Multi-point observations of CIRs

ICMEs as possible sources of variability in CIR-associated ion increases

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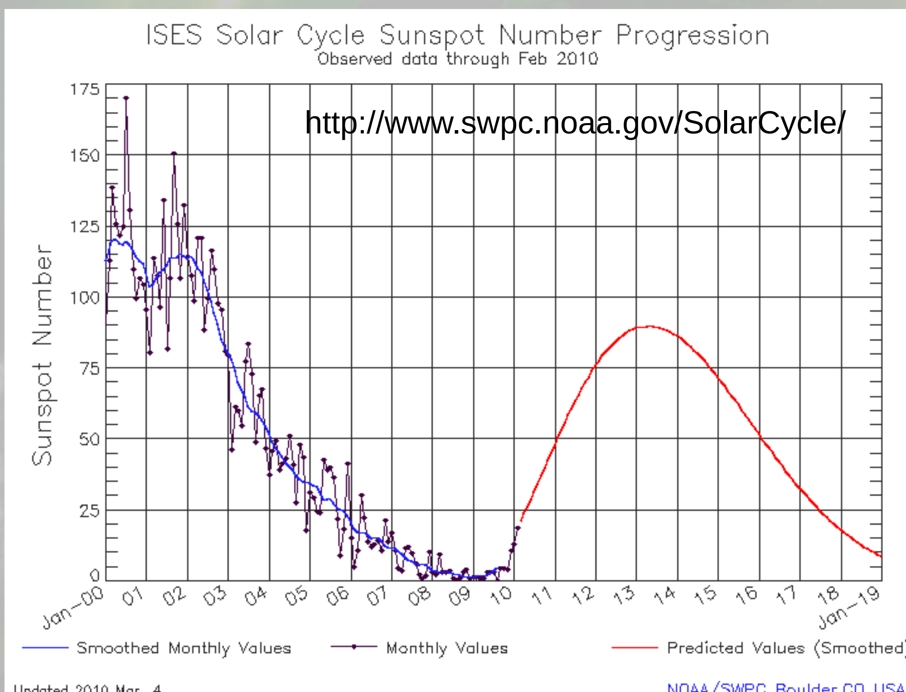
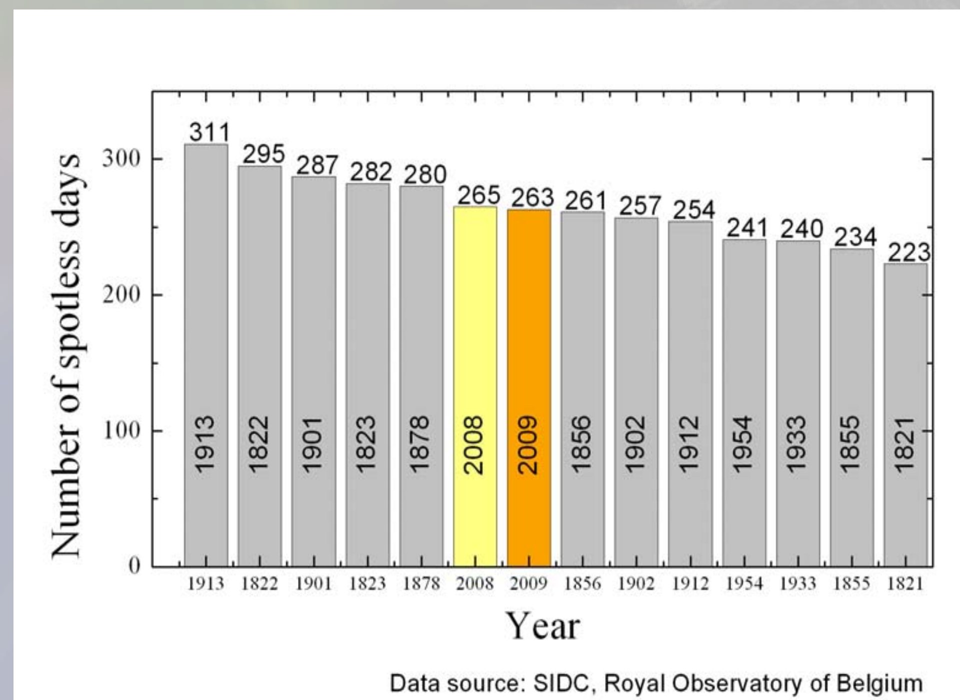
Observation Period

- Period under study: CR 2067.0-2082.0 (Feb 21, 2008 - April 5, 2009)
- Solar minimum between solar cycles 23 and 24. Very low solar activity. 2008 and 2009 are the quietest years since 1913
- Few (<10) SEP events (minor)
- Optimal conditions for the study of SIR/CIR-associated energetic ions





Multi-point in-situ observations

- Goal: comparison of STA and STB observations during the same CIR
  - Correlation with remote-sensing observations of the corona
  - Focus on energetic ion increases
  - Identify causes of discrepancies (discern temporal / spatial variations)

- Basic tools to compare in-situ observations from different s/c during co-rotating events:
  - Ballistic back-mapping:

$$\phi - \phi_0 = \frac{\Omega_S (r - r_0)}{V_{SW}}$$

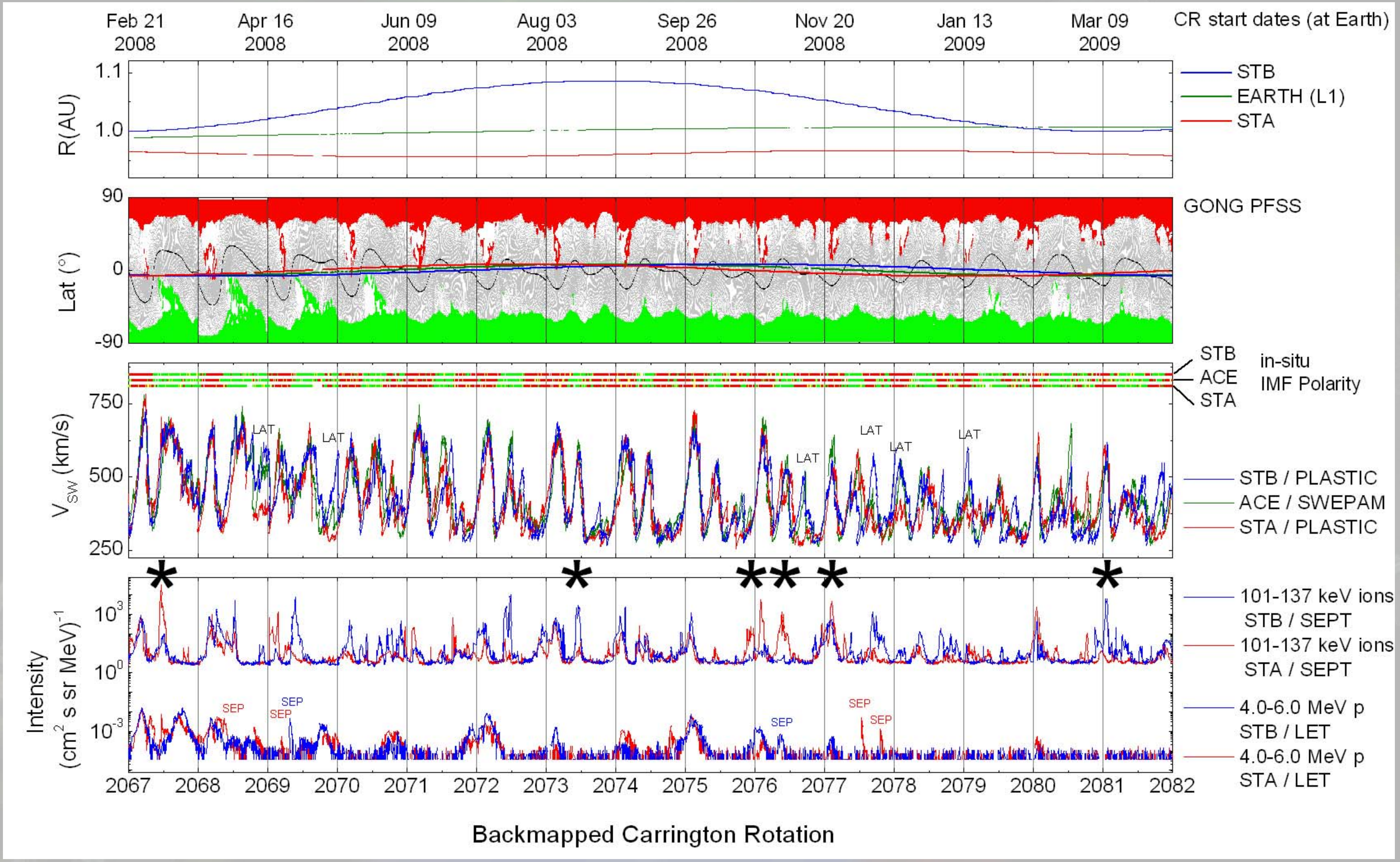
(e.g., Nolte et al., 1976; Schwenn and Marsch,1990; Posner et al., 1999, 2000; Neugebauer et al., 2004).

