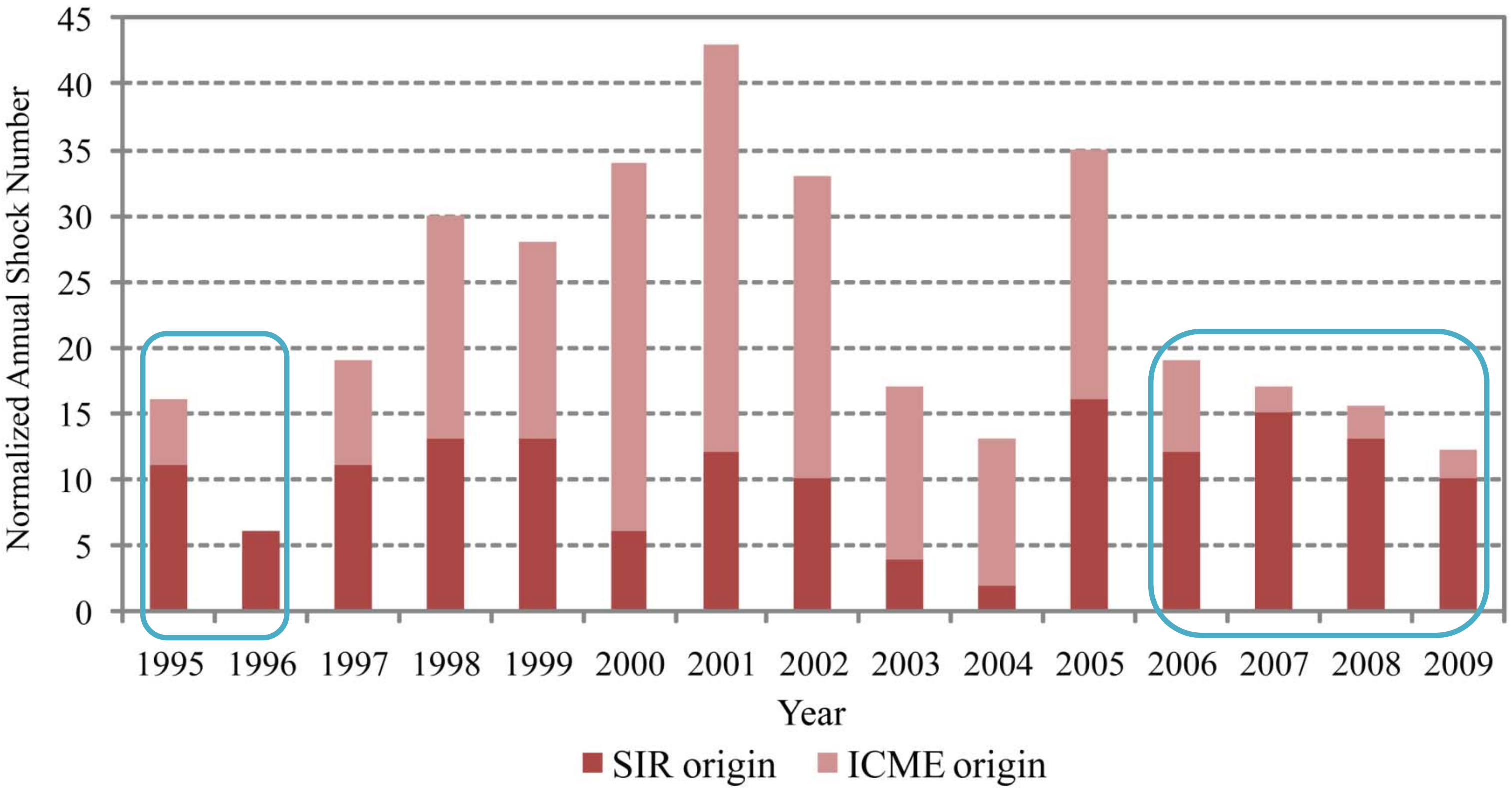
- For SIR with larger speed difference from slow to fast stream, the pressure compression (P_{tmax}) at the SIR is generally stronger
- Averages from 145 SIRs: P_{tmax} = 166±7 pPa, ΔV = 285±7 km/s, B_{max} = 13.3±0.3 nT
- The P_{tmax} and B_{max} are similar to the averages of 1995 – 2006 from Wind/ACE, but the **ΔV is noticeably larger than the average of 1995 – 2006 and much larger than the average during last solar min**

ICMEs Observed by STEREO

- Among 23 ICMEs, 11 are magnetic clouds, taking a fraction of about 48%, larger than other solar cycle phases
- When the spacecraft are separated by about 90^{o} in longitude, their corona and heliospheric images are very useful to find out the CME candidates and track down the CME evolution
- ICME properties during 2007 – 2009 represent the late declining phase and the current deep solar minimum

