Solar Wind Observations during 2007 – 2009: An Unusual Solar Minimum

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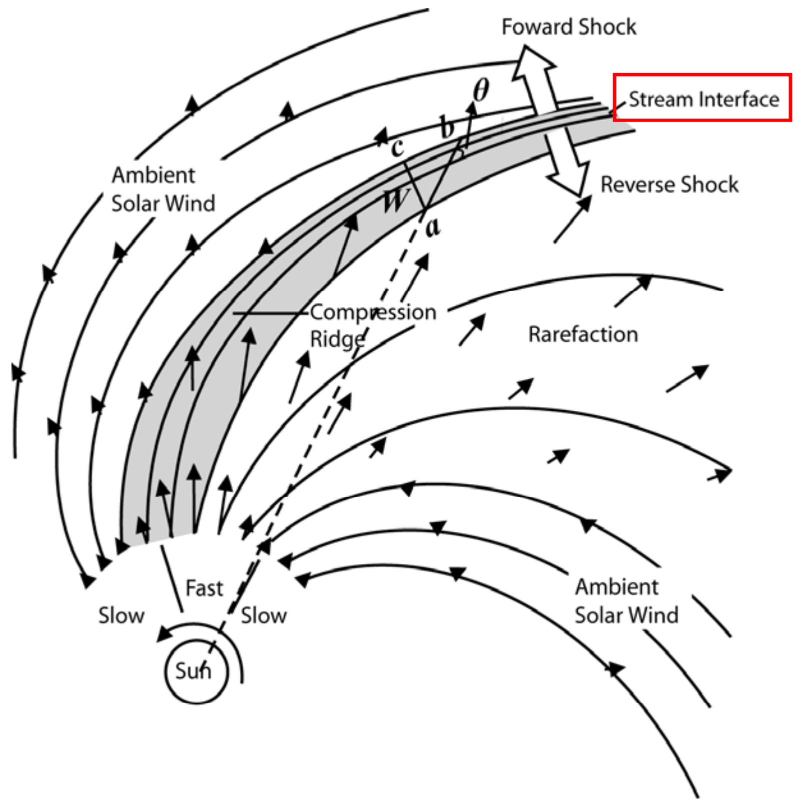
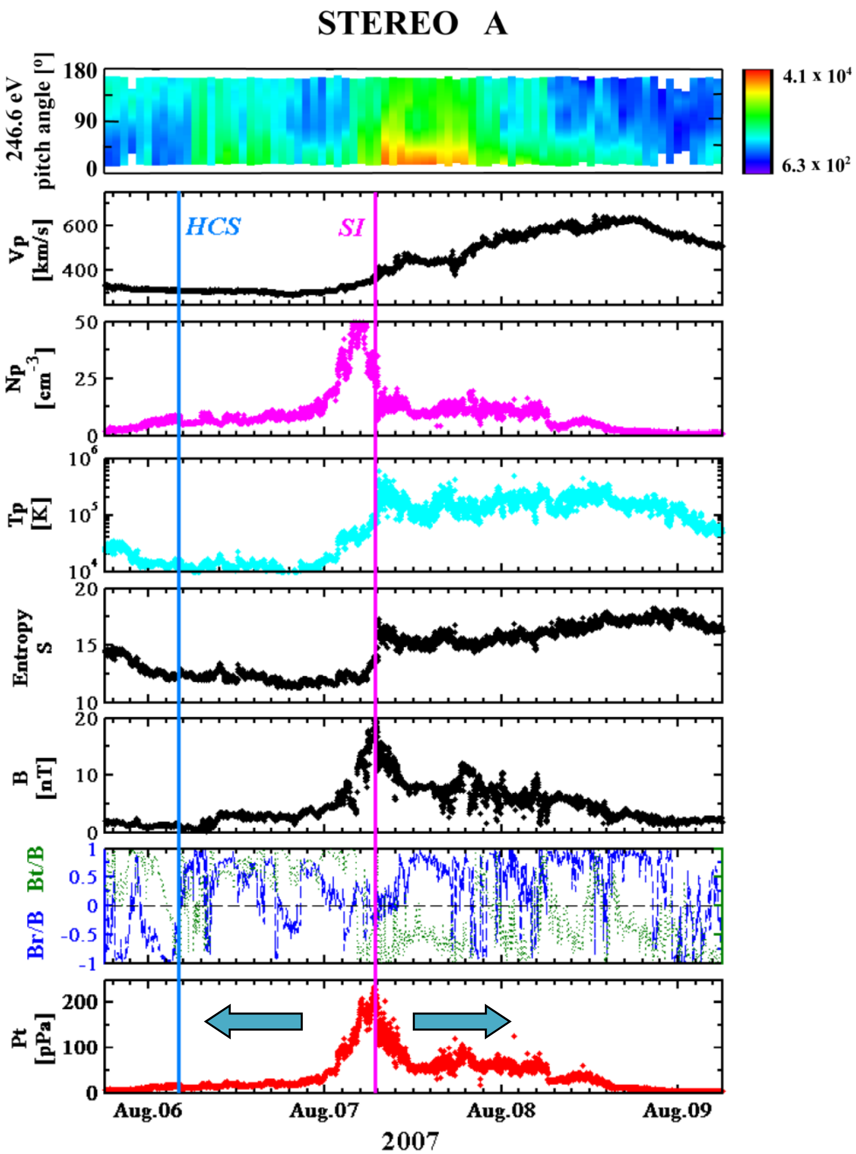
Stream Interaction Region (SIR)

- 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 the predominant 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 forming **shocks**, sometimes a pair of forward-reverse shocks



(after *Pizzo*, 1978)

SIR Identification



(*Jian et al*, 2009)

* **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)**

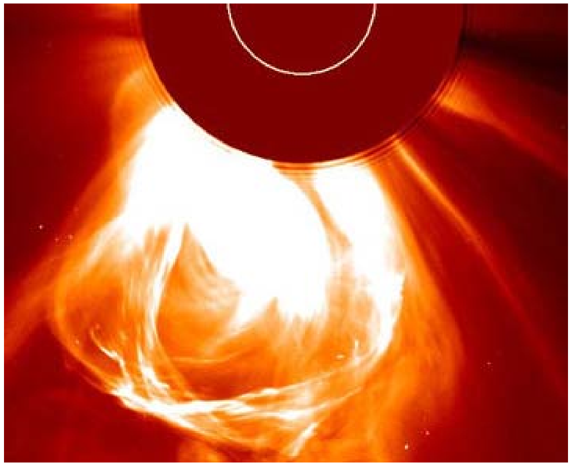
  at the peak of P_t, usually where V_p and T_p increase and N_p begins to drop after a N_p compression region