  - Time-shifting:

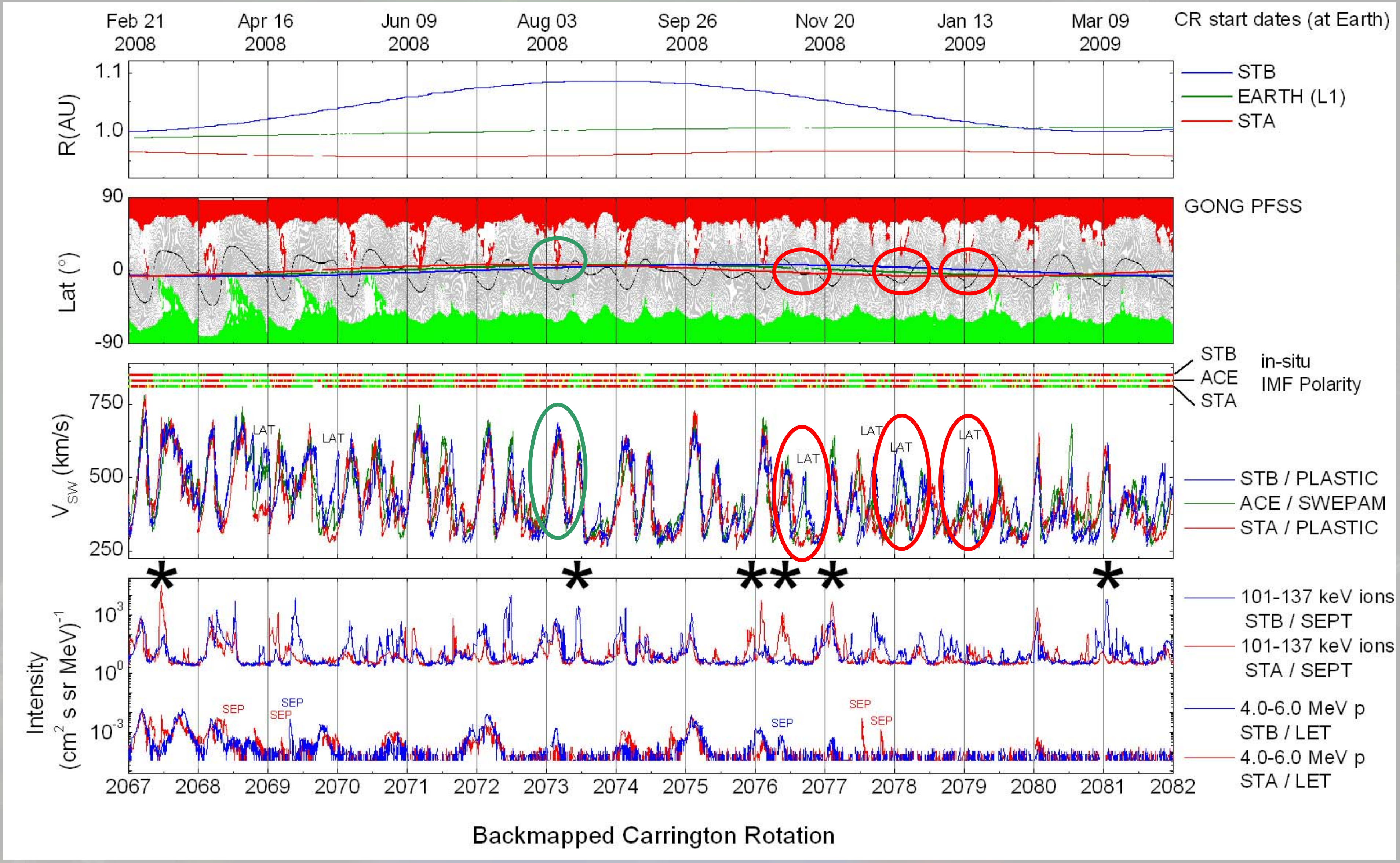
$$t_A - t_B = \frac{\phi_A - \phi_A}{\Omega_S} + \frac{r_A - r_B}{V_{SW}}$$

(e.g., van Hollebeke et al., 1978; Richardson et al., 1998)