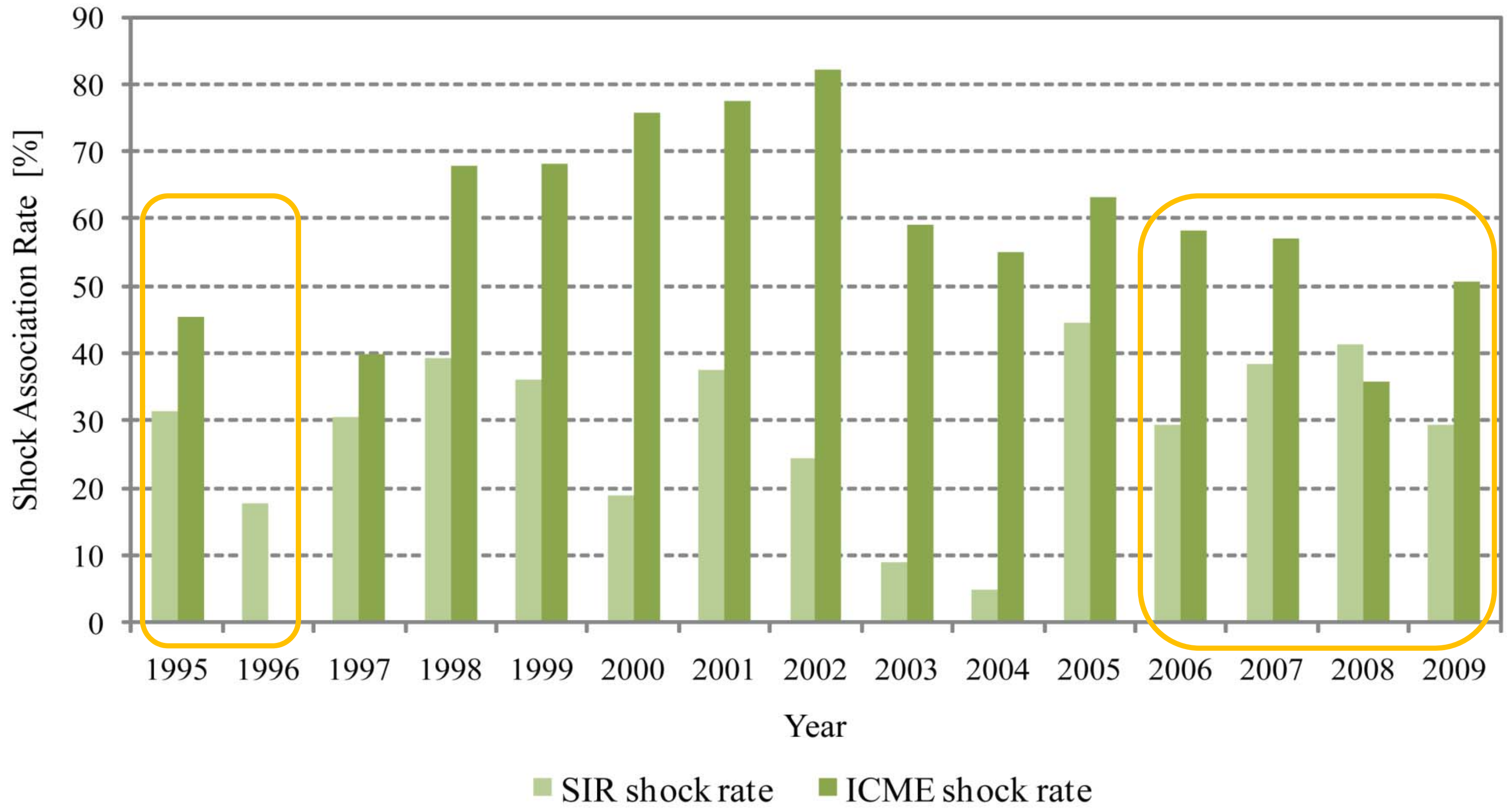
Time	Shock association rate	Duration [hour]	Mean speed [km/s]	Width [AU]	Maximum Pt [pPa]	Maximum B [nT]	Expansion speed [km/s]
1995 – 2006	65.1%	33.5±0.9	505±9	0.40±0.01	254±18	19.1±0.7	154±9
2007 – 2009	43.5%	21.0±2.8	389±11	0.19±0.02	134±18	13.3±1.0	59±7