* **Heliospheric Current Sheet (HCS)**

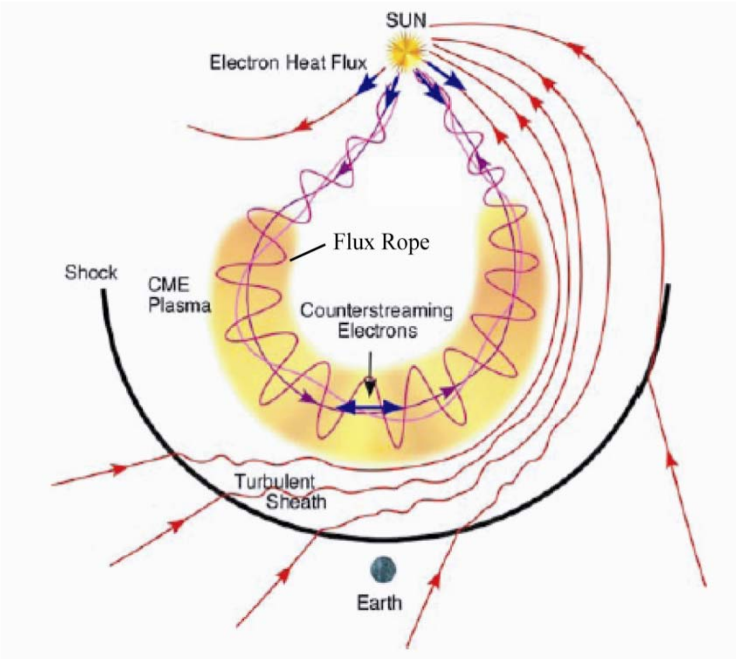
  identified by the changes of the IMF polarity and the suprathermal electron pitch angle

Interplanetary Coronal Mass Ejection (ICME)

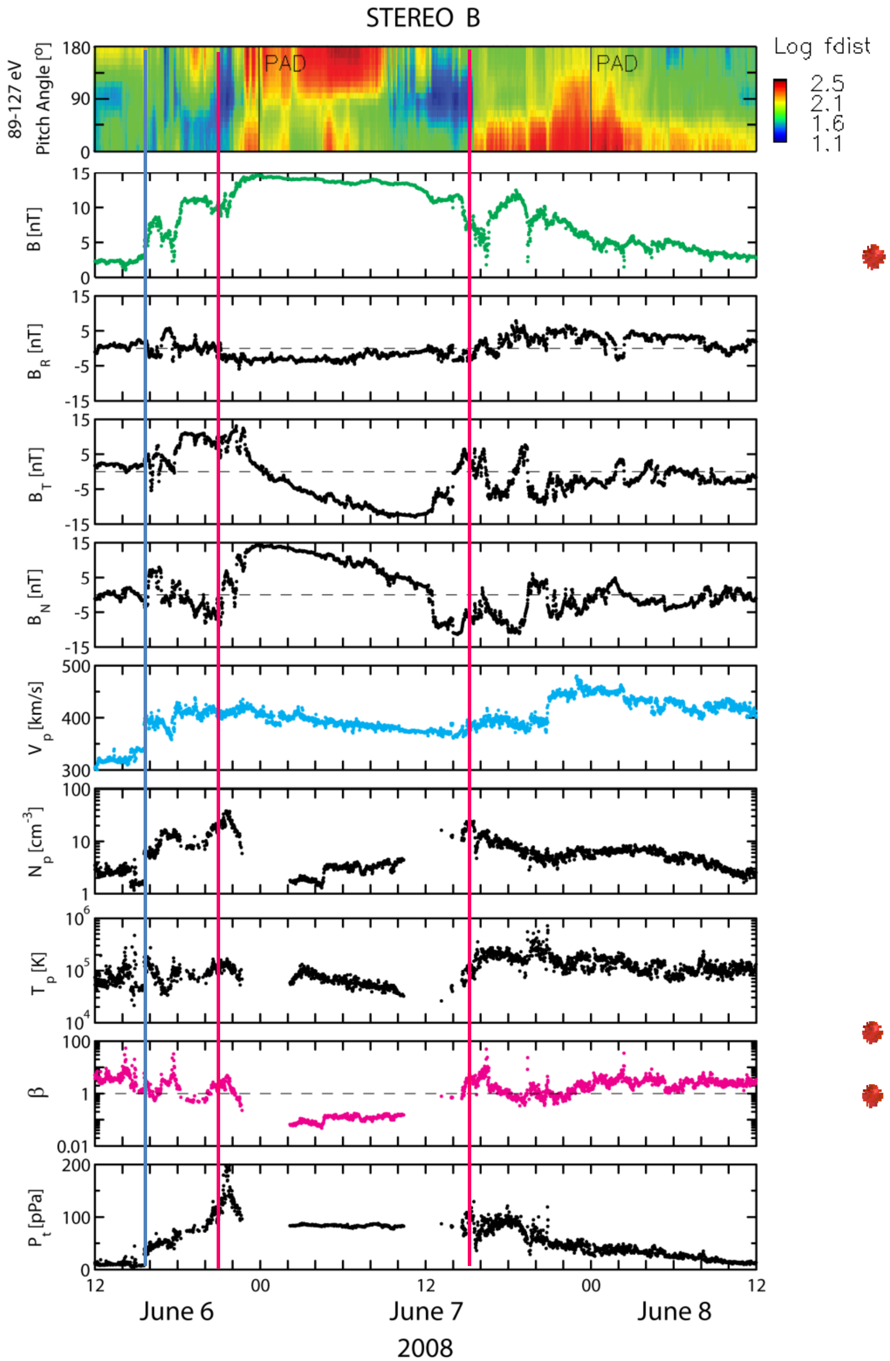
- CMEs typically have a 3-part structure, but as they evolve and expand from the Sun, their signatures are not always distinguishable by spacecraft
- During solar min, the solar and solar wind background are less structured than at solar max, so the ICMEs should be affected less
- However, CMEs during solar min are **weaker and slower** themselves. Hence, some ICMEs are 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 based on 4-years of ISEE 3 observations near solar max (*Gosling*, 1990). We will examine the fractional rate near this solar min



