Solar Wind Stream Interaction Regions (SIRs): Radial Evolution and Solar Cycle Variations

Lan K. Jian[1], J. G. Luhmann[2], R. C. Allen[3],
T. Salman[4,1], C. T. Russell[5], N. Gopalswamy[1]

[1] NASA Goddard Space Flight Center, MD, USA
[2] University of California, Berkeley, CA, USA
[3] Johns Hopkins University Applied Physics Laboratory, MD, USA
[4] George Mason University, VA, USA
[5] University of California, Los Angeles, CA, USA

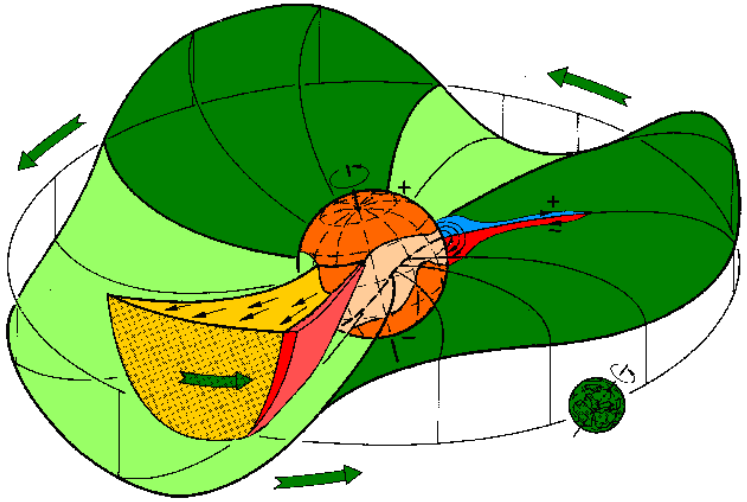
Space Climate 8 Symposium
Kraków, Poland 21 September 2022

Overview

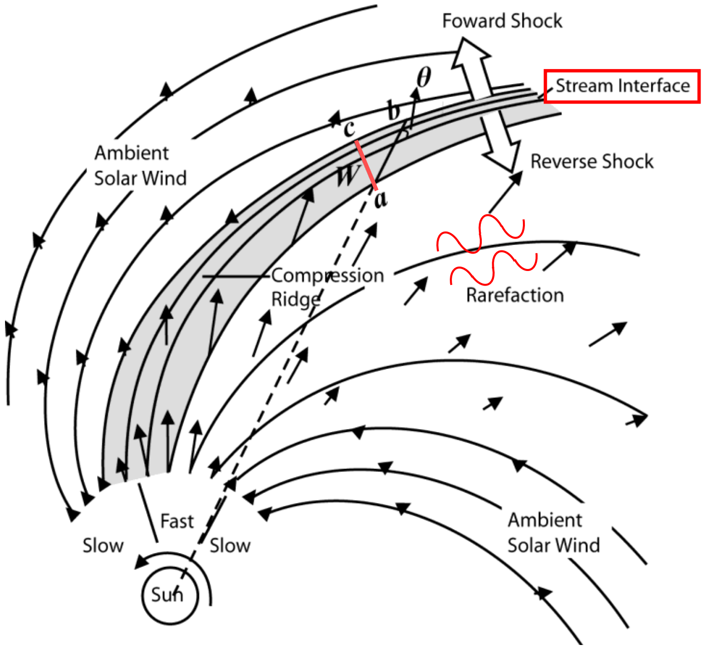
- Introduction, identification, and space weather effects of SIRs
- Modulation of cosmic rays by SIRs
- Radial evolution of SIRs, stream interface, and shock rate
- Solar cycle variations of SIR properties and shocks
- Summary and discussion

Introduction

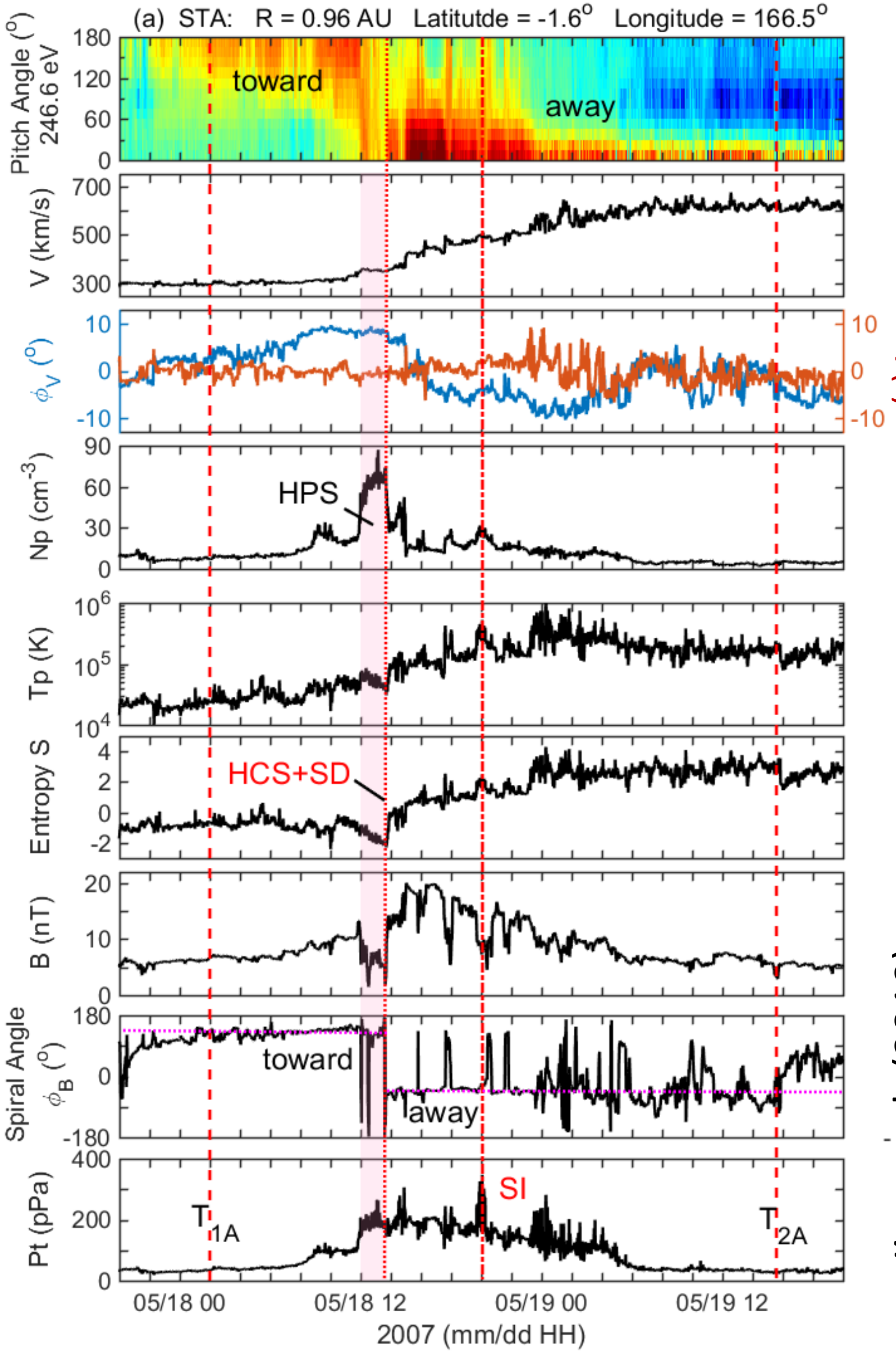
- Fast wind from coronal holes is kinetically hot and tenuous, while slow wind from streamer belt is generally cool and dense. They are threaded by different magnetic field lines and prevented from interpenetrating
- As the Sun rotates, fast wind can overtake the preceding slow wind and form a stream interaction region (SIR) with a pressure ridge at the stream interface
- If the flow pattern is roughly time-stationary, the compression region forms a spiral in the solar equatorial plane that corotates with the Sun → **Corotating Interaction Region (CIR)**
- SIRs = CIRs + Transient SIRs (which do not recur in one or more Carrington rotations)
- The pressure waves associated with the collision steepen with radial distance, eventually forming **shocks**, sometimes a pair of forward-reverse shocks



according to Alfvén (1977)



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



Jian et al. (2019)

Identification of SIRs

* Criteria (by visual inspection)

① Increase of V_p

② Deflection of V_p

③ A pile-up of P_t (*magnetic pressure + perpendicular plasma thermal pressure*) with gradual declines at two sides