Solar Cycle Variation of Interplanetary Shocks: Occurrence Rate



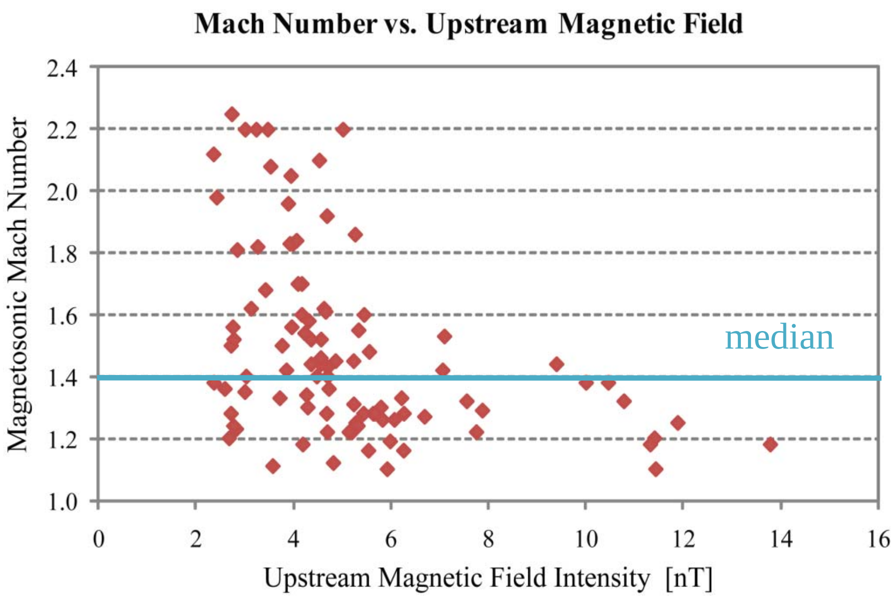
- Annual SIR-origin shock number changes from 2 to 16, with an average of 10. They appear more often in the declining phase
- Annual ICME-origin shock number changes approximately in phase with solar activity, from 0 to 31
- Overall, ICMEs drive more shocks at 1 AU than SIRs

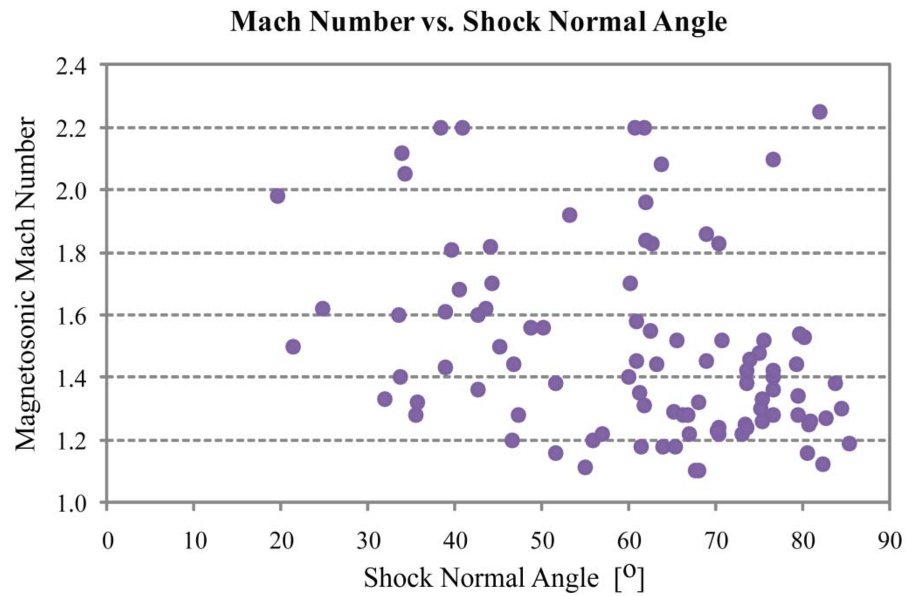
Solar Cycle Variation of Interplanetary Shocks: Association Rate

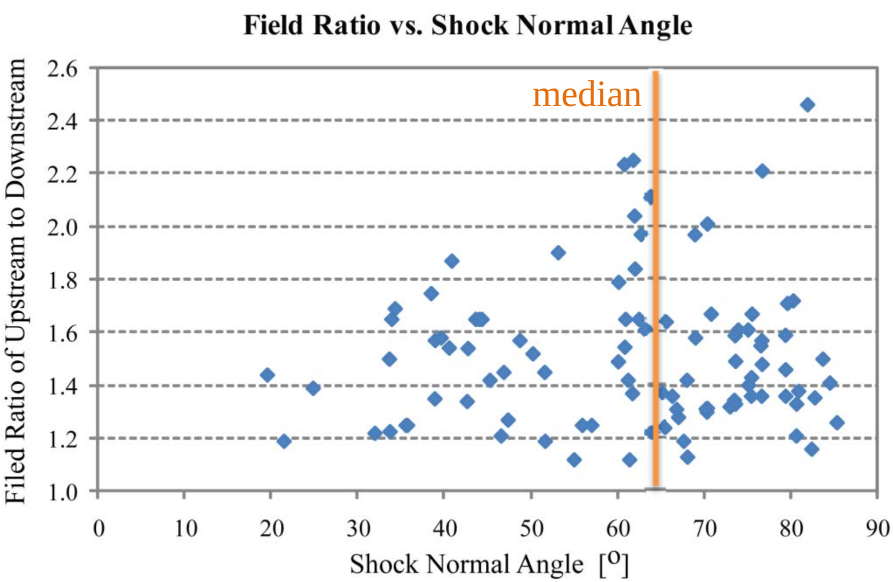


- SIR shock association rate is 29% on average, being higher in the declining phase
- ICME shock association rate is 56% on average, varying almost in phase with solar activity