SOHO



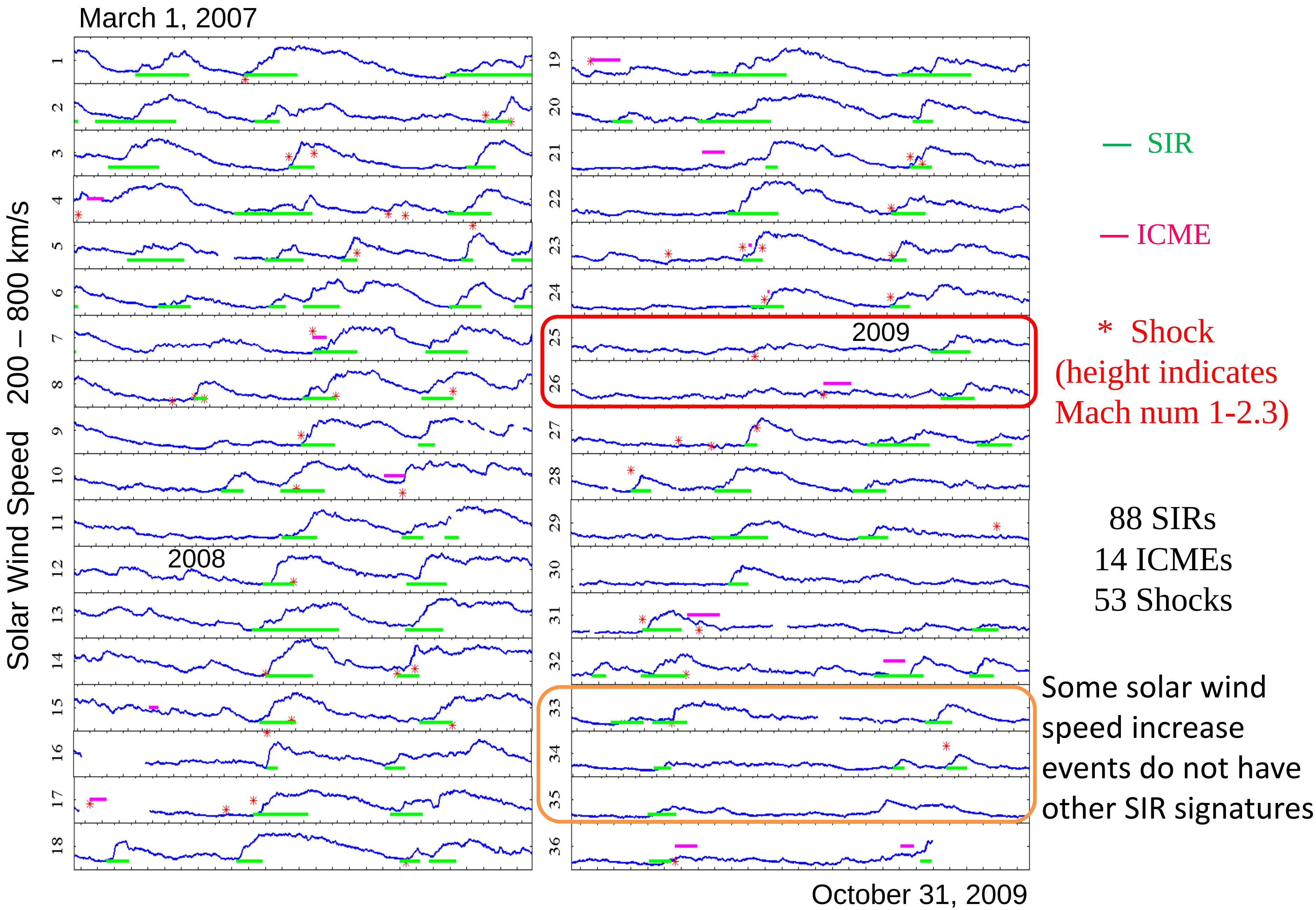
(*Zurbuchen and Richardson*, 2006)



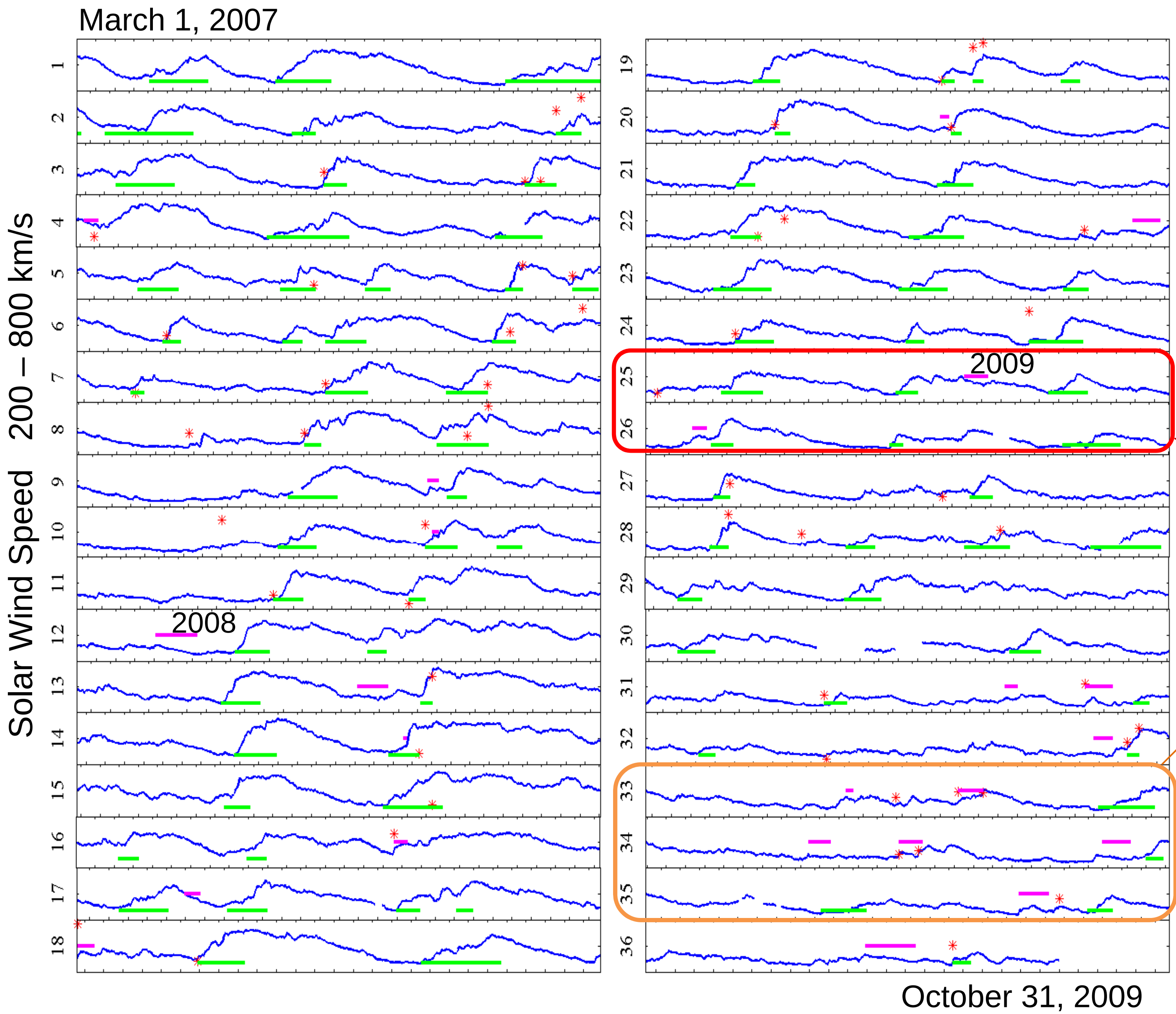
ICME Identification

- **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 (36 Carrington Rotations)



Solar Wind at STEREO B (36 CRs)