Overview of Backmapped observations

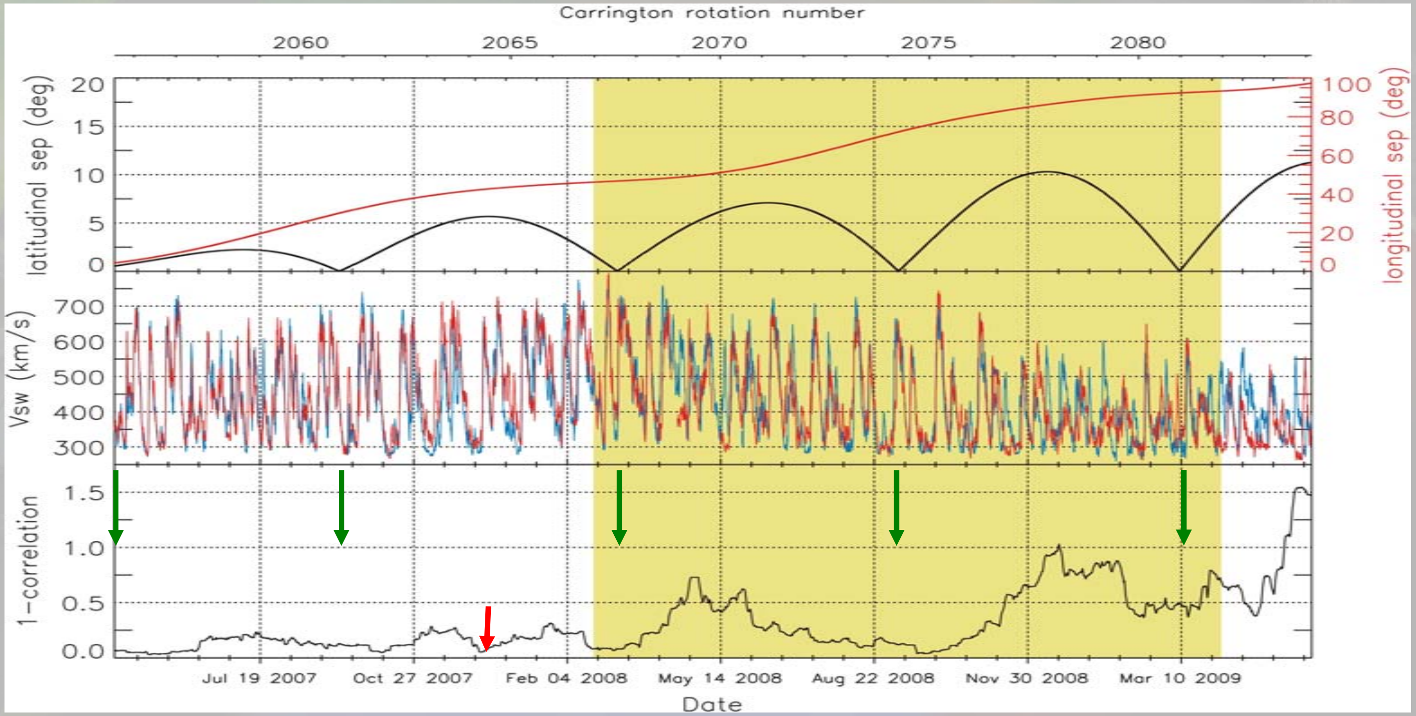


Importance of latitudinal separation

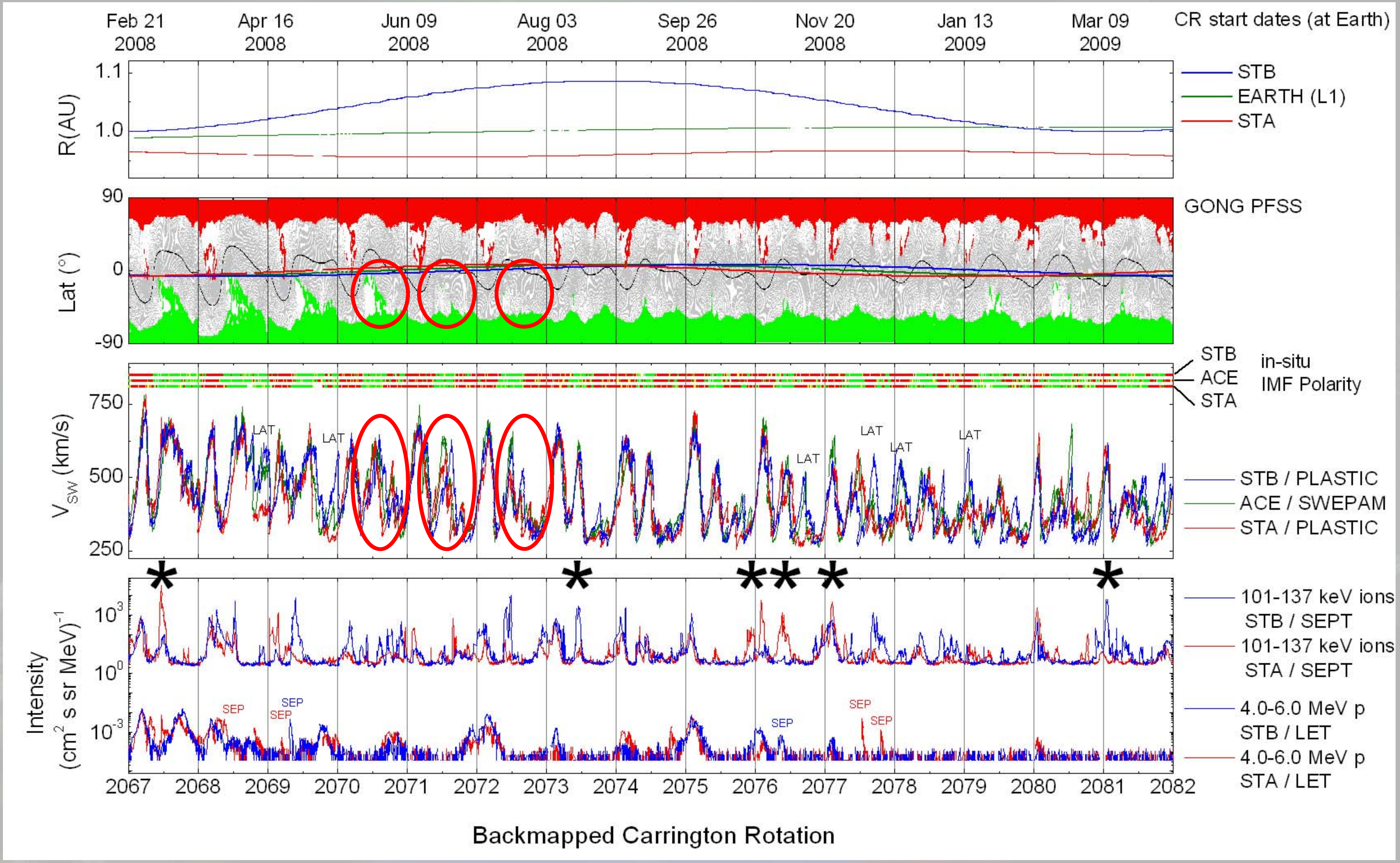


Importance of latitudinal separation

- STA and STB Vsw measurements have been time-shifted to L1 and the correlation coefficient calculated using a running 27-day window (approach similar to Opitz et al, 2009). This allows the study of the correlation of solar wind structures observed by the two STEREO as the long. and lat. separations vary
- Tendency to better correlation when $\Delta\theta \rightarrow 0$ ↓
- Slowly decreasing trend as the longitudinal separation increases.
- Occasionally highly correlated structures are found during periods of relatively large latitudinal separation (e.g. Dec. 2007) ↓



Coronal hole changes



Coronal hole changes

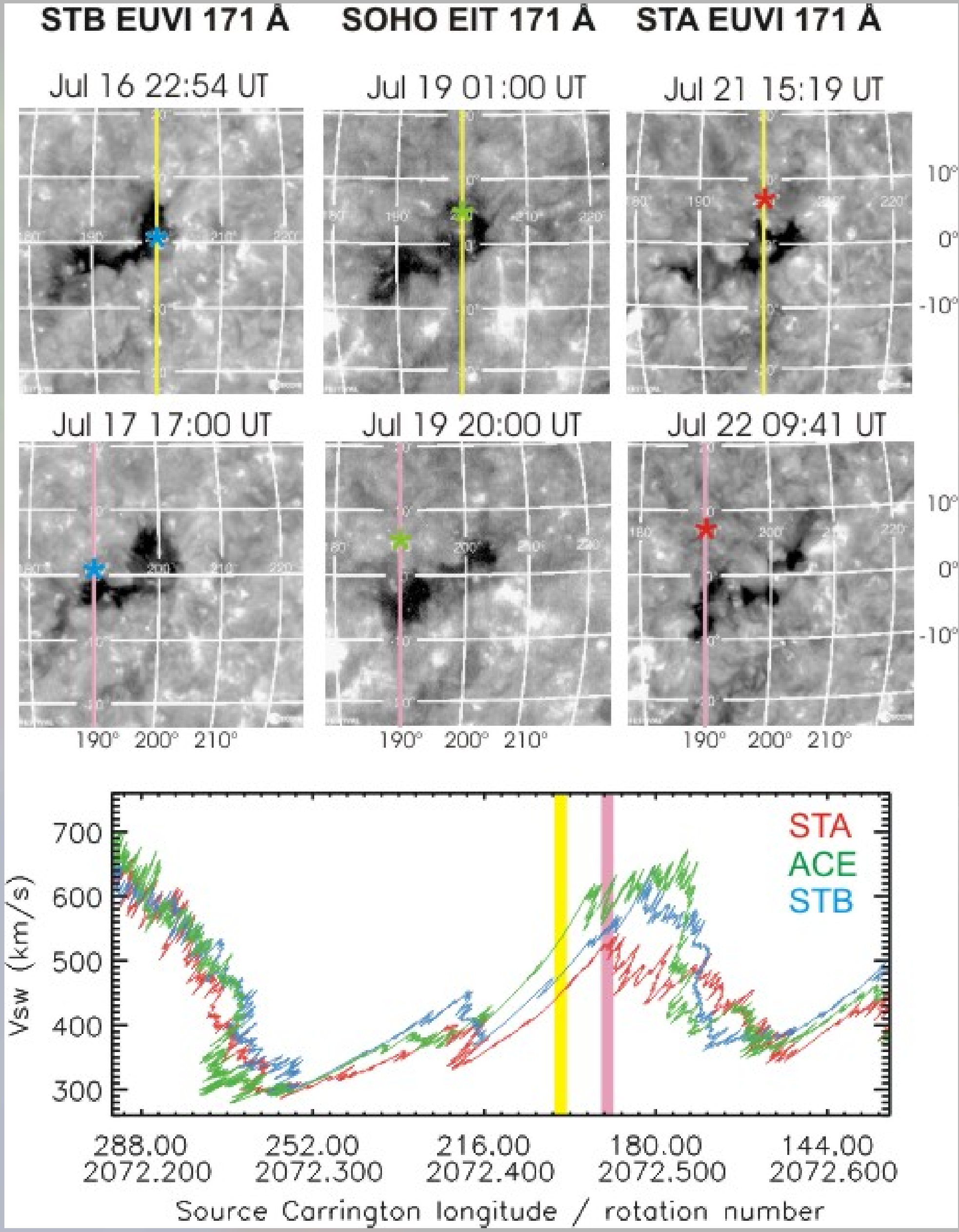
- Coronal hole changes produce changes in the HSS observed in-situ (e.g. Broussard, 1978)

⇒ Changes in the shape or magnetic topology of coronal holes give rise to changes in the SIR structure at 1 AU

  – This effect is easy to track in the long term (>1 CR), e.g. CR 2070

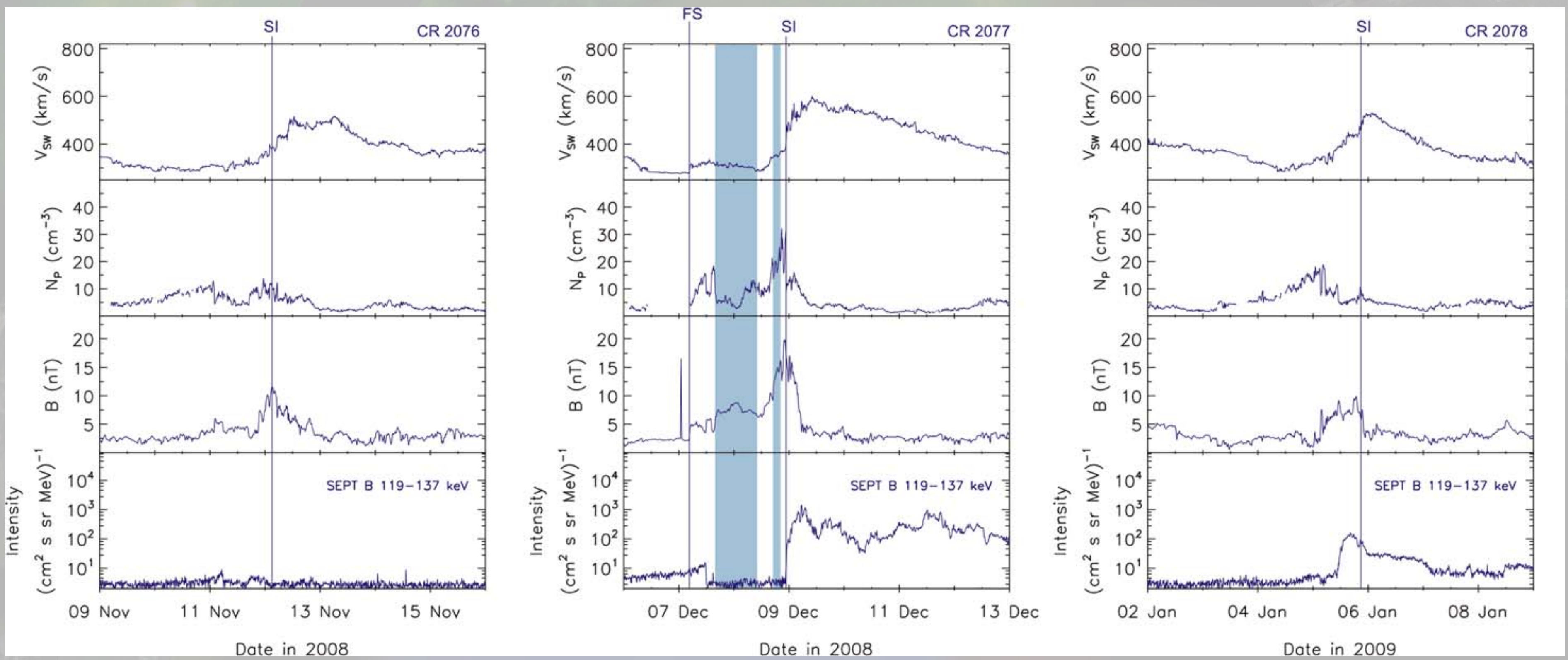
  – But difficult to study in the short term (<1 CR) using multi-s/c data