Correlation between Shock Parameters

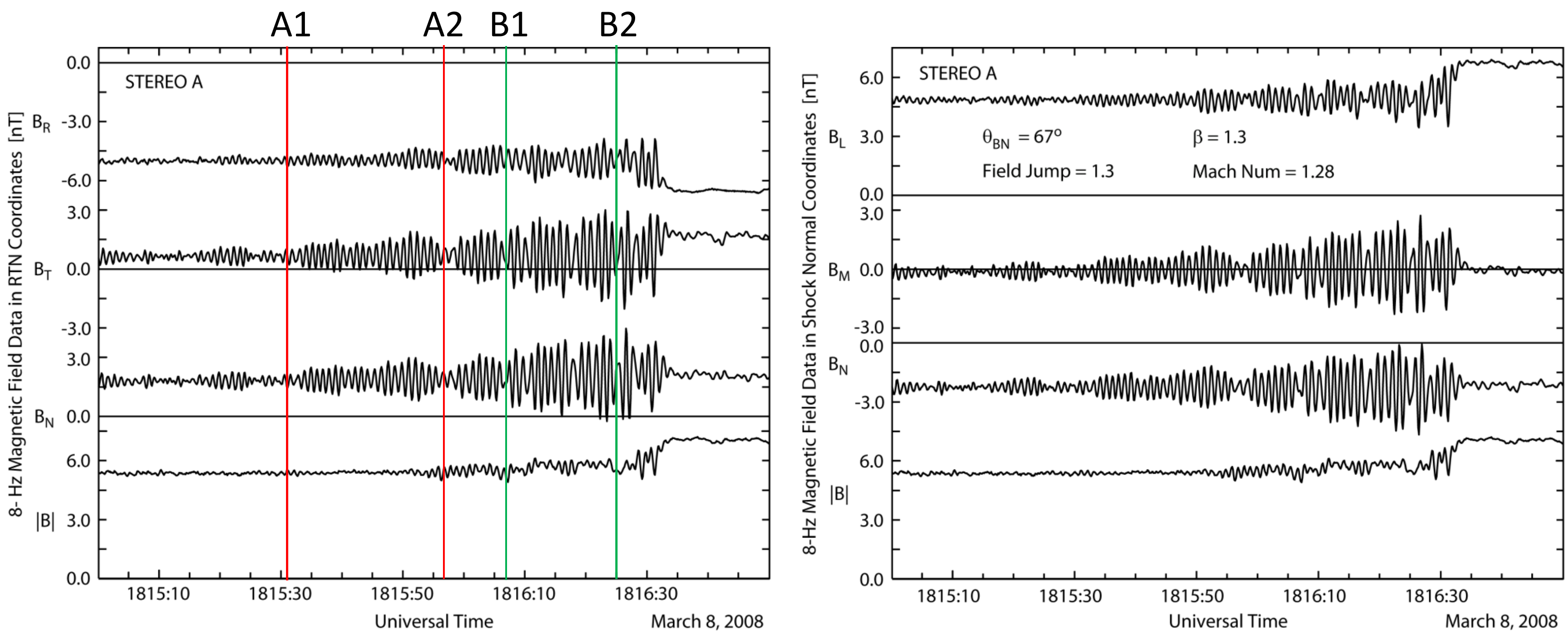






- Mach number is fairly variable for low upstream magnetic field and is generally small for high upstream field
- Mach number does not have clear correlation with shock normal angle
- Field ratio across shock roughly increases with shock normal angle, and is more variable for quasi-perpendicular shocks

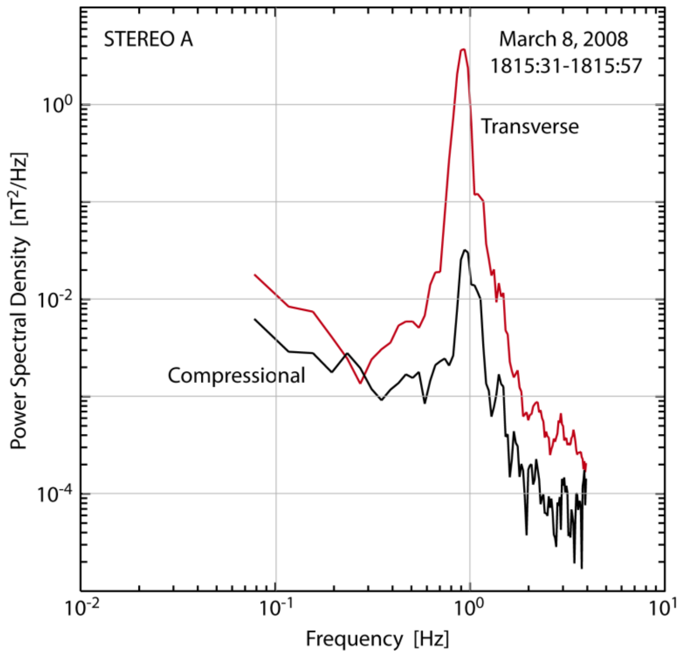
Interplanetary Shock with Whistler Waves