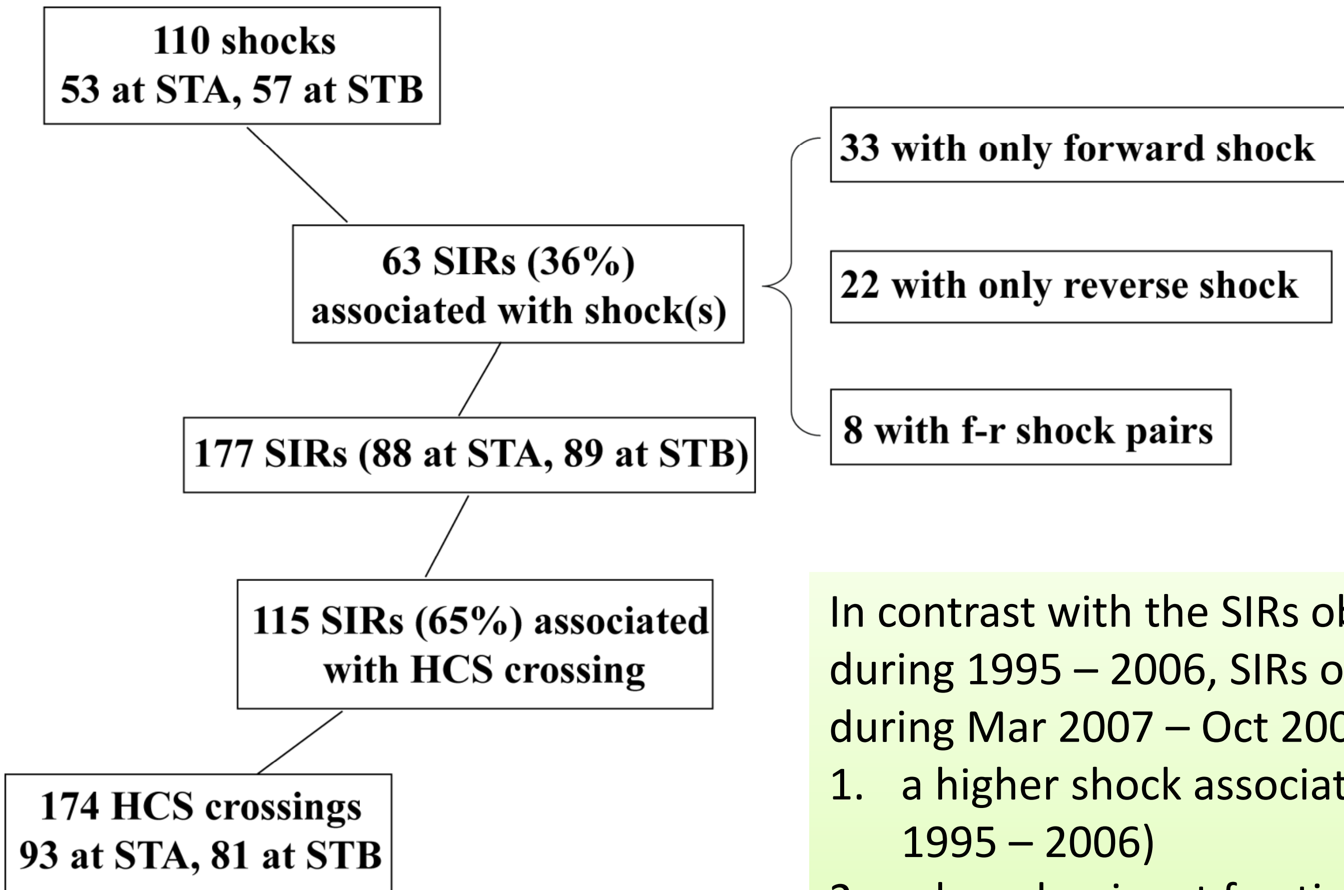
89 SIRs
23 ICMEs
57 Shocks

Separation of A and B s/c: 10° in latitude, 90° in longitude

More ICMEs at STB. A and B s/c: a few degrees offset in latitude, 105° - 120° longitude offset

SIRs Observed by STEREO

March 2007 – October 2009



The difference mainly occurred in late 2008 – early 2009 & Oct 2009

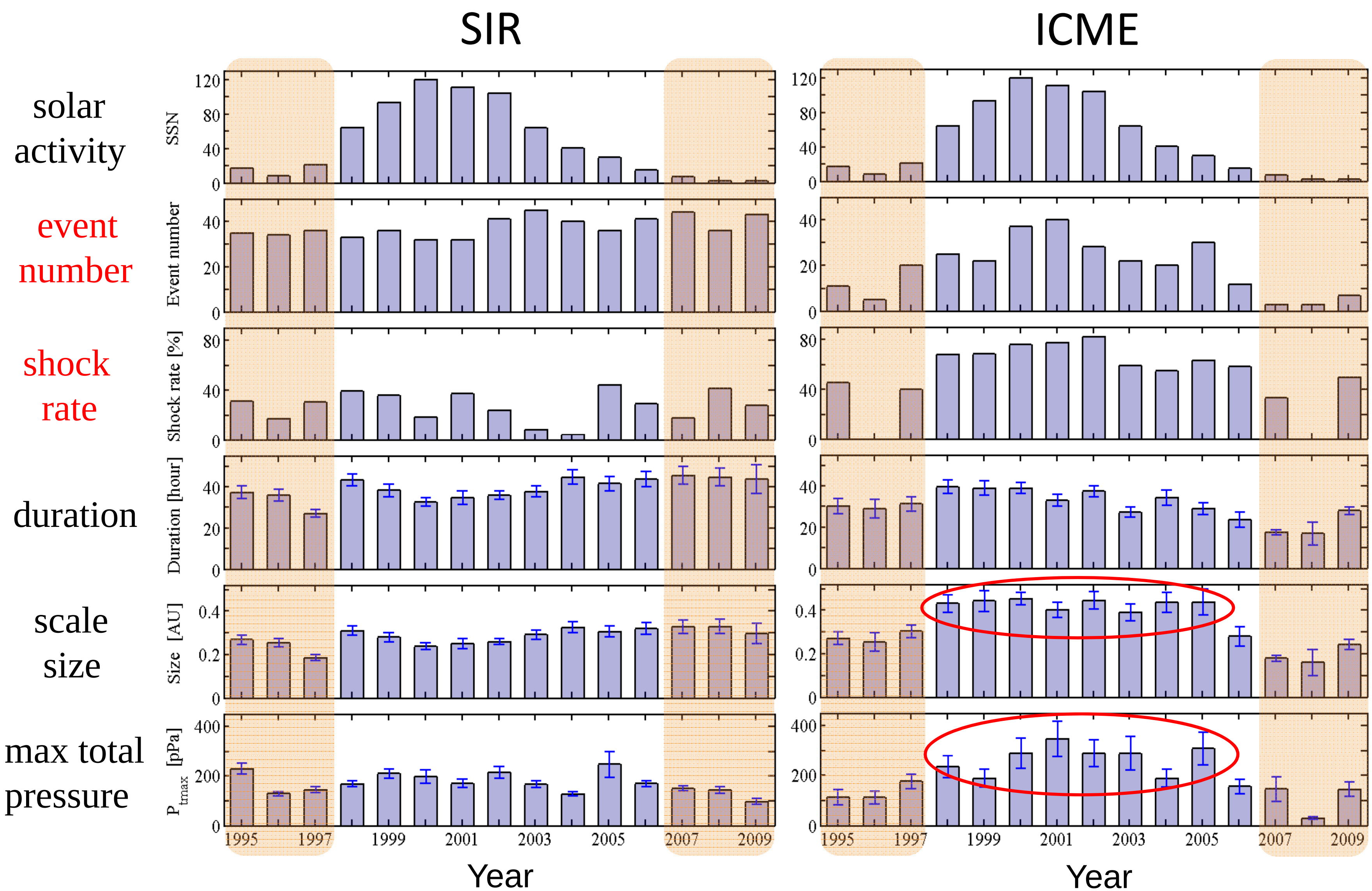
In contrast with the SIRs observed by Wind/ACE during 1995 – 2006, SIRs observed by STEREO during Mar 2007 – Oct 2009 have