- Example: CR 2072 (July 2008). Event associated with a near-equatorial coronal hole extension with positive polarity



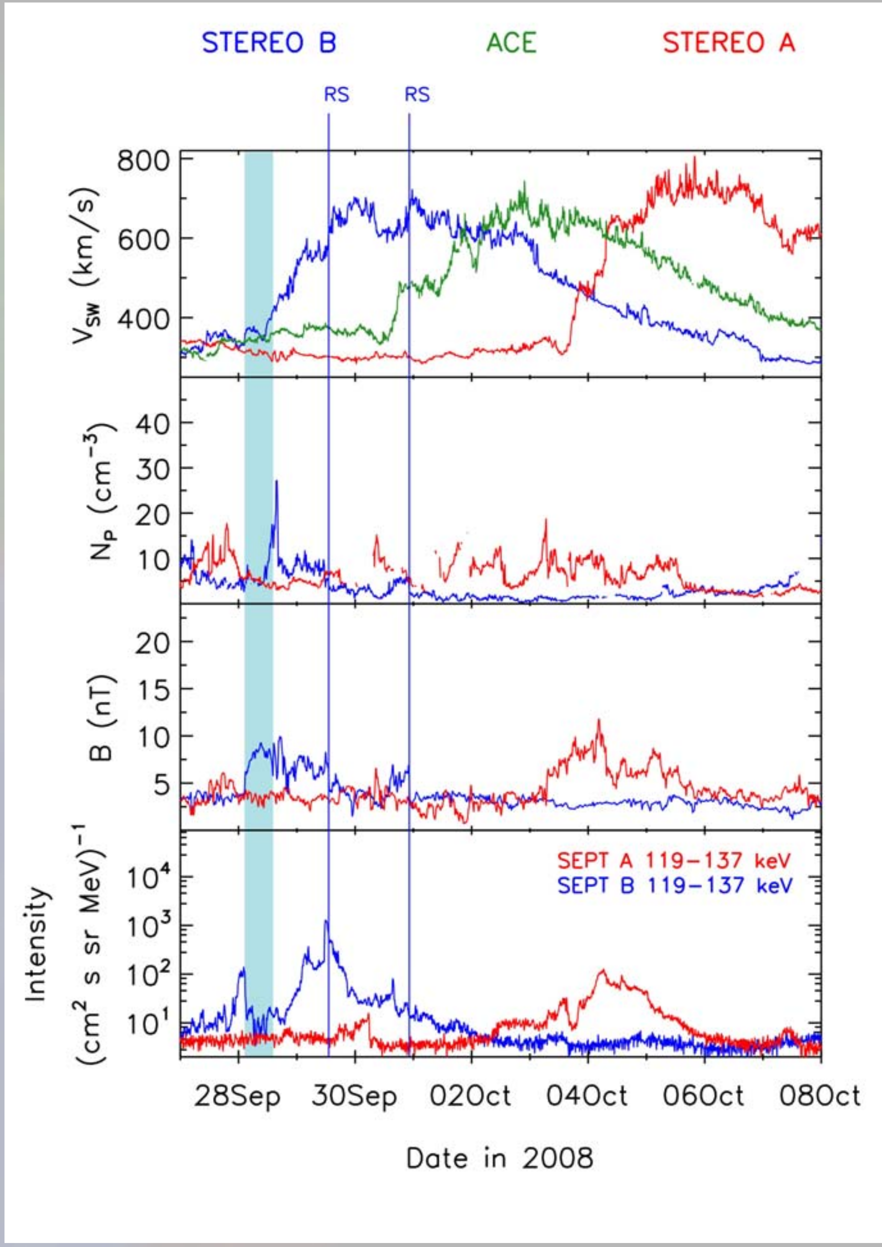
Possible influence of interplanetary transients

- Slow ICMEs or small scale transients are frequently found in the slow solar wind preceding high-speed streams at 1 AU (e.g. Kilpua et al, 2009)
- Example 1: CIR event observed by STB on Dec 7-13, 2008 (CR 2077)
  - No ICME signatures near the CIR for CR 2076 and 2078.
  - Two ICMEs during CR 2077. Higher density and magnetic field peaks. Enhanced 119-137 keV ion increase
  - However, the HSS was faster and broader during CR 2077 → unclear whether the ICME plays some role in the enhanced compression and particle acceleration. No multi-sc observation due to latitudinal separation.



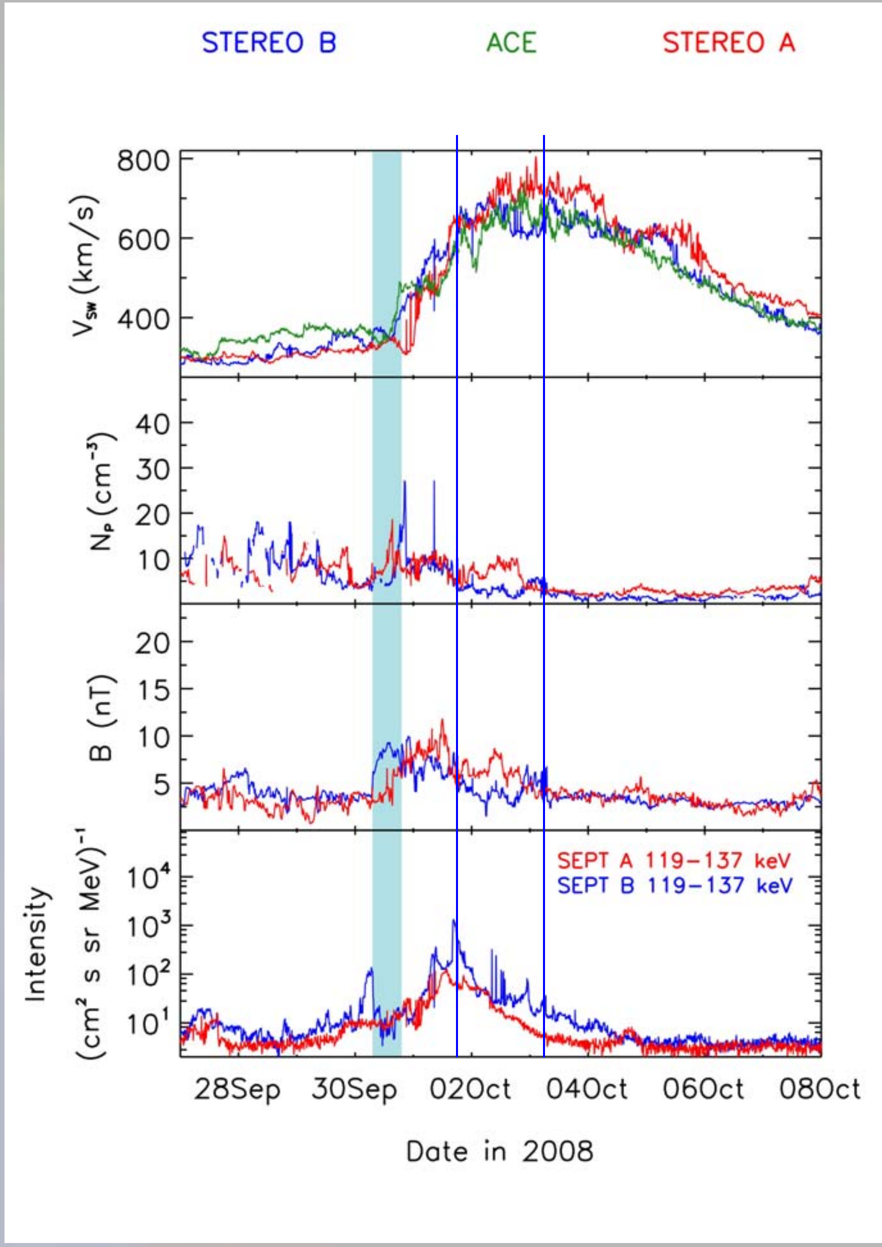
Possible influence of interplanetary transients