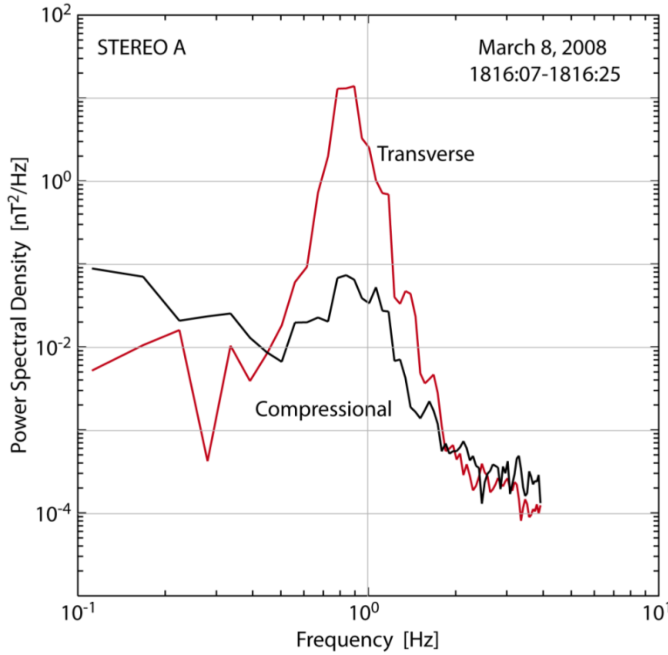
- We find 11 shocks (11.6%) with whistler waves among the 95 interplanetary shocks observed by STEREO during Jan 2007 – Mar 2009. Among the 11 shocks, 7 are quasi-perpendicular, 7 have magnetosonic Mach number larger than 1.6
- In contrast with ion cyclotron waves (ICWs), the whistler waves are right-handed in the plasma frame, and their frequency in the s/c frame is about 1 Hz, larger than the ICW median frequency of 0.28 Hz

Analysis of Whistler Waves

Region A1-A2



Region B1-B2



The whistler wave in Region A1-A2: frequency in s/c frame (f_{sc}) is 0.914 Hz, ellipticity is 0.991, propagation direction **k** is 0.905**R**-0.109**T**-0.411**N**

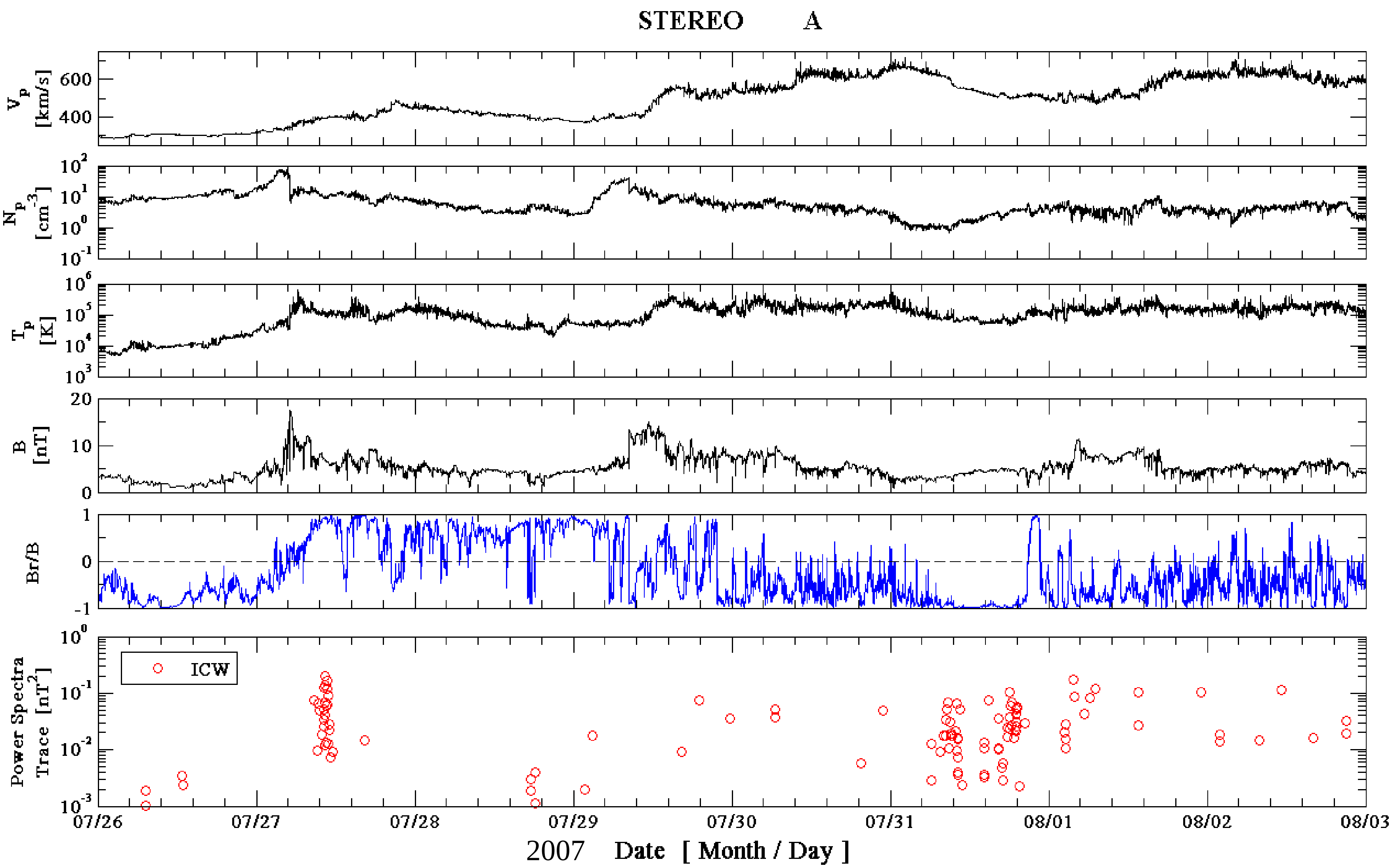
1) From Doppler Shift $\Omega_{sc} = \omega_{sc} - \mathbf{k}\cdot\mathbf{V}_{sc}$ ➔ $5.743 = \omega_{sw} + 3.62\times10^5 k$