④ Increase and then decrease of N_p

⑤ Increase of T_p

⑥ Compression of **B**, usually associated with **B** shear

⑦ Change of entropy $\ln(T_p^{1.5}/N_p)$

* Stream Interface (SI)

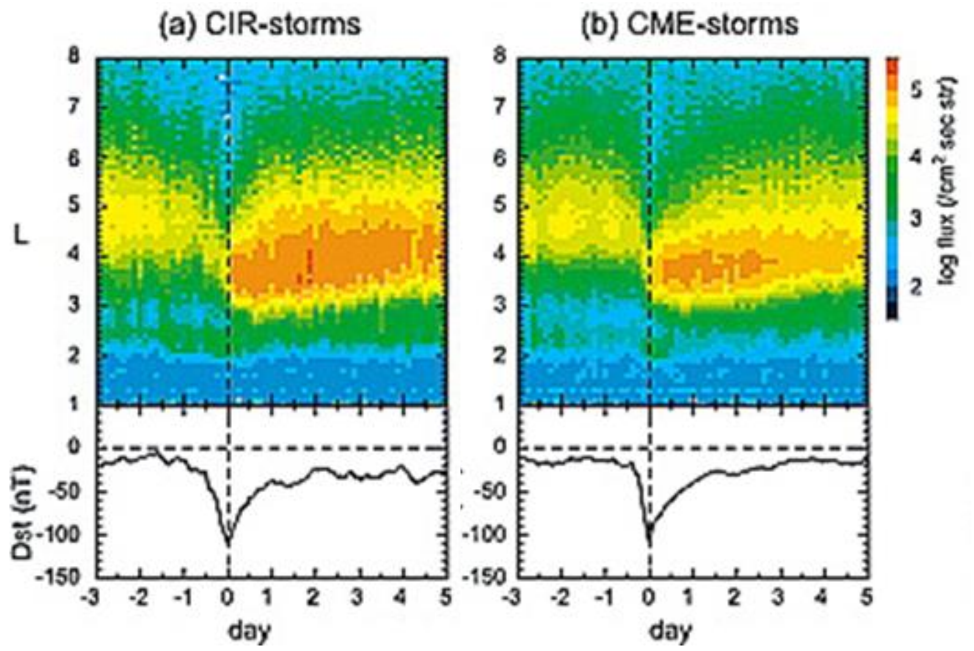
- The boundary separating the slow and fast wind
- Because ~80% of SIRs don't have a clear SI from plasma and mag data, we define SI at the peak of P_t

* Heliospheric Current Sheet (HCS)

Identified by the changes of the IMF polarity and the suprathermal electron pitch angle distribution

Space Weather Effects of SIRs

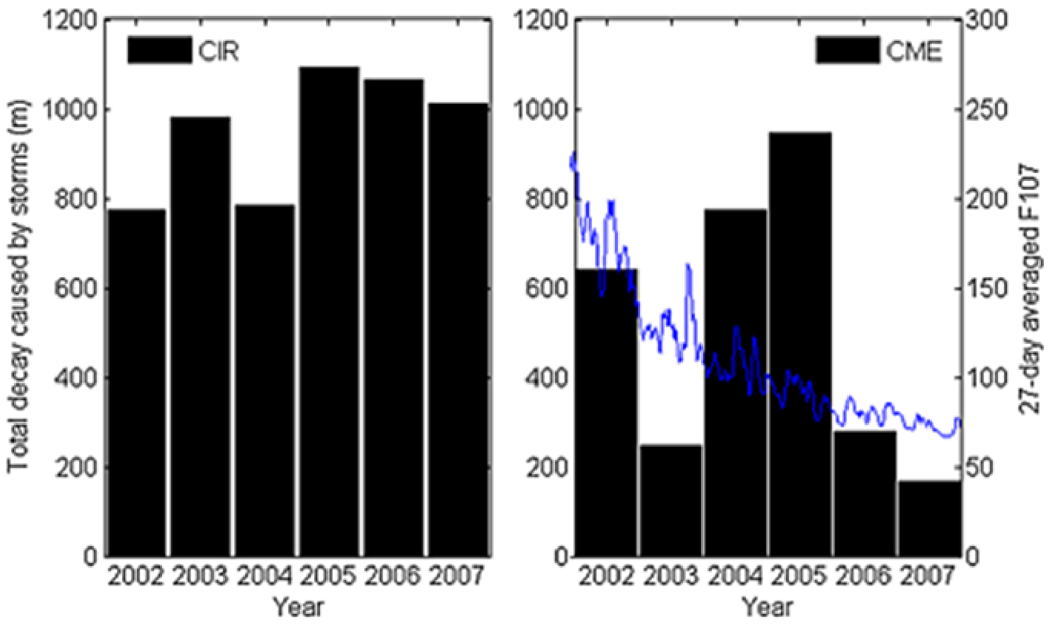
1996-2004 NOAA-12,15 >300 keV electrons



Miyoshi & Kataoka (2005)

CHAMP (Challenging Minisatellite Payload) ~450 km

Chen et al. (2014)



- About 13% of the 88 intense geomagnetic storms (Dst ≤ -100 nT) in 1996-2005 were associated with SIRs (Zhang et al., 2007), with the minimum Dst reaching -128 nT
- Southward B_z fluctuations associated with Alfvén waves in the fast wind cause the high-intensity long-duration continuous AE activities (Tsurutani and Gonzalez, 1987)
- Large-amplitude Alfvén waves in SIRs and the following fast wind can drive a series of particle injections and affect the evolution of the outer radiation belt (centered at ~4 Re) more effectively than CMEs
- SIR-driven storms last longer and have a larger effect on the total orbital decay for satellites in the thermosphere than CME-driven storms