- Example 2: Sep 2008 Event
- $\Delta\theta$ = 3.8º → both STEREO observed very similar structures for both, plasma and energetic ions

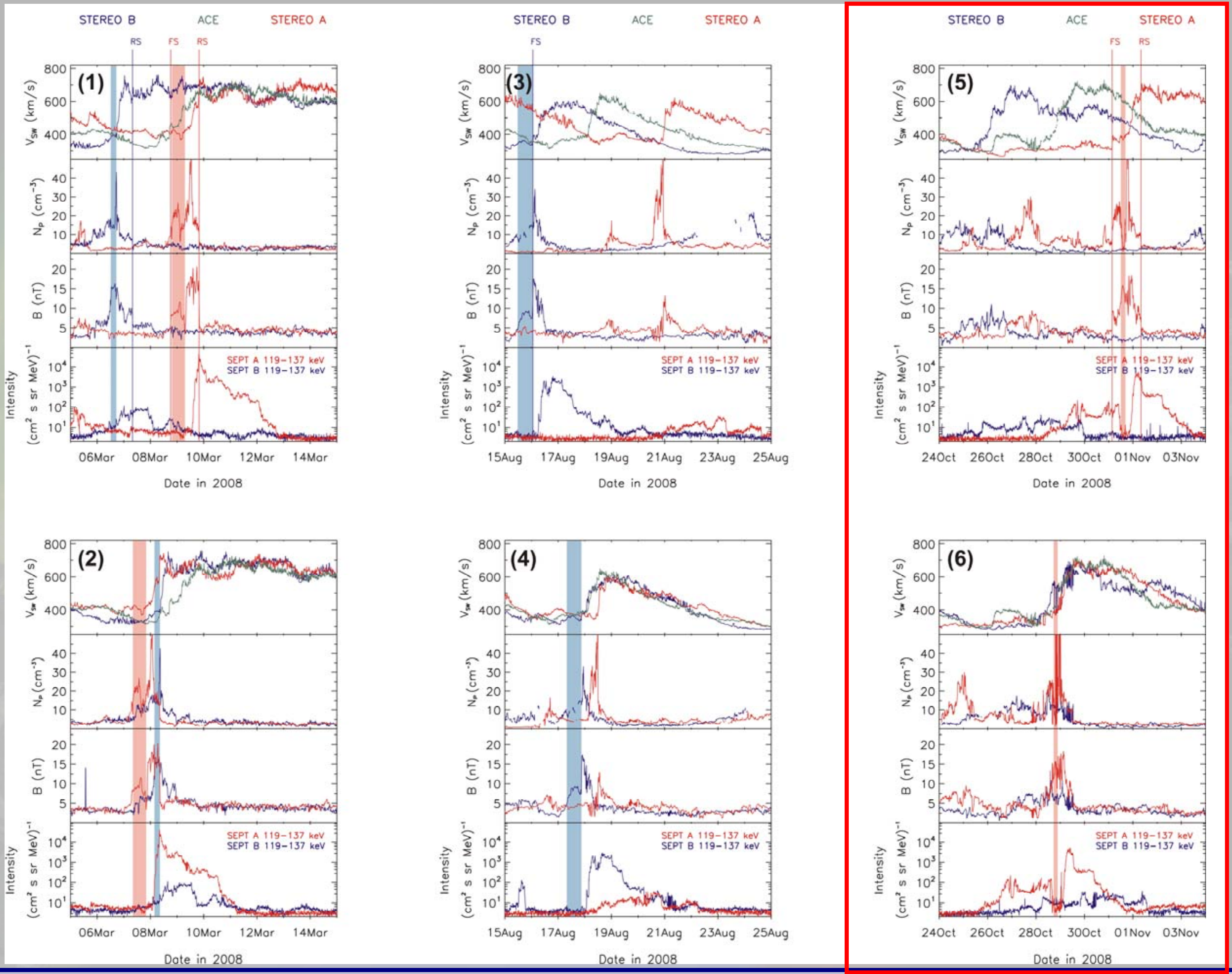


Possible influence of interplanetary transients

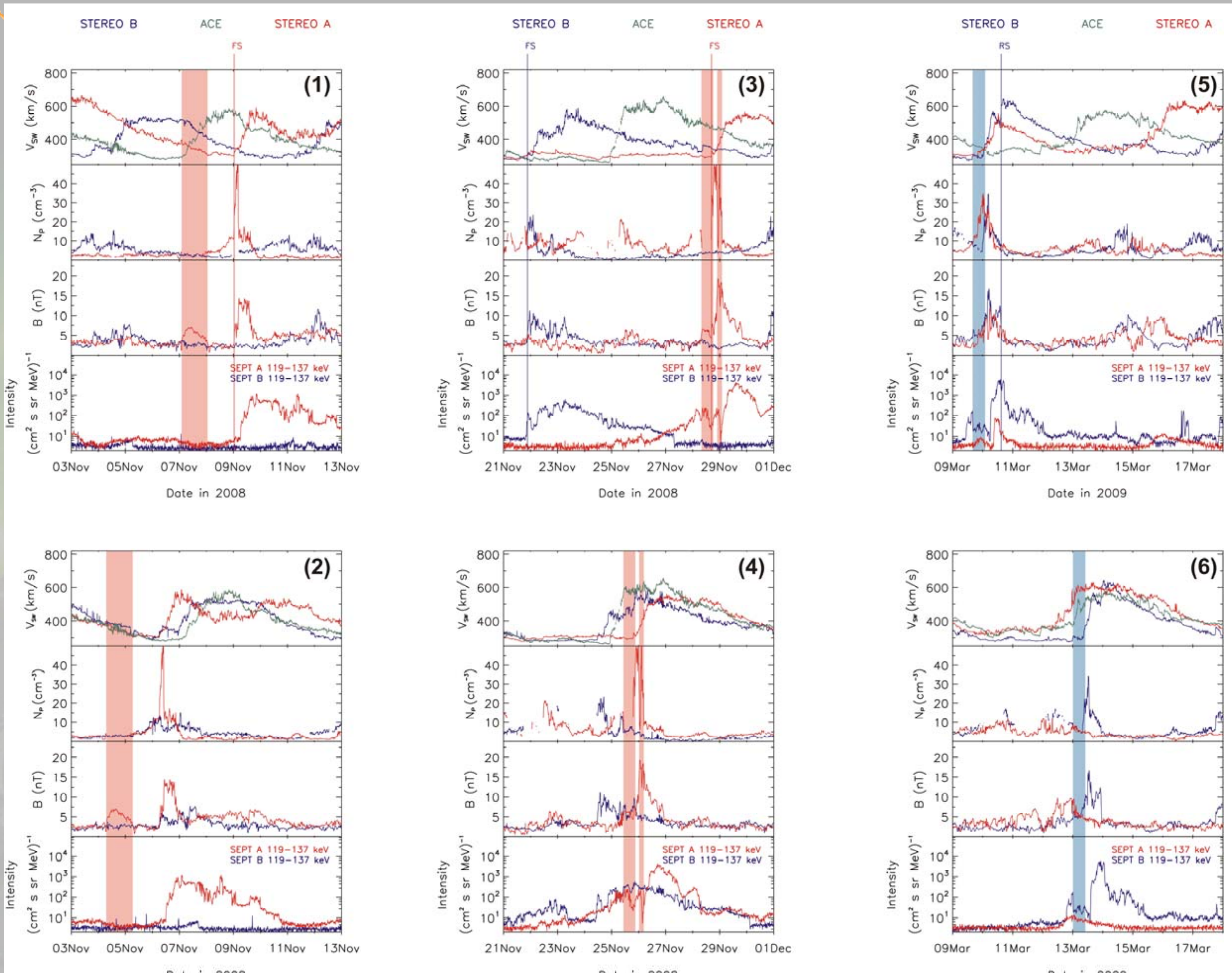
- Example 2: Sep 2008 Event
- Δθ = 3.8º → both STEREO observed very similar structures for both, plasma and energetic ions
- STA: no ICME, no shocks
- STB: ICME in front of the high-speed stream (Sep 28 02:30-14:00 UT) . SI at 15:42 UT. Two RS
- STB observed enhanced 119-137 keV ions during the absolute intensity max, in coincidence with an in-situ reverse shock