2) From Dispersion Relation $V_A^2/(\omega_{sw}/k)^2 = \Omega_{ce}\Omega_{ci} / (\omega_{sw}+\Omega_{ce})(\omega_{sw}+\Omega_{pc})$

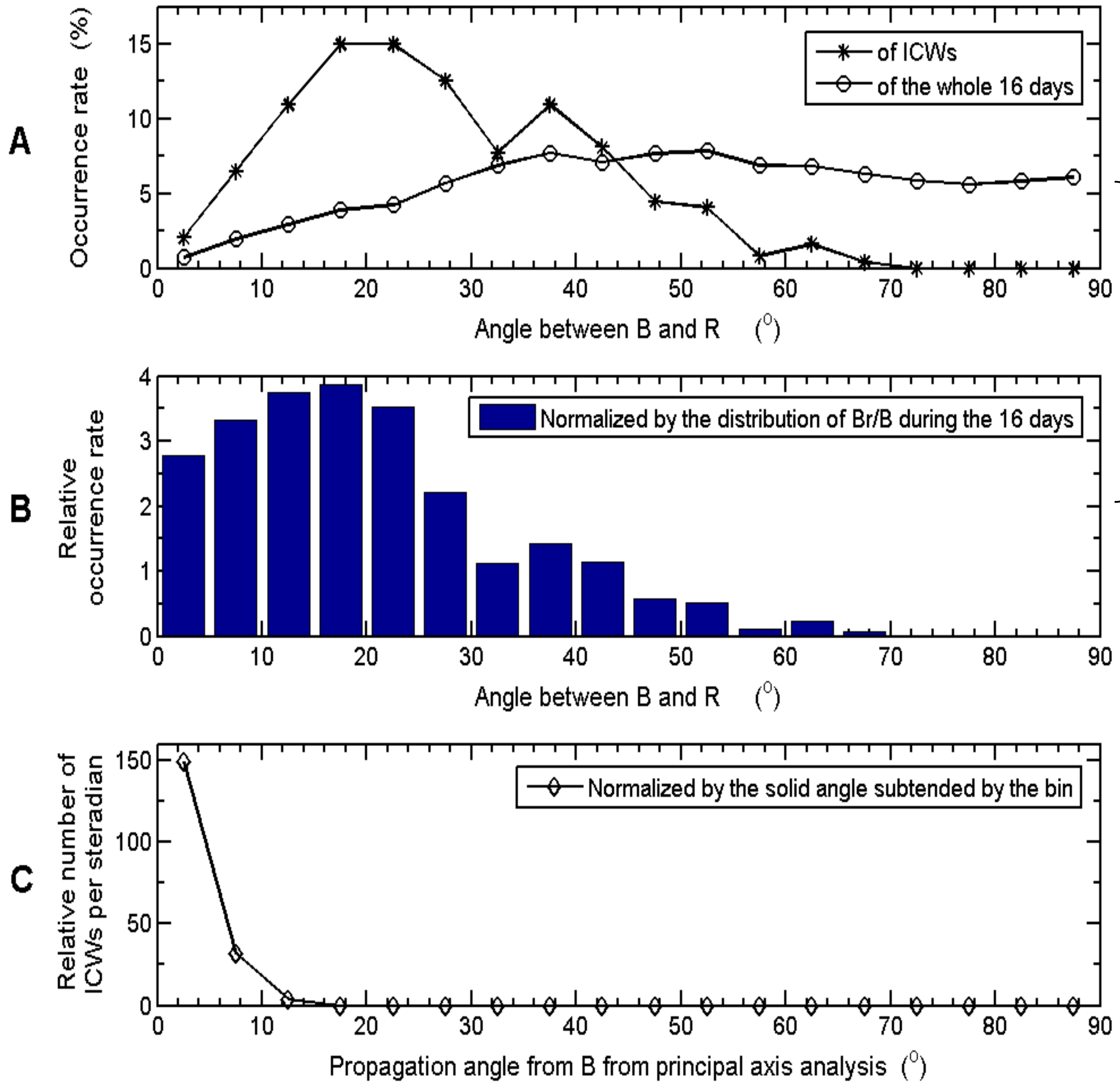
➧ The wave angular frequency in the plasma frame (ω_{sw}) is 0.812 rad/s, **larger than proton cyclotron frequency** (Ω_{pc}) 0.517 rad/s, but much smaller than the electron cyclotron frequency (Ω_{ce}) 950 rad/s (Thank Robert Strangeway for discussion)