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 higher CIR fraction

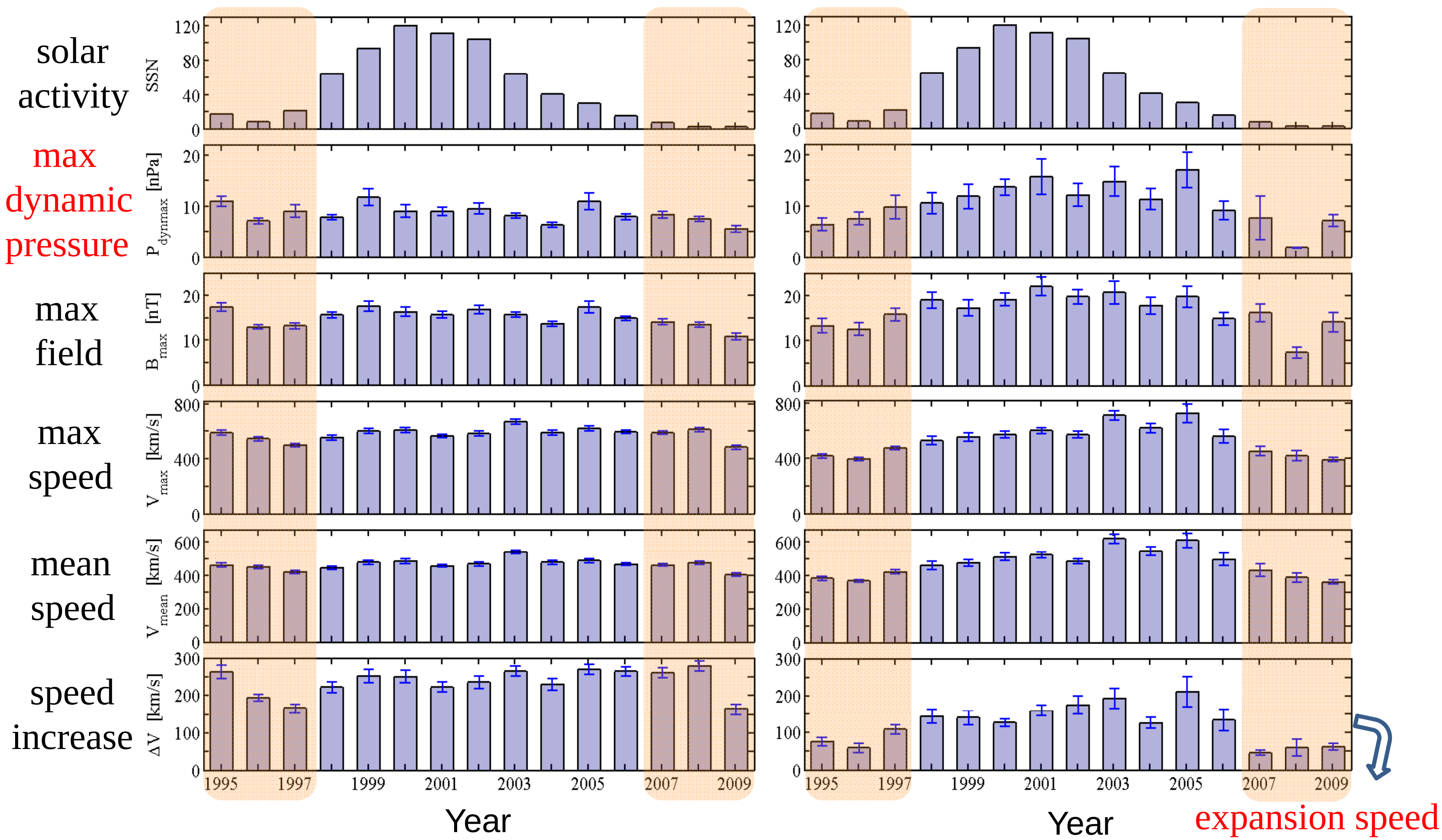
ICMEs Observed by STEREO

- Among 37 ICMEs, 23 are magnetic clouds, taking a fraction of about **62%**, larger than other solar cycle phases
- During Mar 2007 – Oct 2009, **STB observed 9 more ICMEs than STA**
  - The latitude offset (up to 11°) and longitude offset (up to 120°) between STA and STB.
  - Nature of the asymmetric distribution of the active regions. There are more active regions in one hemisphere
  - A small number ICMEs at the early rising phase to be statistically significant
  - The ICMEs are generally small during this period, and observations offset by a few degrees latitude may miss it
- SECCHI at one STEREO s/c does not always see the source CMEs for the ICMEs encountered by the other STEREO s/c, even when the twin s/c are separated by about 90°, and even for the well-defined ICMEs

Solar Cycle Variations of SIRs and ICMEs at 1 AU: Jan 1995 – July 2009 (Wind/ACE)