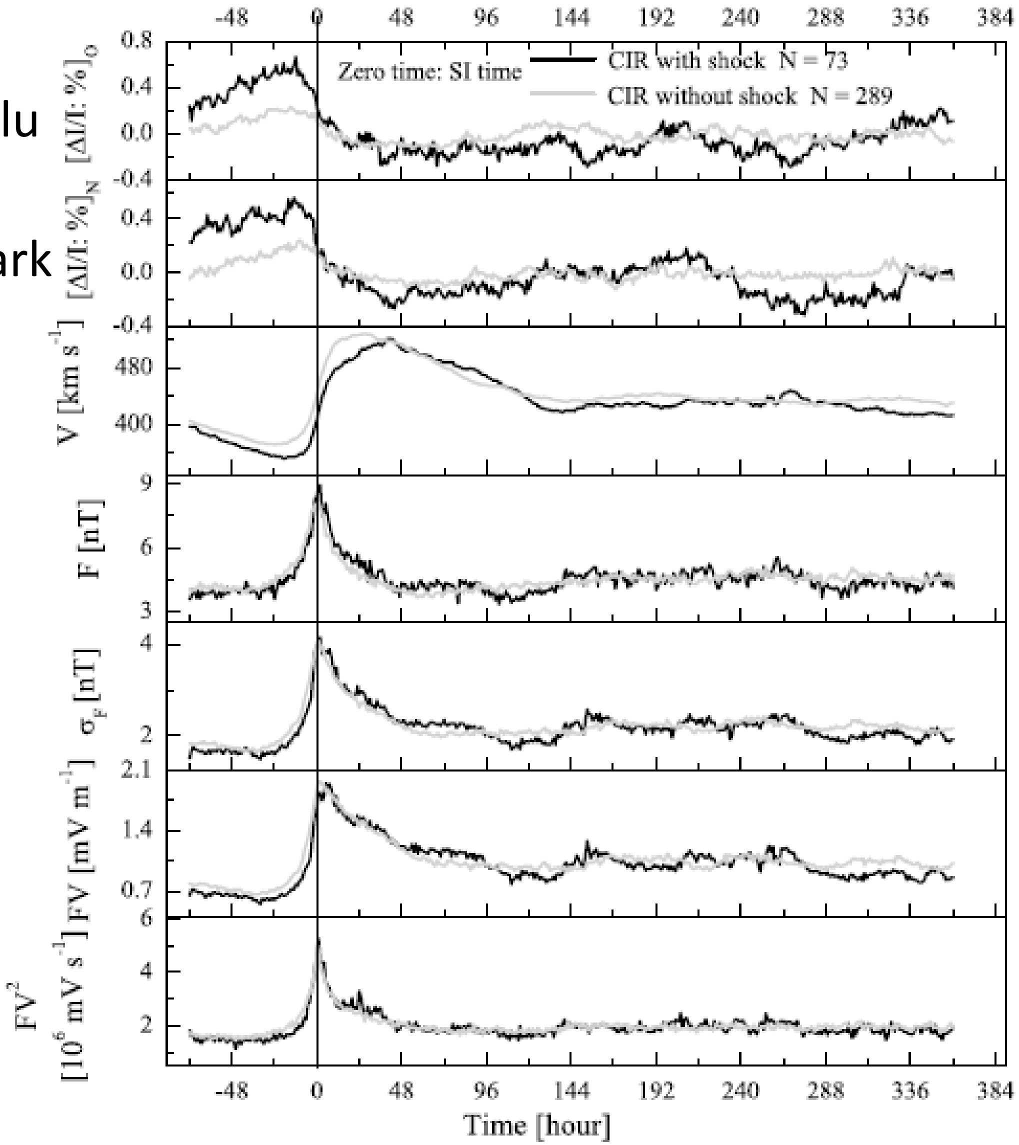
Modulation of Cosmic Rays by SIRs

Galactic cosmic ray intensity **decreases** across SIRs

- Increased turbulence in SIR may impede the entry of cosmic rays
- Cosmic rays are swept away from the Sun more efficiently in the fast wind
- GCR drifts due to gradients and curvature in IMF -> GCR intensity modulates with the distance relative to HCS
- Enhanced drifts of particles out of SIR due to stronger fields within SIR

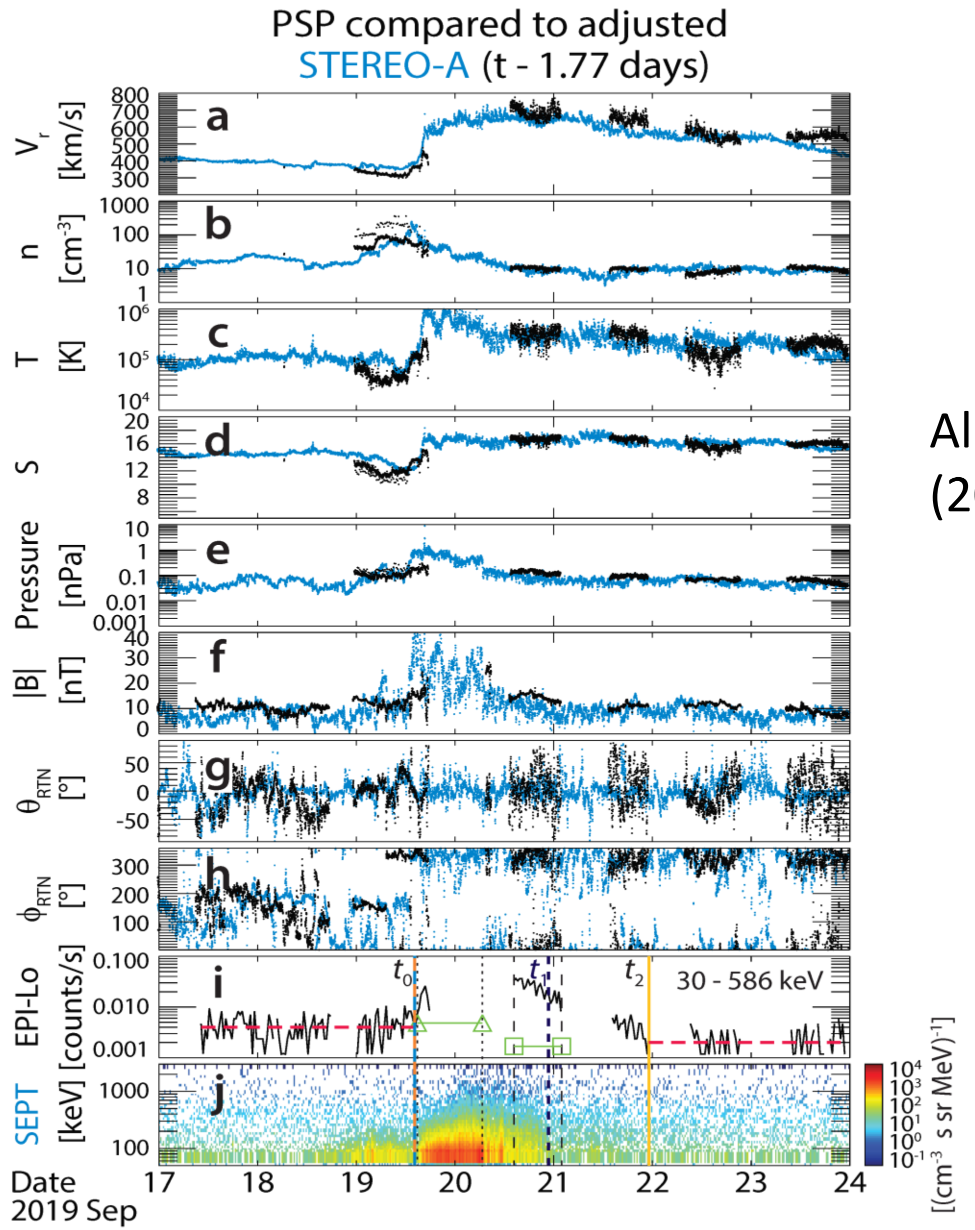
SIRs in 1995-2009

Neutron Monitor
Oulu
Newark

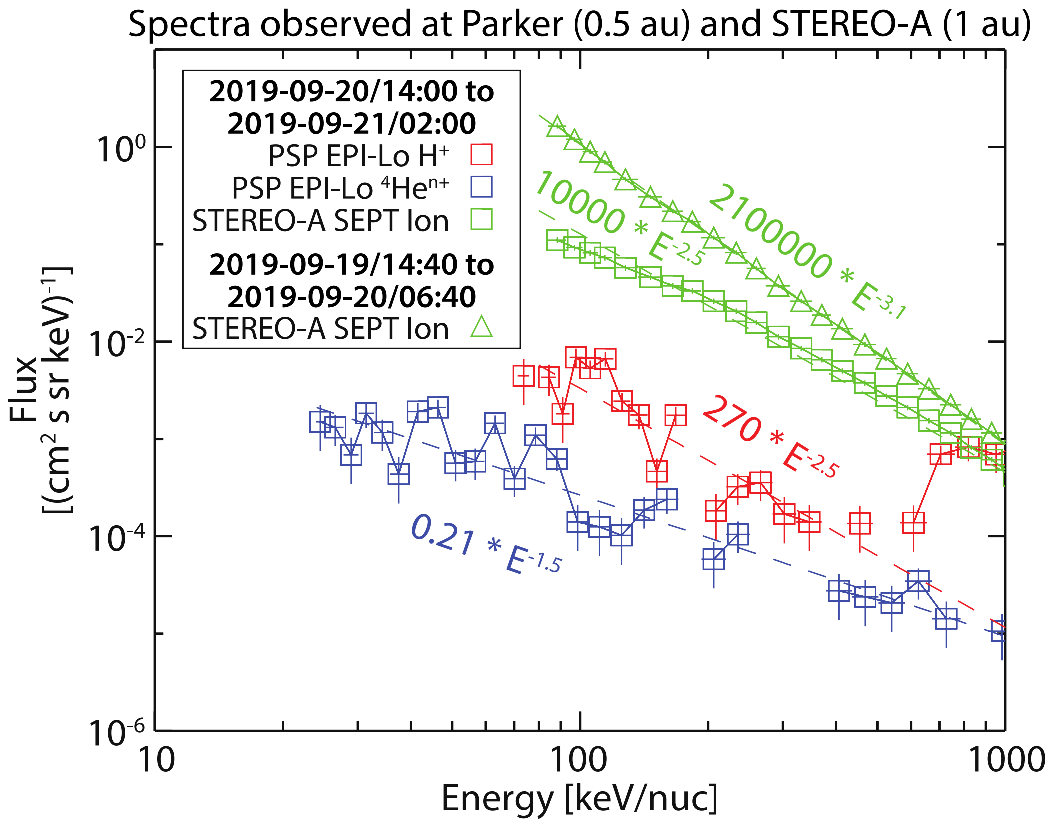


Badruddin and Kumar (2016)