Ion Cyclotron Waves at STEREO

Criteria: |ellipticity| > 0.7, polarization rate > 70%, *long axis of the elliptic wave is perpendicular to both B and propagation direction (LH in plasma frame)*



Angle Distribution of ICWs in Solar Wind



246 wave events

Waves appear more often when field is more radial than usual

Waves propagate mostly along the field direction

(*Jian et al.*, 2009b)

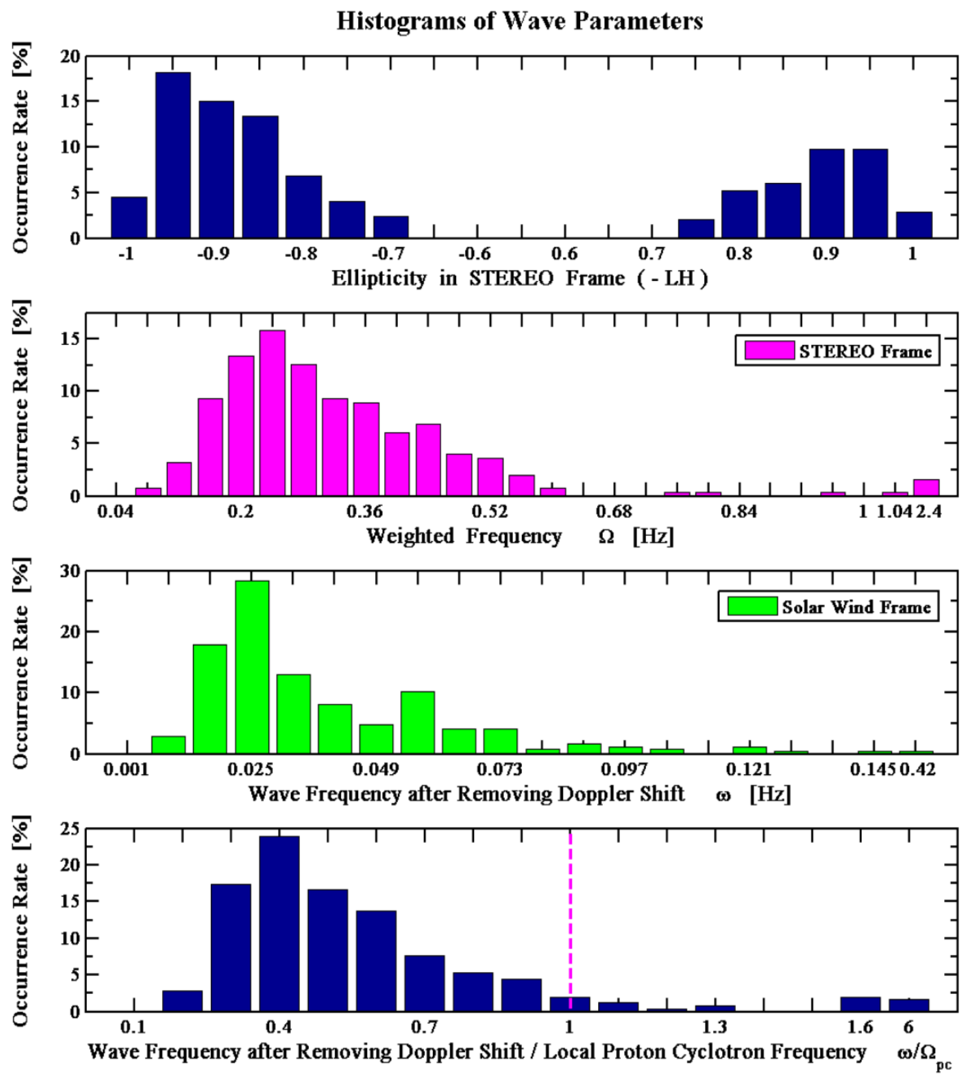
Ion Cyclotron Wave Properties

- Although they appear left-handed (LH) or right-handed (RH) in STEREO frame, the wave properties and comparison of LH/RH waves suggest all the waves are **intrinsically LH in plasma frame**. The RH waves in the s/c frame should be those propagating toward the Sun but being blown outward by the super-Alfvénic solar wind