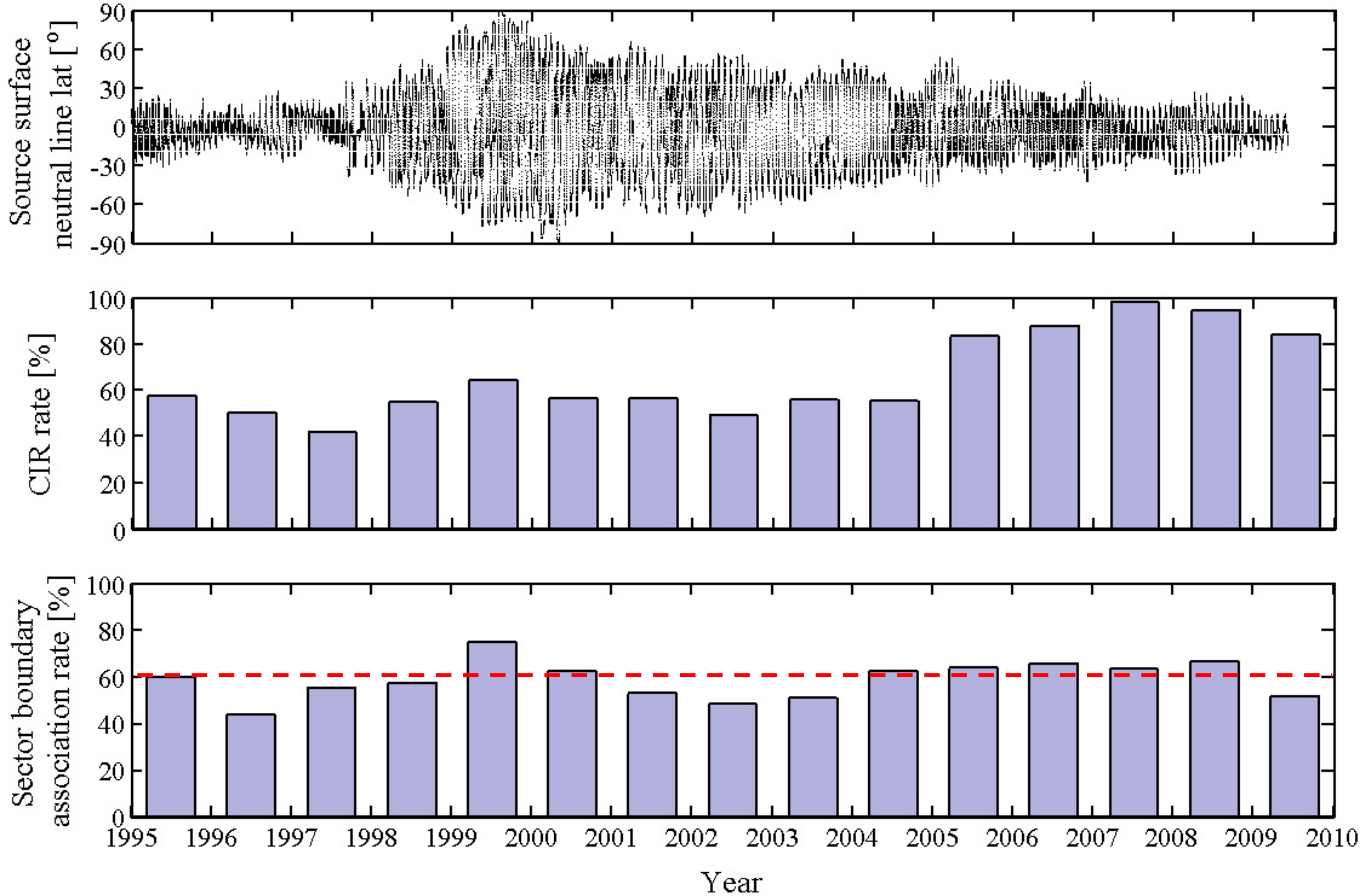


Solar Cycle Variations of SIRs and ICMEs at 1 AU (cont.)



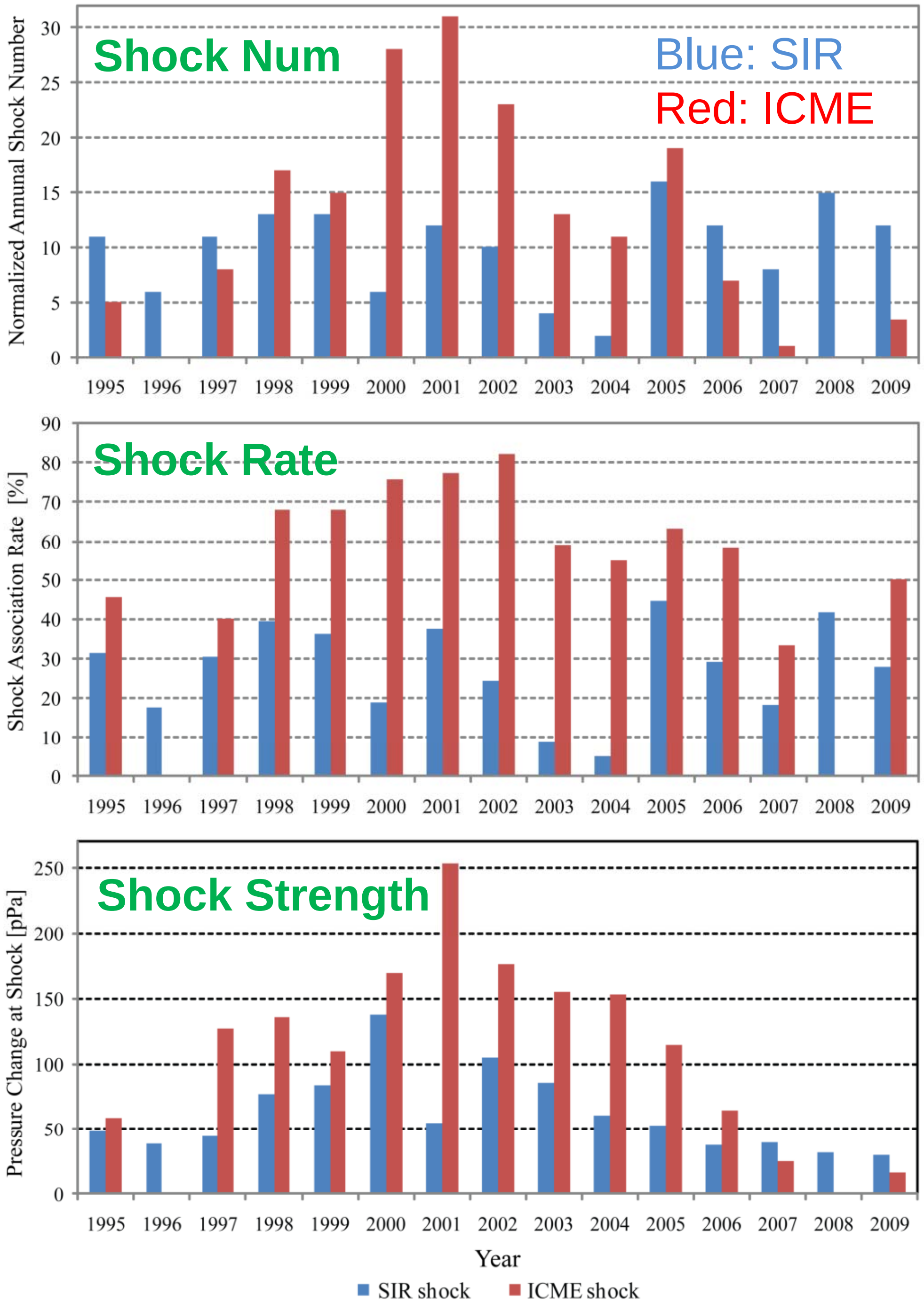
Solar Cycle Variation of SIRs: Recurrence Rate & Sector Boundary Association Rate

recurring SIRs



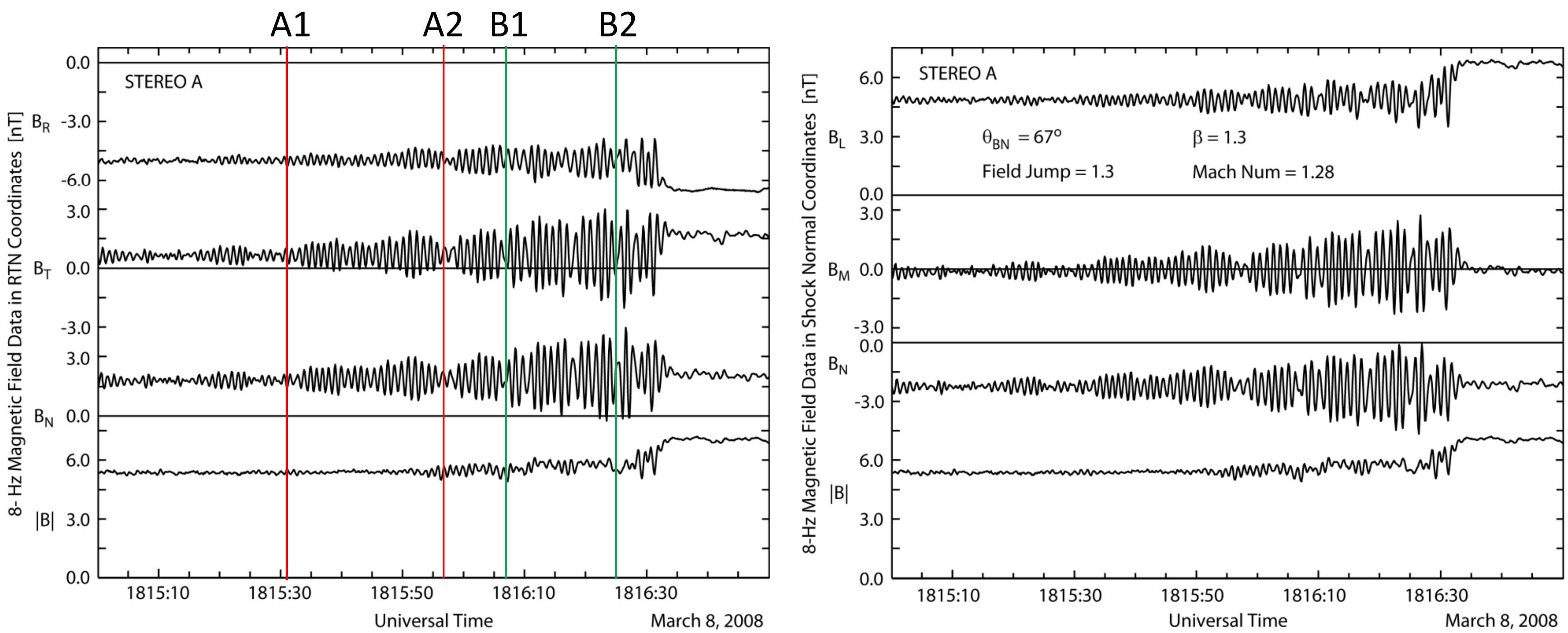
- SIRs recur more often at solar min 23/24 than the last minimum
- Not every SIR is associated with sector boundary crossing. The association rate changes ±20% over the 15 years