Radial Evolution of SIRs from 0.5 to 1 AU

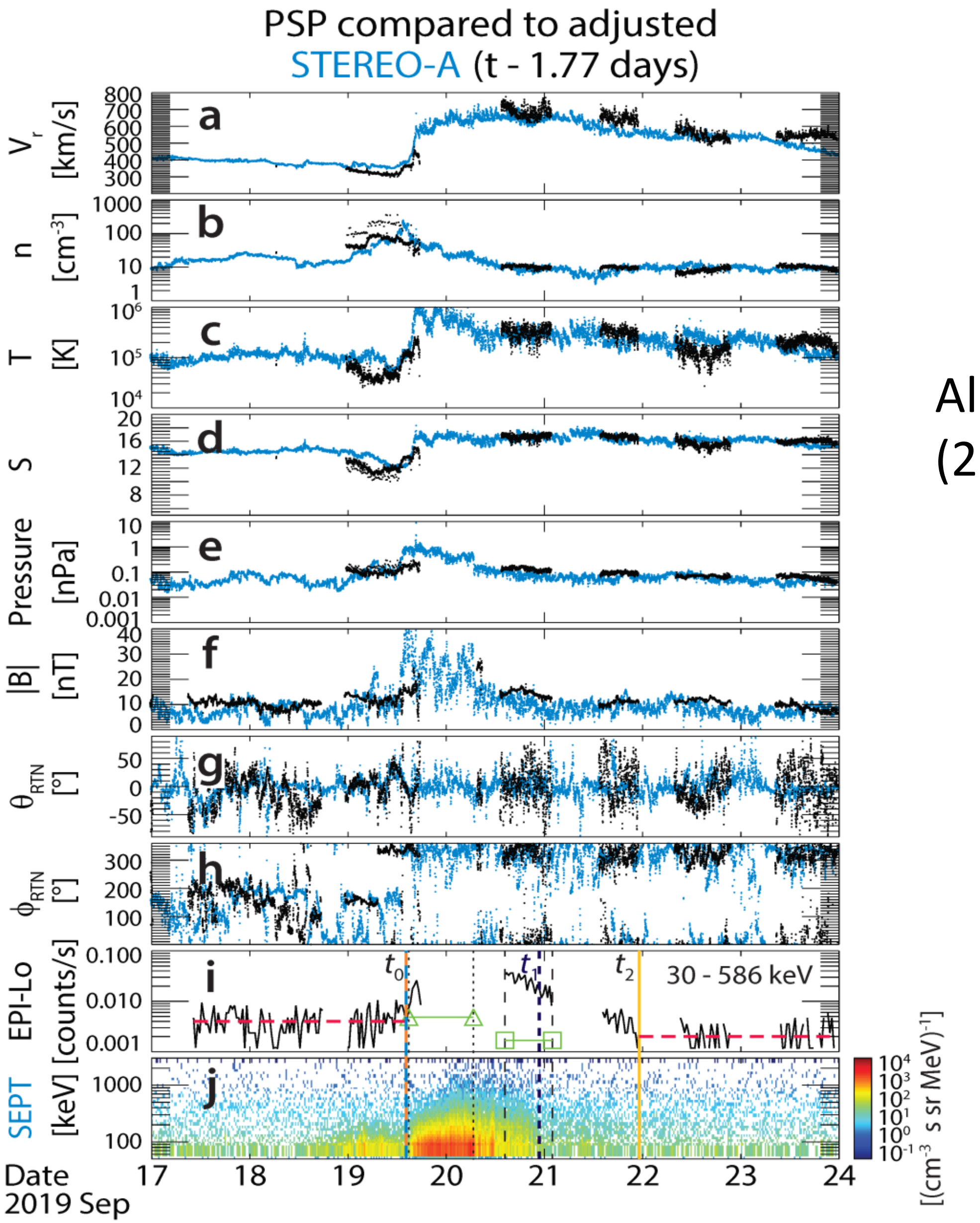


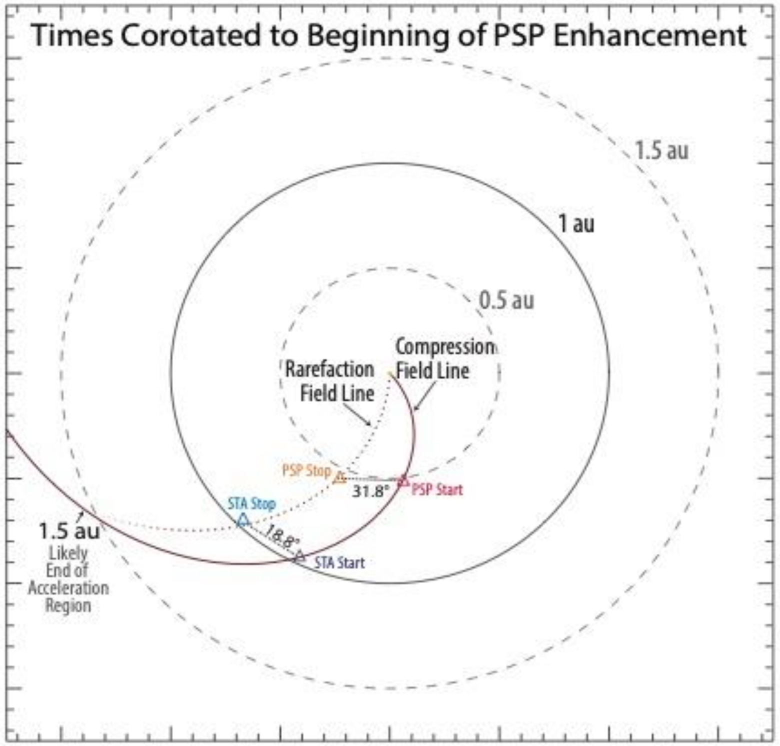
Allen et al. (2021)



- Spectra indices are similar at PSP and STA for the fast wind interval (boxes). The intensity of suprathermal ions at STA is ~40 times stronger than at PSP
- Wider longitudinal spread at PSP than at STA is due to the magnetic field line topology at the SIR

Radial Evolution of SIRs from 0.5 to 1 AU

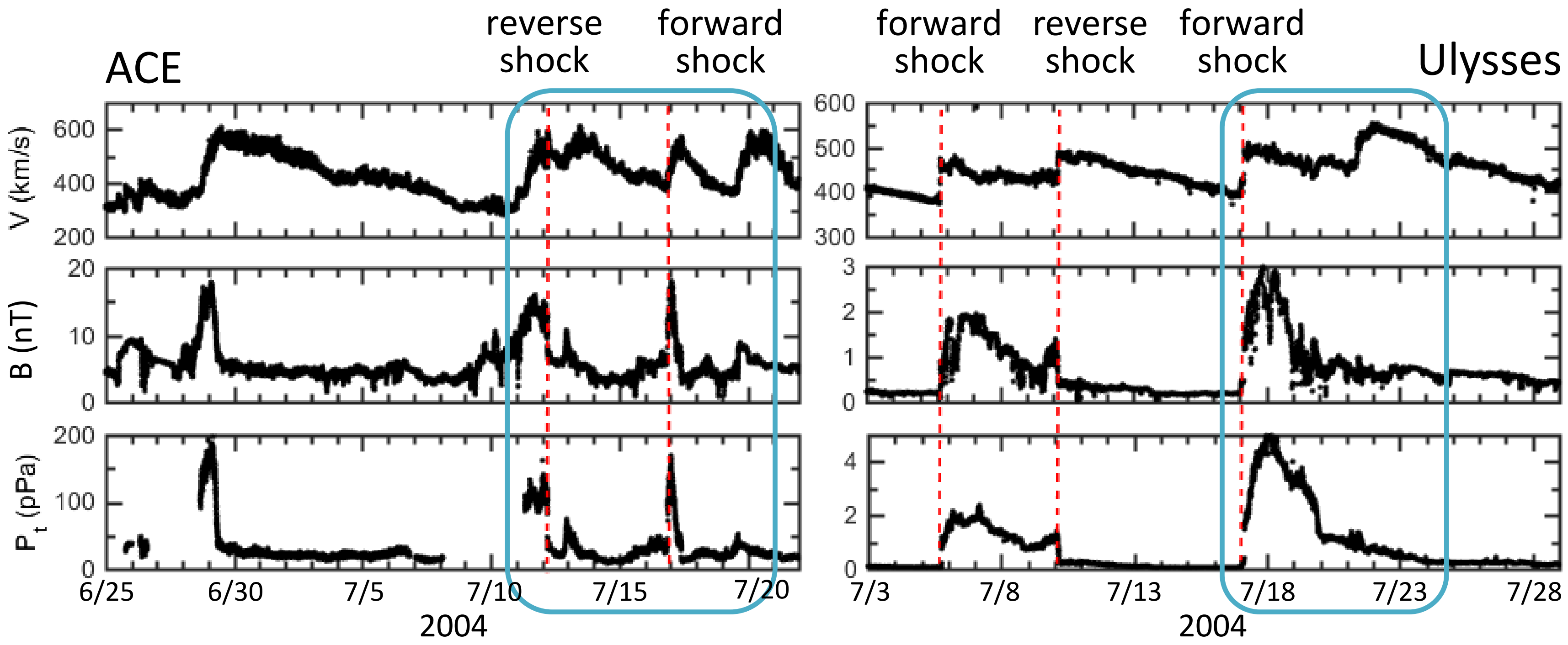




Allen et al. (2021)