A search for ICME effects on CIR ion increases

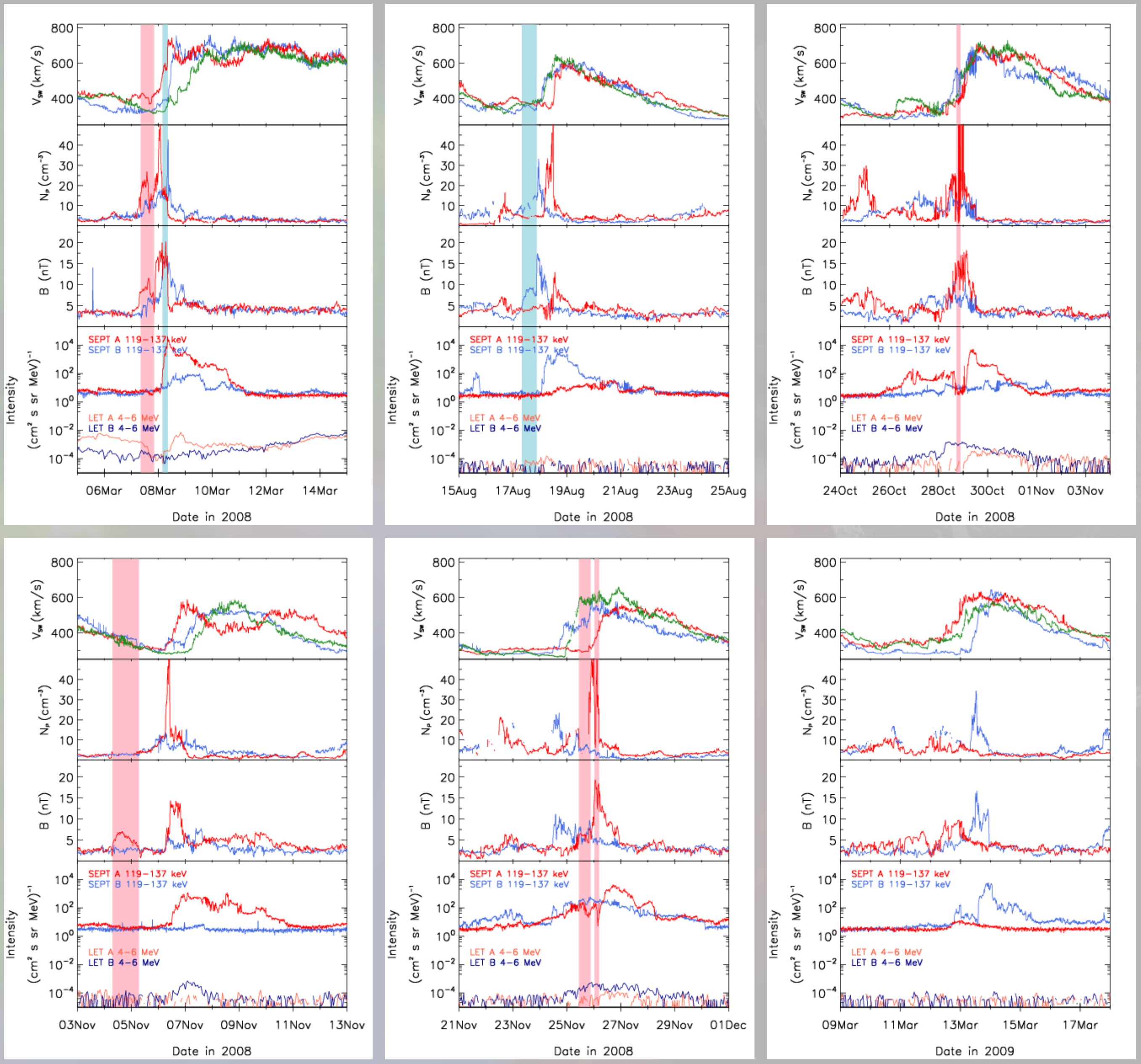


A search for ICME effects on CIR ion increases



Behavior at ~MeV energies

- Few MeV ions remain most of the times unaffected
- Higher flux normally at STB
- Connection to distant shock

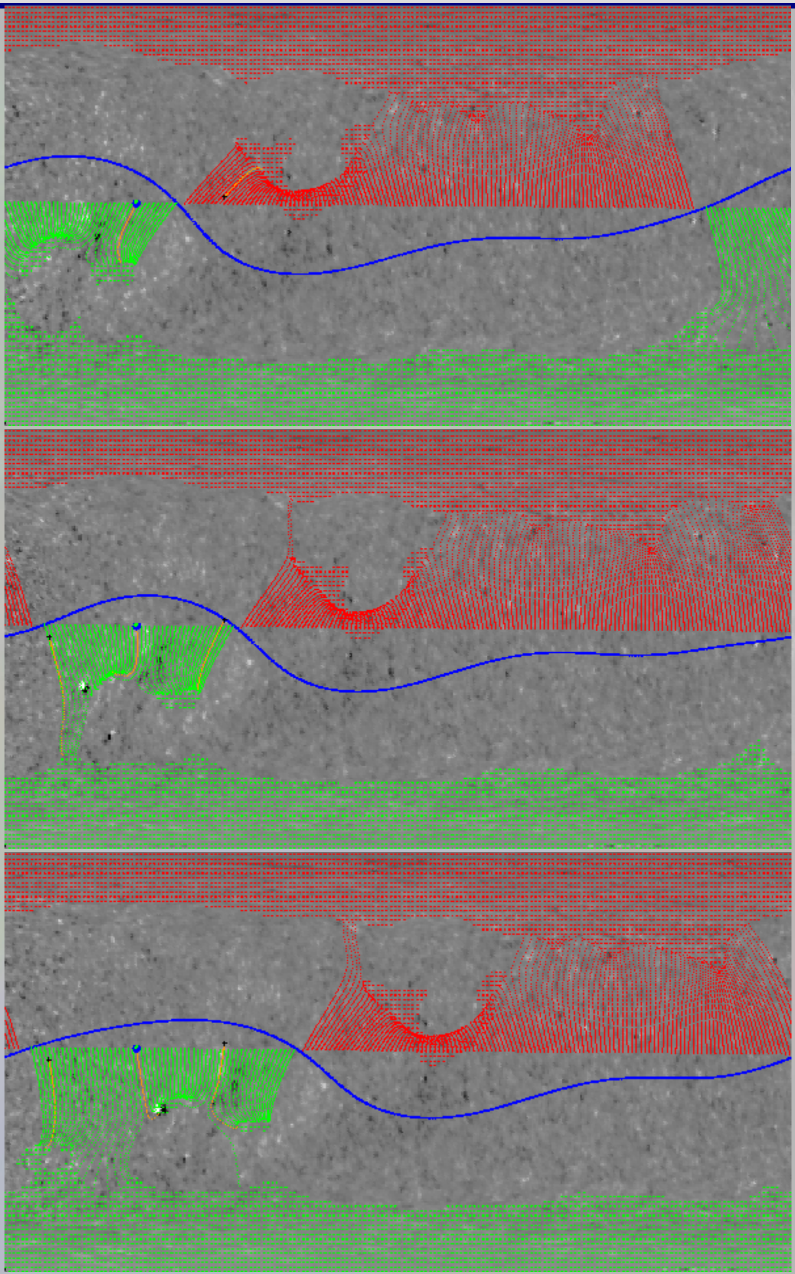


Conclusions

- **Heliographic latitudinal separation is a common source of discrepancies in the CIR structure observed by different spacecraft**. This effect can be significant even for separations of a few degrees but its importance varies from case to case depending on the proximity to the latitudinal boundaries and also on the morphology of the coronal hole.
- Discrepancies can be still present excluding pure spatial effects (latitudinal effects, radial gradients) $\Rightarrow$ **CIRs are not ideal stationary structures showing identical characteristics at two spacecraft** separated by co-rotation times of several days. The sources of temporal variations can be found at the Sun (coronal hole evolution) or in the interplanetary medium (interaction with transient structures in the slow wind).
- We presented **several cases where the presence of an ICME in the vicinity or embedded in the CIR for one spacecraft is accompanied by enhanced ~100 keV ion acceleration**.
  - ICME passage coincides normally with particle decreases (closed magnetic topology)
  - Stronger acceleration when higher B in the CIR compared to the ICME.
  - Several MeV ions mostly unaffected, higher intensities normally at STB $\Rightarrow$ MeV protons come mainly from CIR-shocks located beyond 1 AU $\Rightarrow$ importance of local phenomena for the acceleration of ~100 keV ions during CIRs.
  - Theoretical modeling approach for ICME+CIR regions would allow further progress.