Solar Cycle Variation of Shocks (Wind/ACE)



- Annual SIR shock number and shock rate are slightly higher in the declining phase
- Annual ICME shock number and shock rate change approximately in phase with solar activity. ICME shock rate is always larger than SIR, except solar min, 1996 & 2008
- Overall, ICMEs drive more shocks than SIRs, with a higher shock rate
- Pressure change at shocks varies in phase with solar activity, for both SIRs and ICMEs
- At 1 AU, ICME shocks are generally stronger than SIR-driven shocks

Interplanetary Shock with Whistler Waves

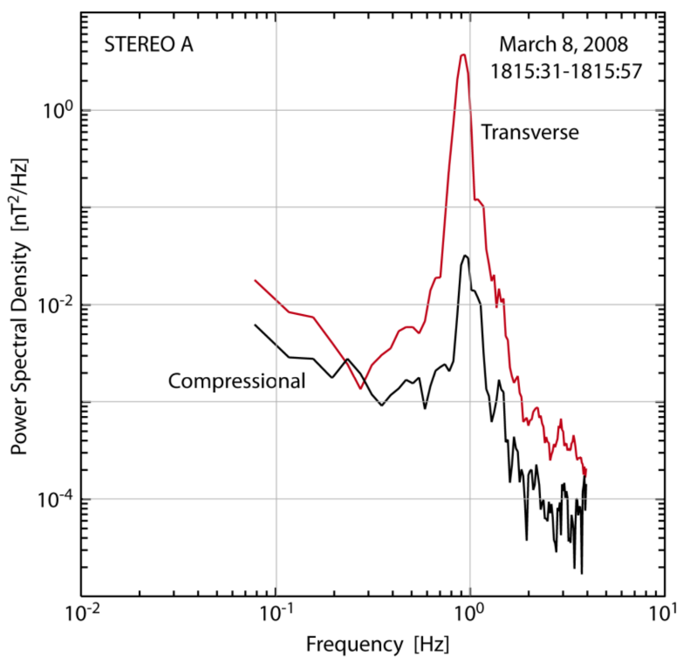


- We find 15 shocks (13.6%) with whistler waves among the 110 interplanetary shocks observed by STEREO during Jan 2007 – Oct 2009. Among the 15 shocks, 9 are quasi-perpendicular; 8 have magnetosonic Mach number larger than 1.6

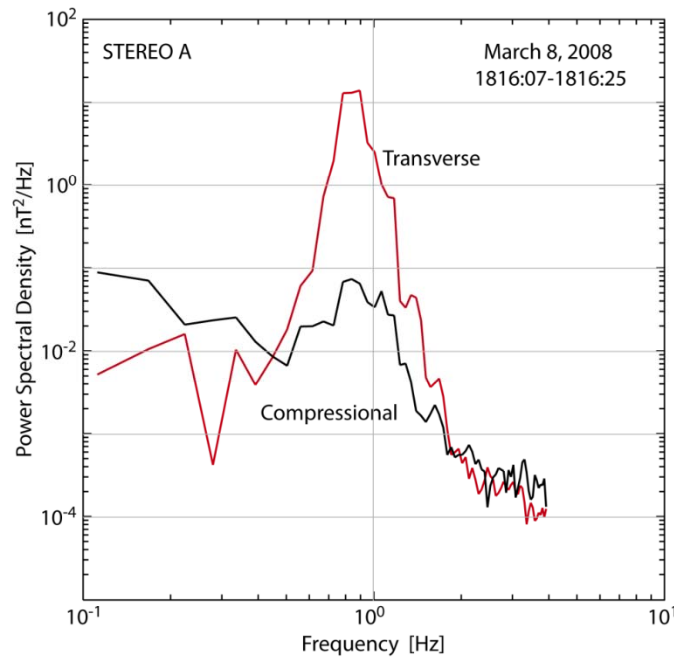
- In contrast with ion cyclotron waves, the whistler waves are right-handed in the plasma frame, and their frequency in the s/c frame is about 1 Hz, larger than the ICW median frequency of 0.28 Hz

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)