- Wider longitudinal spread at PSP than at STA is due to the magnetic field line topology at the SIR
- It is not clear whether (1) a shock is developed a little further than 1 AU and accelerates the particles, or (2) compressive acceleration generates the observed suprathermal particles through stochastic processes in the unshocked compression region due to the velocity gradient across the CIR

Radial Evolution of SIRs to 5 AU



After Jian et al. (2011)

- At 0.72, 1, and 5.3 AU, more SIRs have a **longer trailing part** after the stream interface than the leading part before the interface
- At 5.3 AU, about **36%** of SIRs and 37% of CMEs are in hybrid events
- From 0.72 to 5.3 AU, the declining rates of P_{dyn}, P_t, and B are higher for the general solar wind than for SIRs

Radial Evolution of SIRs to 5 AU (cont.)

Jian (2008)

More transient SIRs close to the Sun

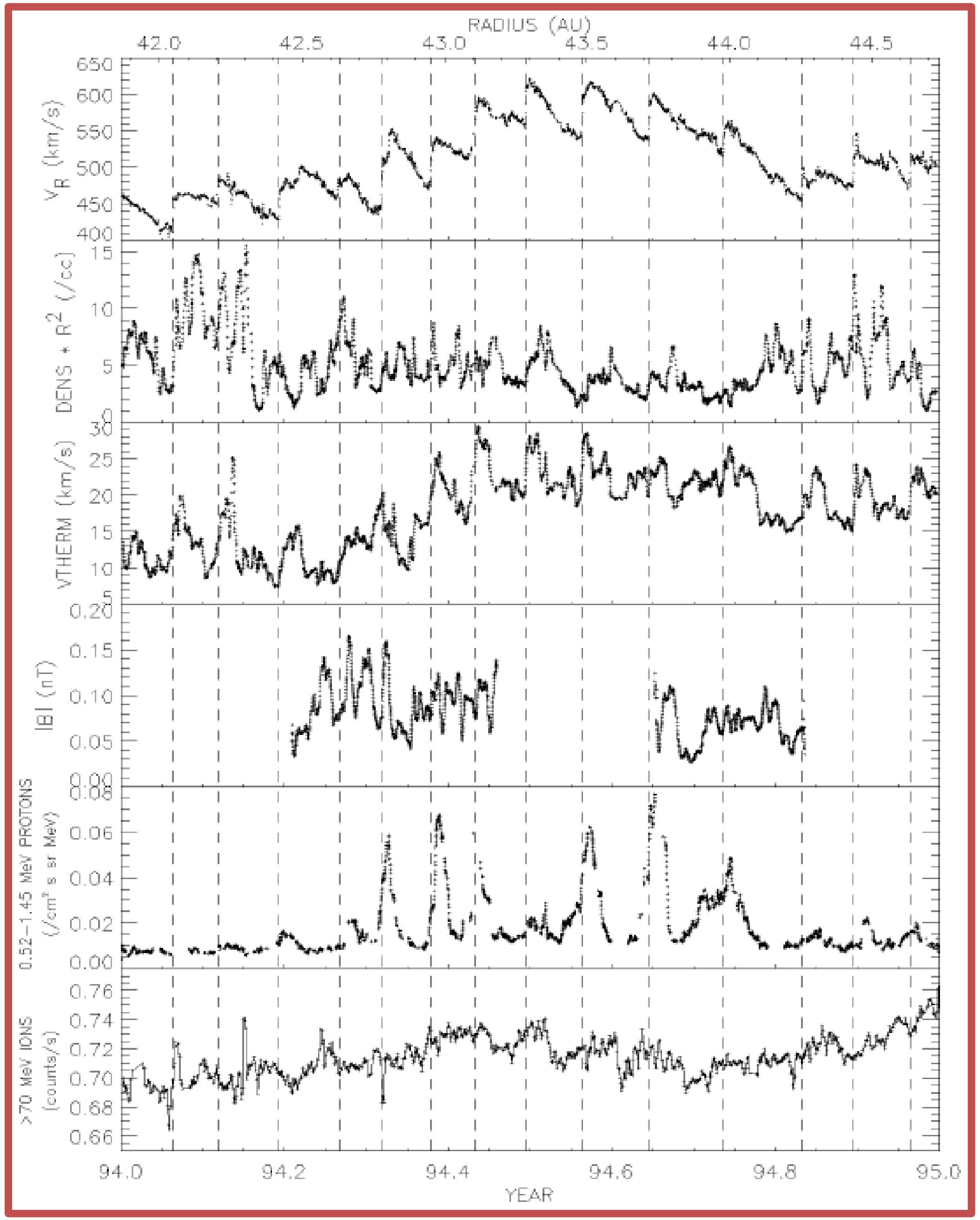
Heliocentic distance	0.72 AU	1 AU	5.3 AU
No. of SIR (per year)	34.2	37.6	17.6
CIR fraction	**48.8%**	**66.8%**	**74.1%**
SIR shock association rate	***3.4%***	***25.9%***	***90.7%***
CIR shock association rate	*3.0%*	*30.0%*	*90.0%*
SIR sharp discontinuity association rate	**8.8%**	**19.5%**	**9.4%**
CIR sharp discontinuity association rate	4.6%	19.9%	12.8%

- SIR shock rate increases greatly from 0.72 to 1 AU, suggesting the region between them is like an **incubator** region for SIR shocks
- SIR width increases almost linearly with the heliocentric distance (Jian et al. 2008)
- The properties of SIRs and CIRs are similar, except that CIRs are usually associated with long-lasting and larger coronal holes
- We should not ignore the transient and non-recurrent SIRs, because they can drive shocks at a similar rate as CIRs, and they have similar sizes, speeds, magnetic fields, and pressures as CIRs

- Sharp discontinuity: N_p decrease and T_p increase concur within a **10-min** time window (~2.4×10^5 km) near the P_t ridge and during accelerating solar wind
- The steepening of SI may have taken place between 0.72 and 1 AU, probably due to the increasing compression of the fast wind against the slow wind
- As the SIRs propagate further out, plasma instabilities acting in the shear layer between the slow and fast streams may have smoothed out some sharp interfaces