- After removing the Doppler shift

$$\Omega = \omega - \vec{k} \cdot \overrightarrow{v_{sc}} = \omega + \frac{\omega}{v_{ph}} \hat{k} \cdot \overrightarrow{v_{sw}}$$

the wave angular frequency is 0.19 rad/s, **generally smaller than local proton gyro-frequency** Ωpc (0.1B rad/s), while whistler wave frequency is larger than Ωpc



(*Jian et al.*, 2009b)

Summary

- We have surveyed stream interaction regions, interplanetary coronal mass ejections, and interplanetary shocks up to March 2009
- In contrast with other time, during the late declining phase and the current deep solar minimum
  - SIRs recur more often, drive more shocks, and occur more often near the HCS crossing
  - ICMEs are weaker and smaller, drive fewer shocks, and are observed with flux ropes more often
- During Dec 2008 – Jan 2009, four SIRs were observed by STEREO B, not by STEREO A. Meanwhile, STEREO A saw multiple HCS crossing, not STEREO B. This suggests even the large-scale structures can vary significantly between two spacecraft
- Using high resolution magnetometer data, we have studied interplanetary shocks more comprehensively, such as the relationship between shock parameters, and the whistler waves at shocks
- We also see ion cyclotron waves discretely and extensively in the solar wind, which preferentially appear at radial IMF. They are unlikely driven by the above large-scale structures, and should originate much closer to the Sun

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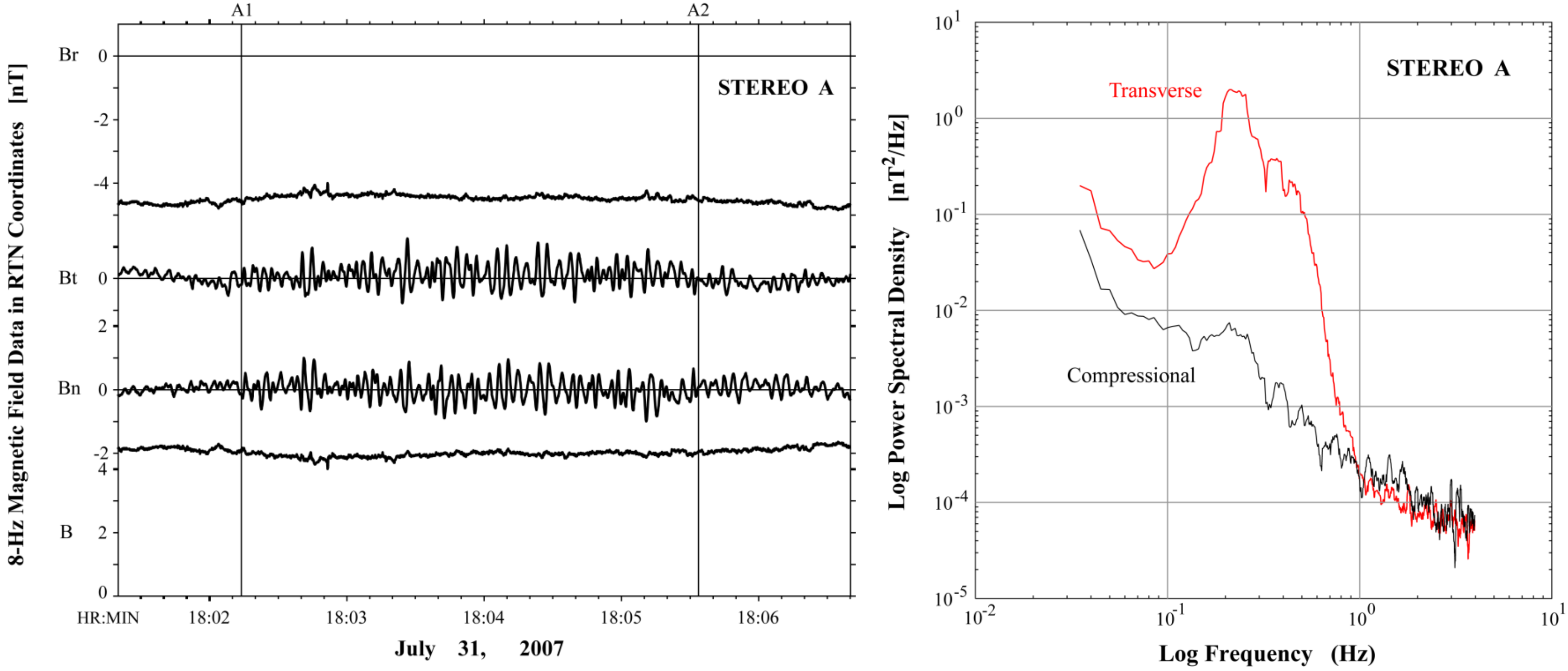
Example of Strong ICW



- a wave ellipticity of -0.95, a percent polarization of 95.2%
- a propagation angle from magnetic field is 1.2^o
- Using 8-Hz magnetic field data from STEREO, we have observed many waves like the one shown above.