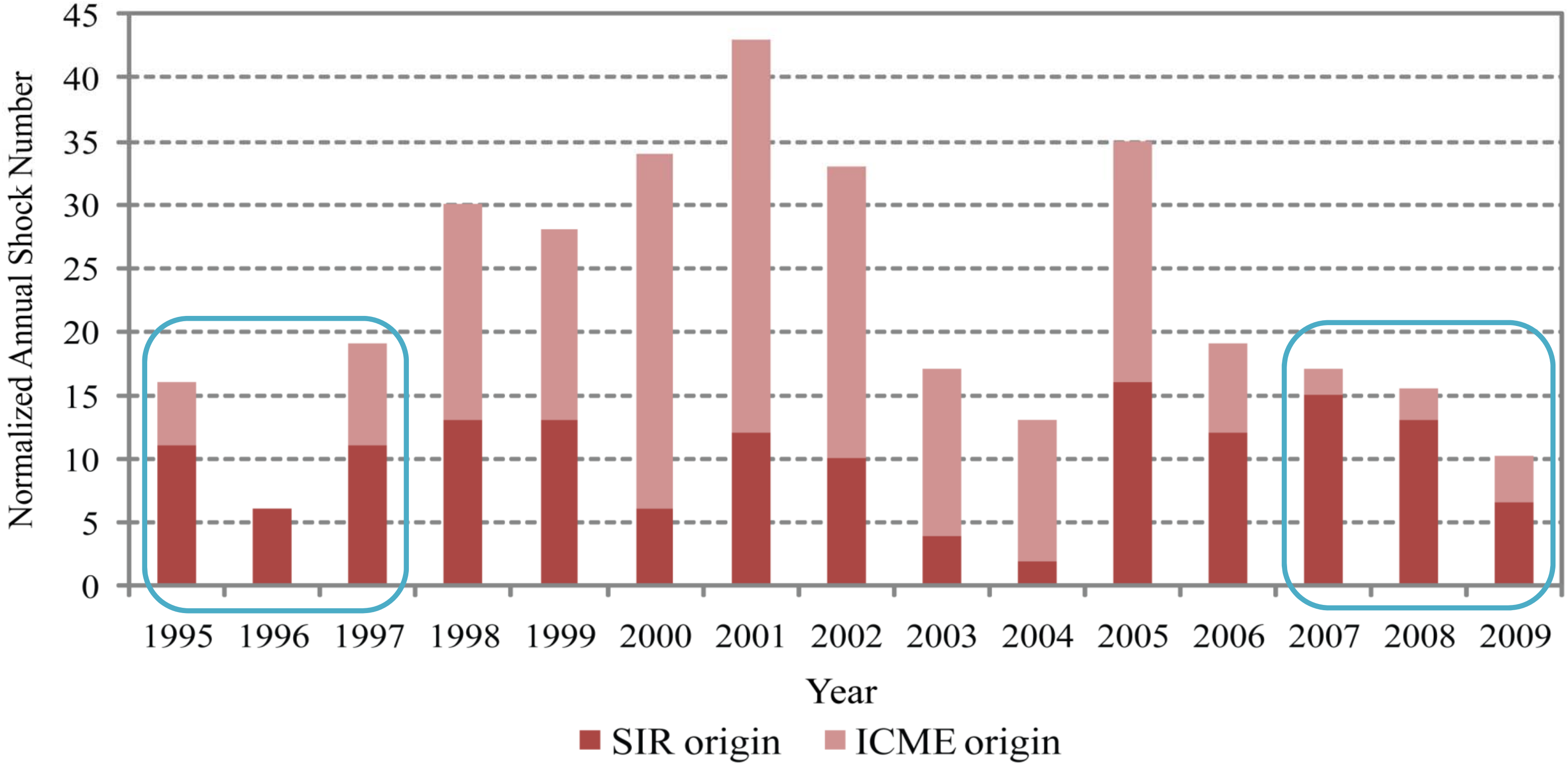
Summary and Discussions

- We have surveyed SIRs, ICMEs, and interplanetary shocks up to Oct 2009
- 2007 – 2009 covers the late declining phase, deep solar minimum, and the early rising phase. Comparing with other times, during this period,
  - Solar wind is much slower. No SIRs are observed for several CRs and even when there are SIRs, the fast wind is typically only 400s km/s
  - SIRs recur more often, drive more shocks
  - ICMEs are weaker and smaller, drive fewer shocks, and are observed with flux ropes more often. In 2009, the ICME occurrence rate and shock rate began to rise although the solar wind remains very slow

  - The association rate of SIR with HCS needs more detailed investigation. Some HCS crossings are ambiguous, as the changes of the IMF polarity and the suprathermal electron pitch angle sometime only last 3 or 4 days
- We note there are significant differences of solar wind and solar wind structures between STA and STB, as they are separated more and more. We will use the heliospheric models to further study it
- Using high resolution magnetometer data, we have studied interplanetary shocks more comprehensively. The various waves associated with the shocks provide a natural laboratory to study shocks

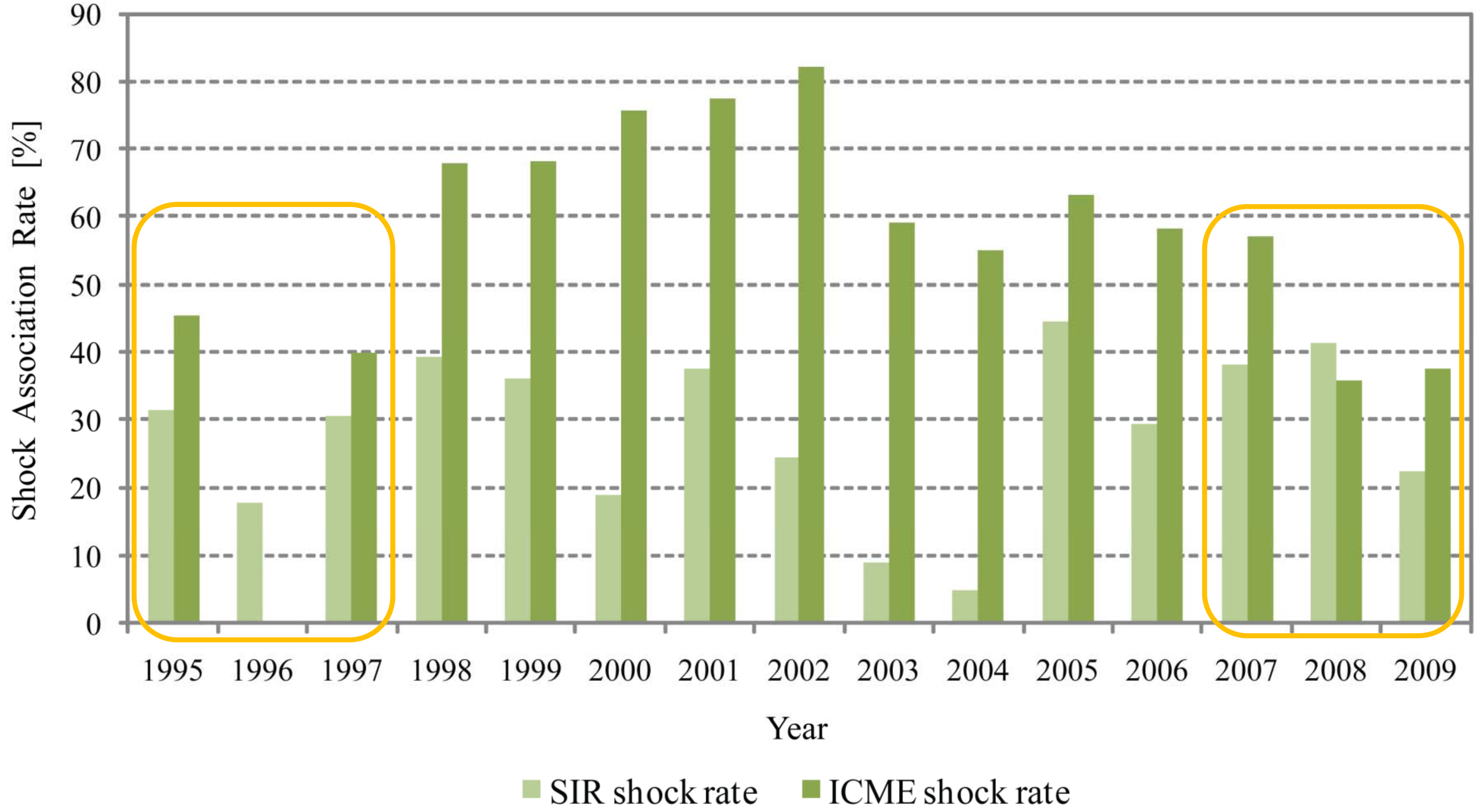
backup

Solar Cycle Variation of Shocks: Occurrence Rate (2007 – 2009 Using STEREO)



- 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
- In 2009, the SIR-origin shock number began to decrease while the ICME-origin shock number began to increase, indicating the **rising phase of solar cycle 24**

Solar Cycle Variation of Shocks: Association Rate (2007 – 2009 Using STEREO)



- SIR shock association rate is 28% on average, being higher in the declining phase
- ICME shock association rate is 55% on average, varying almost in phase with solar activity
- In 2009, the ICME shock rate began to rise and became larger than SIR shock rate