Evolution of SIRs in the Middle Heliosphere

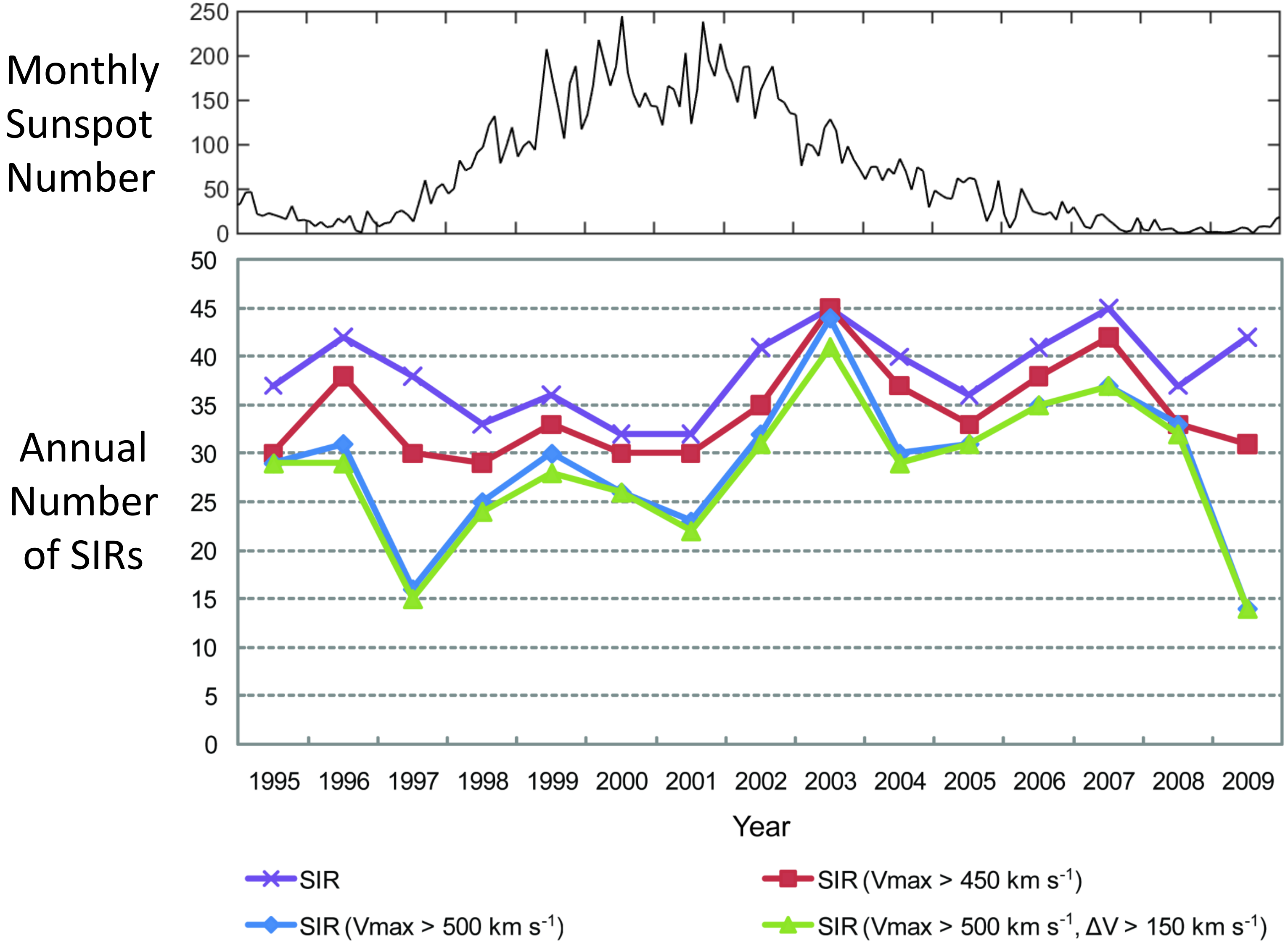
- Beyond 5 AU, SIRs expand and interact to form merged interaction regions (MIRs)
- Voyager 2 observed 14 MIRs in 1994 at ~ 43 AU. Some of them are associated with energetic proton events (0.5-1.45 MeV)
- Count rate of cosmic rays (>70 MeV ions) often decreases at MIRs, although not always



Voyager 2

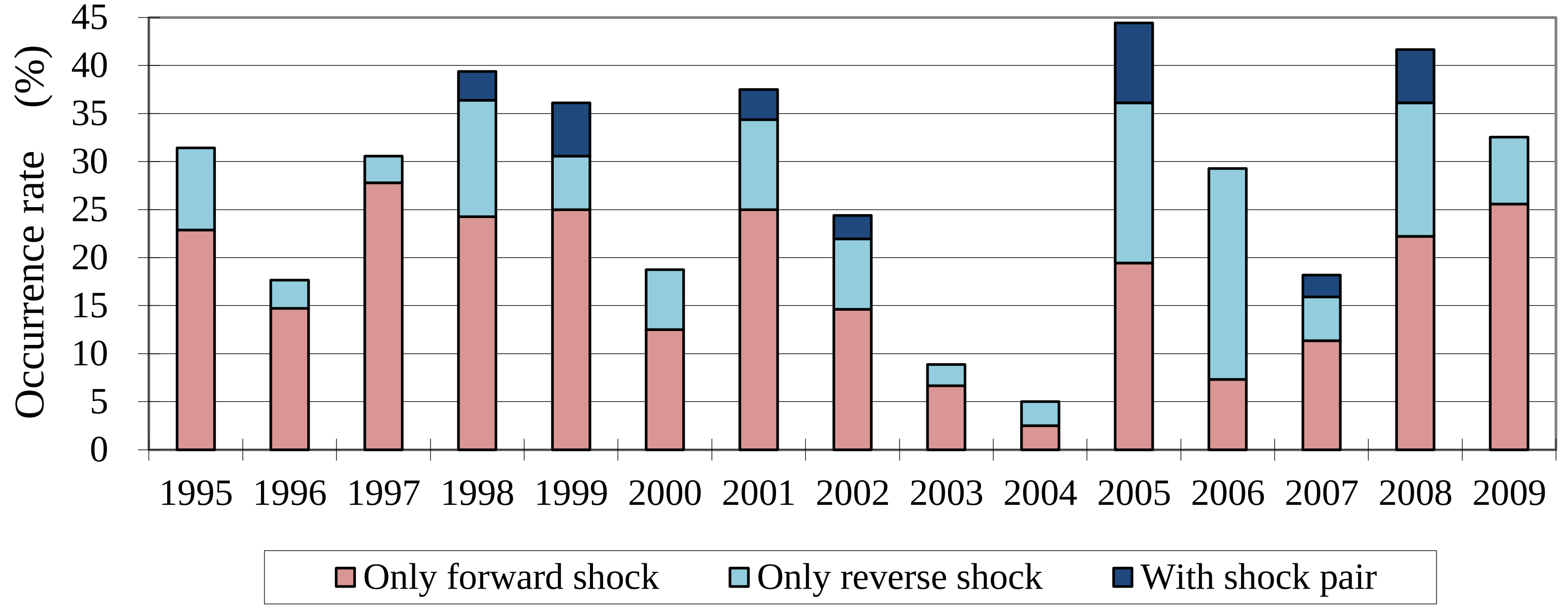
Lazarus et al. (1999)

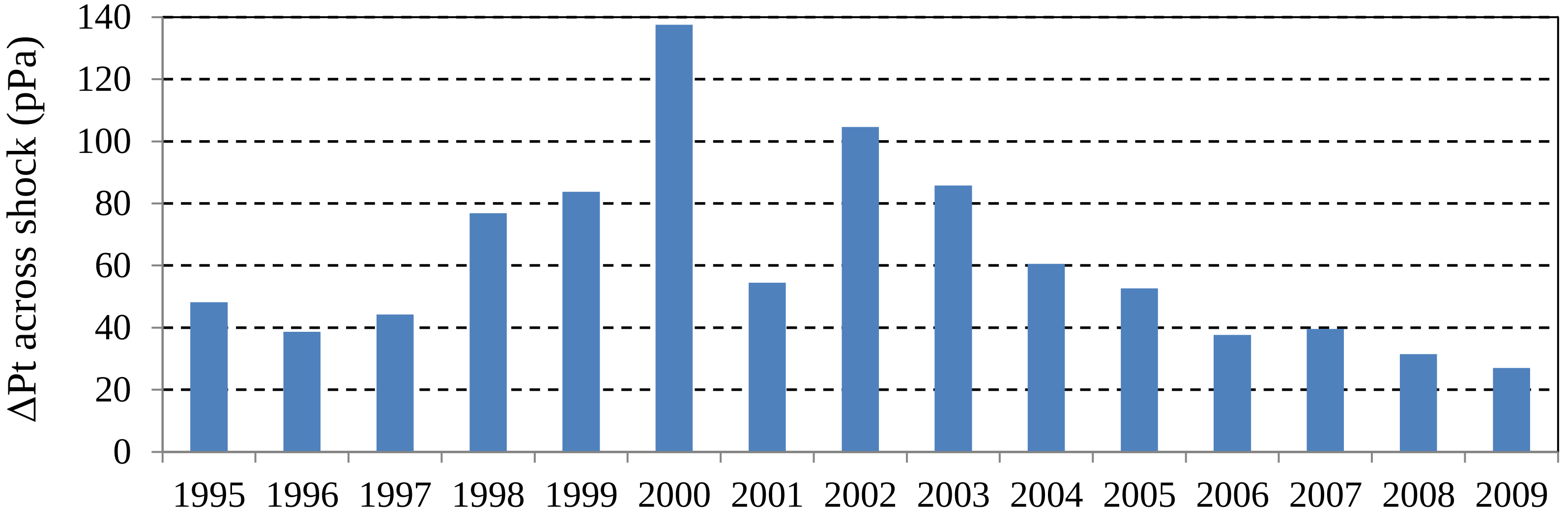
Annual Occurrence Rate of SIRs from Wind/ACE Survey at L1



Jian et al. (2011)