Additional slides

Coronal hole changes (GONG PFSS, July CH)



Abstract

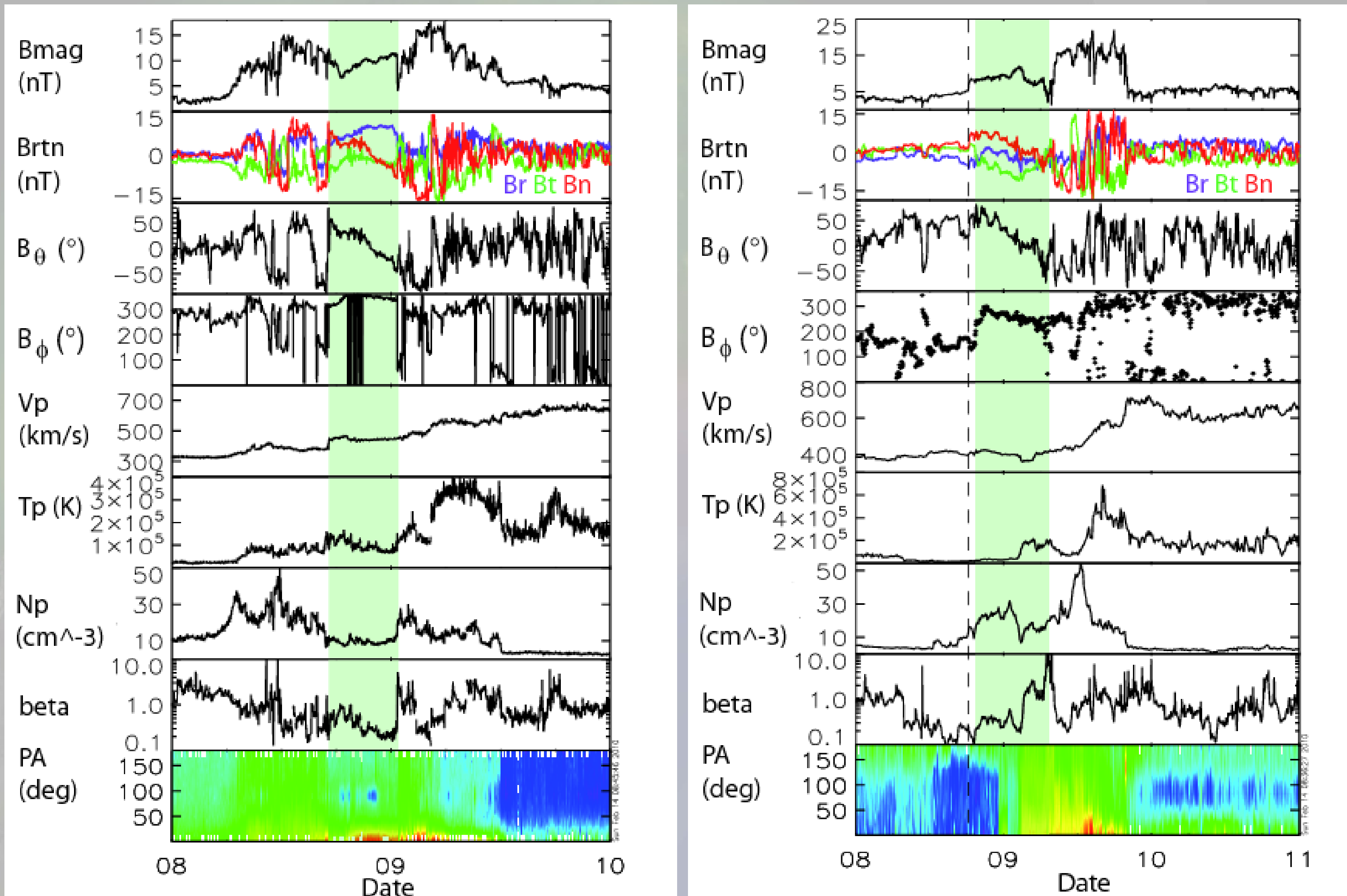
In the absence of solar activity, Co-rotating Interaction Regions (CIRs) are a prevailing source of energetic ions observed near 1 AU. The twin STEREO spacecraft launched in October 2006, together with other near-Earth spatial observatories, offer an excellent platform for multi-point studies of CIRs. Since the spacecraft are located at different longitudes, time-shifting and backmapping techniques are needed in order to compare plasma and particle data measured by different spacecraft at different times but associated with the same CIR. The analysis of CIR events during the extended quiet period between February 21, 2008 and April 5, 2009 (Carrington rotations 2067 to 2082) provides evidence that CIR-associated energetic ions frequently show significant differences, particularly at sub-MeV energies. We found discrepancies in the structures observed by different spacecraft which cannot always be attributed to the latitudinal separation between the spacecraft or to changes in the coronal hole which generates the high-speed stream. We present several cases where these differences are linked to the presence of Interplanetary Coronal Mass Ejections (ICMEs) or small-scale interplanetary transients in the vicinity or embedded within the CIR. Evidence of the possible role of ICME-CIR interactions as sources of temporal variations in the CIR-associated ion increases are presented and discussed.

Outline

Event Dates (B)	Approx. Lat sep(°)	Approx. Long sep (°)	s/c which observes ICMEs
March 6-10, 2008	<0.1	46 (3.1 days)	A & B (different)
Aug 15, 2008	3.1	67	B
Sep 28, 2008	3.2	76	B
Oct 31, 2008	7.7	81	A
Nov 7, 2008	8.4	82	A
Nov 25-26, 2008	9.8	85	A
Dec 7-8, 2008	10.3	86	B
March 13, 2009	0.8	92 (6.4 days)	B