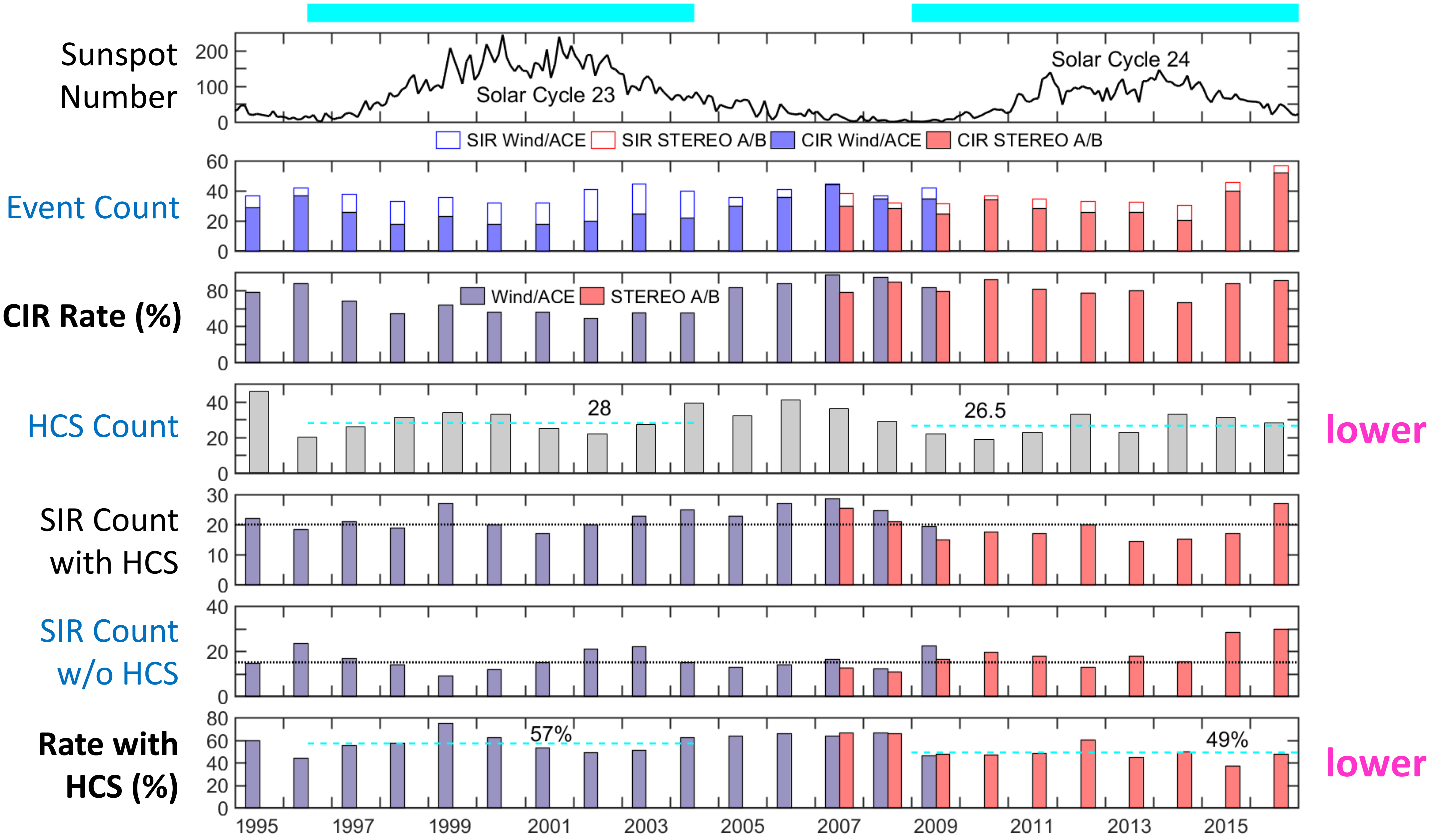
SIR-Driven Shocks: Occurrence Rate & Pressure Change



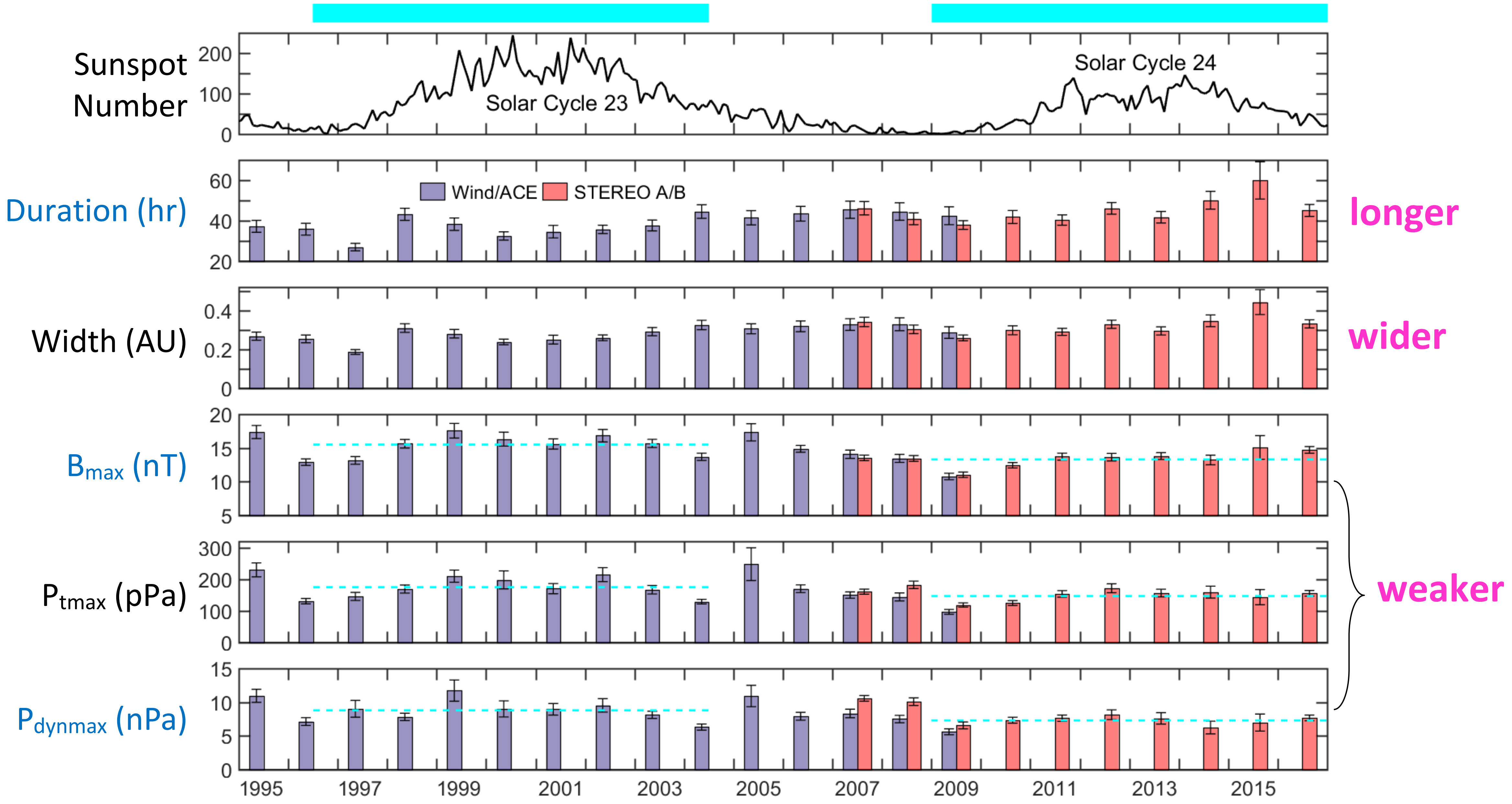


After Jian et al. (2011)

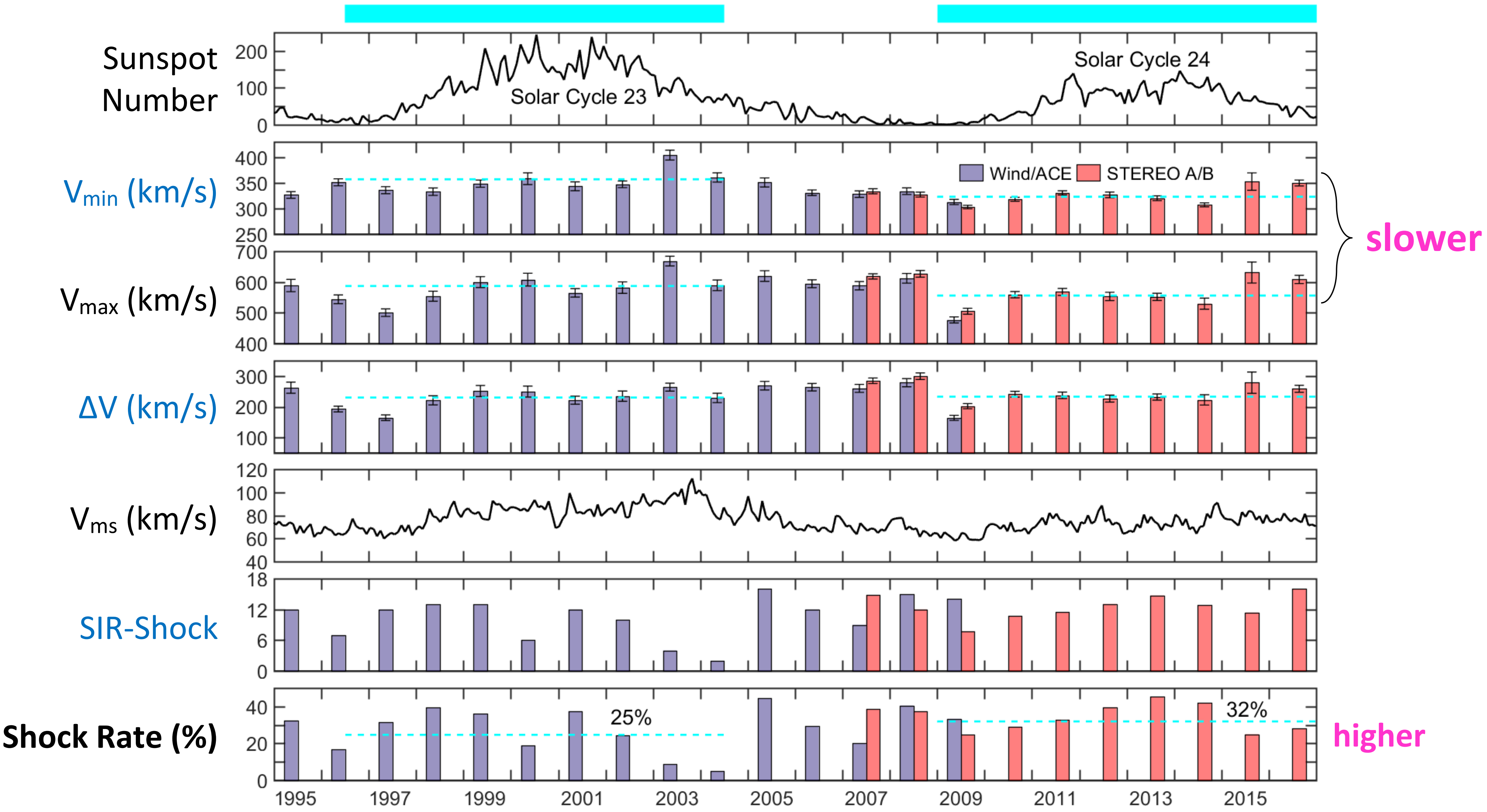
Solar Cycle Variations of SIR Properties - I



Solar Cycle Variations of SIR Properties - II



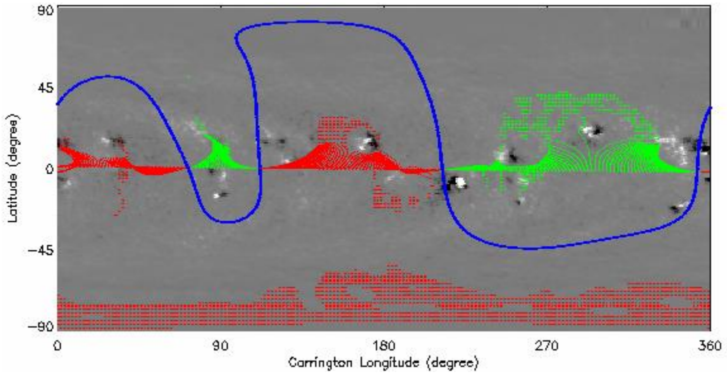
Solar Cycle Variations of SIR Properties - III



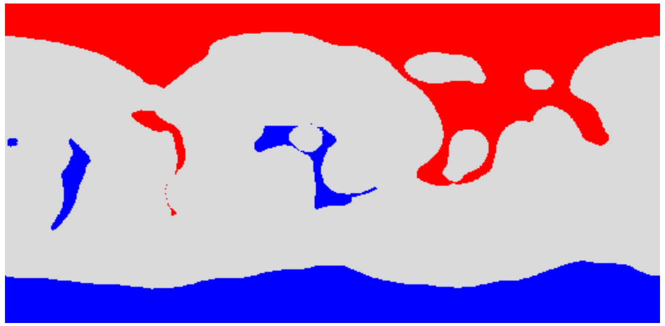
Implication of More SIRs with Lower HCS Association Rate in 2016

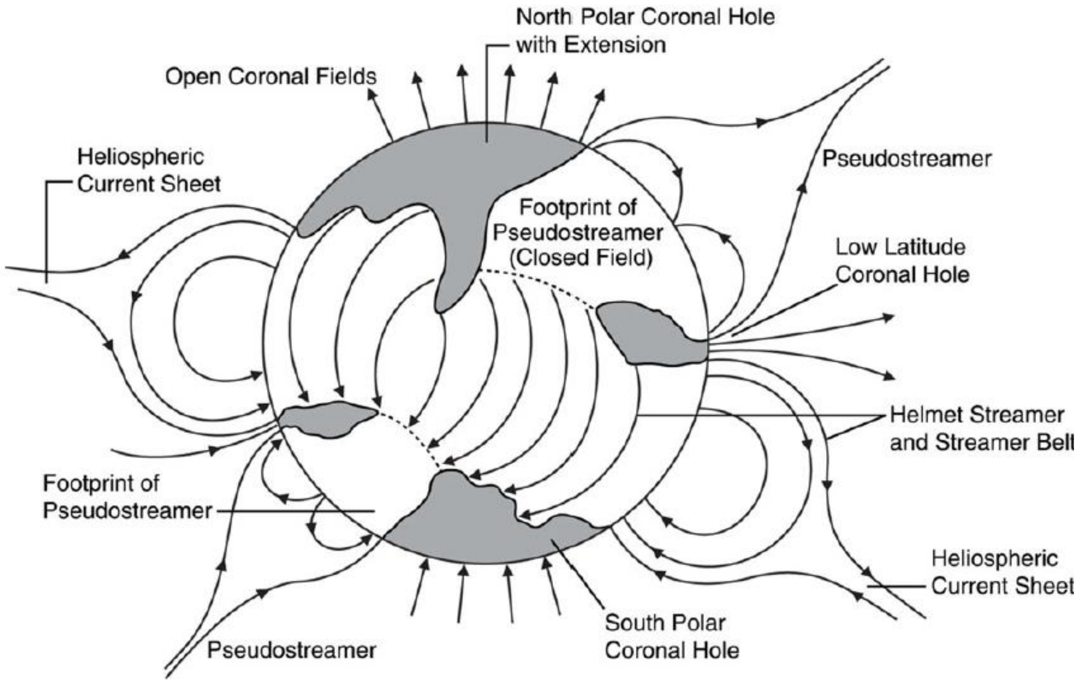
CR 2177
June 2016

GONG Input – PFSS Model



HMI Input – MAS Model





Luhmann et al. (2012)

- In 2016, there are more SIRs and they recur more often than before. The SIR-HCS association rate is lower than before
- The SIRs not associated with HCSs may be related to the pseudostreamers on the Sun
- All the above implies there are perhaps more relatively stable small coronal holes on the Sun in 2016

Summary and Discussion

- SIRs occur throughout a solar cycle, typically more than 30 events per year. They can impact the space weather largely
- On average, ~2/3 of SIRs last more than one Carrington rotation at 1 AU. This recurrence rate is higher in the declining phase and solar minimum when the Sun is less active
- As SIRs evolve, they drive more shocks at a greater heliocentric distance, and form merged interaction regions at tens of AU. The stream interface between slow and fast wind seems to steepen first and then become smooth as SIRs evolve to 5.4 AU
- The SIRs are generally weaker and slower in cycle 24 than in cycle 23, consistent with a weaker solar cycle
- The higher shock rate in cycle 24 (32%) than in cycle 23 (25%) might be attributed to slower magnetosonic speed in the ambient solar wind. Most (~60%) of them are forward shocks
- The HCS association rate of SIRs is lower in cycle 24 (49%) than in cycle 23 (57%), probably because there are more pesudostreamers in cycle 24