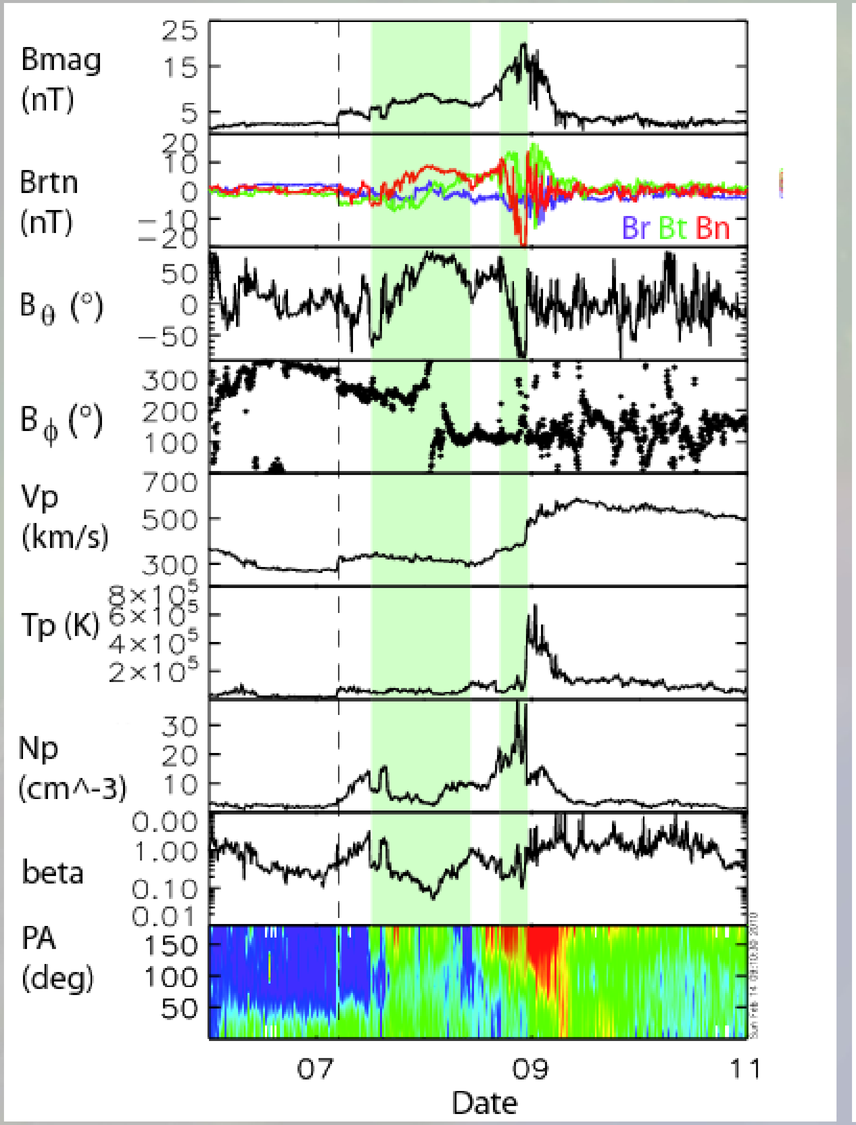
ICME signatures

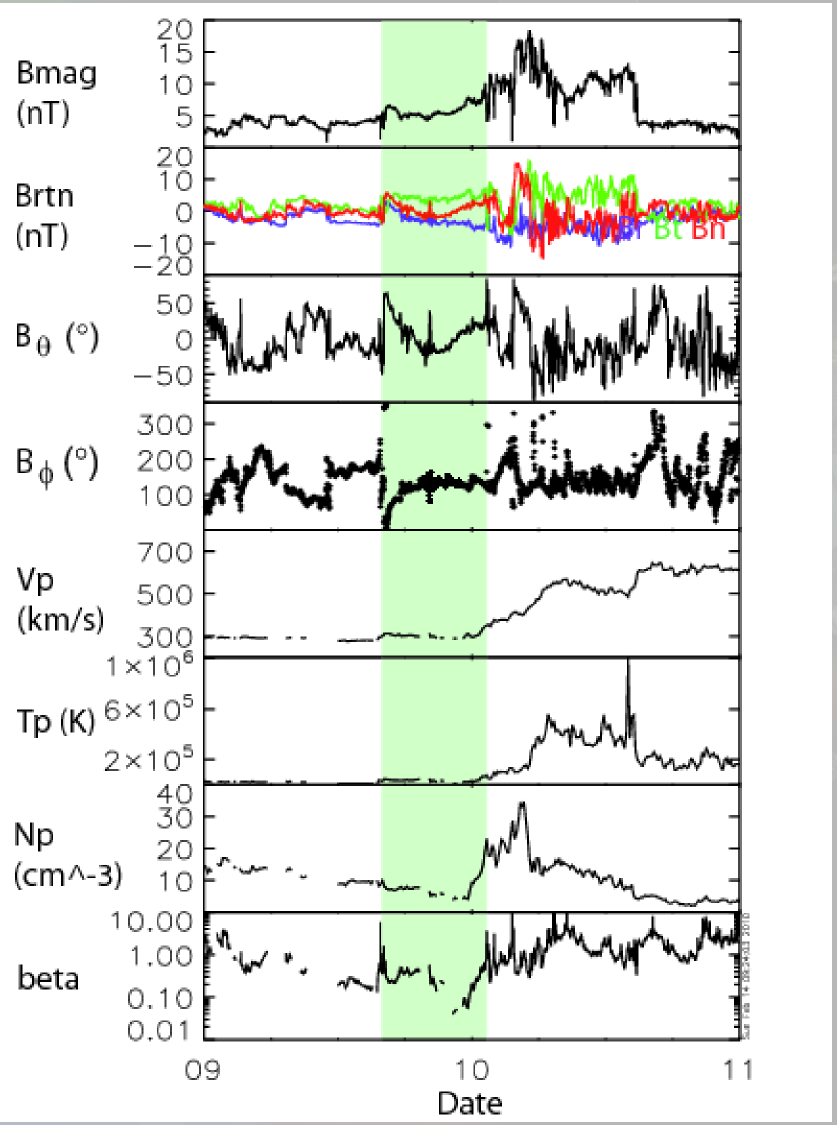
- March 2008



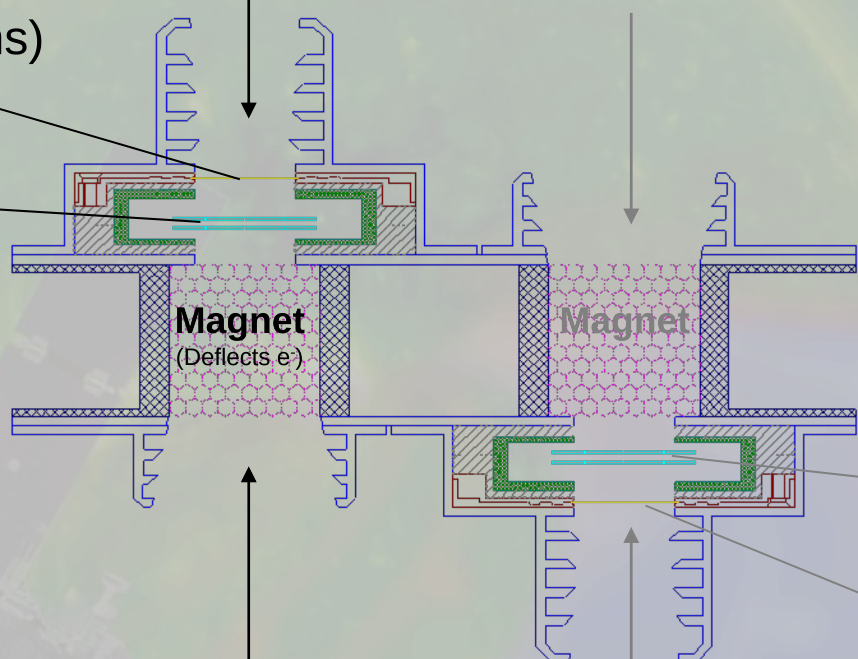
ICME signatures

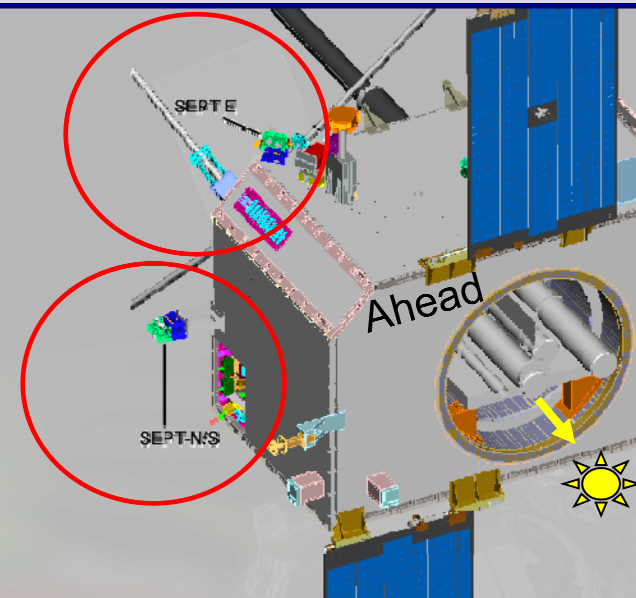
- December 2008 and March 2009





STEREO/SEPT (Solar Electron Proton Telescope)



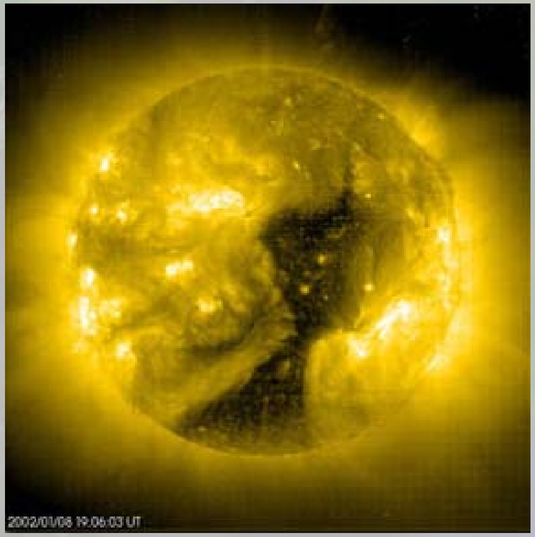


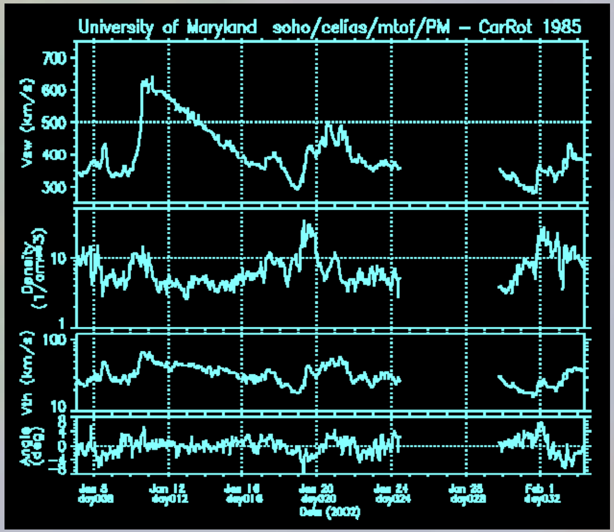
8 Telescopes per s/c: 2×North, 2×South, 2×Sun (along IMF), 2×Anti-Sun (along IMF)

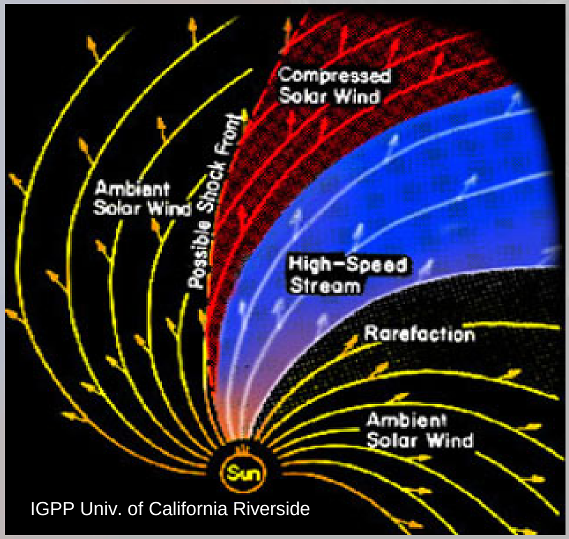
(Old slides)

Corotating Interaction Regions

- Coronal holes → High speed solar wind streams → Compression regions in the IP medium
- Radial evolution → eventually forward-reverse shock pairs bounding a co-rotating interaction region (CIR) are formed (typically beyond 2 AU)
- CIR-associated shocks → Particle acceleration (up to 10-20 Mev ions and hundreds of keV electrons)
- Stream Interface: sharp boundary separating fast and slow wind within a CIR, → characteristic in-situ signatures (density drop, temperature rise, flow shear, compositional differences…)

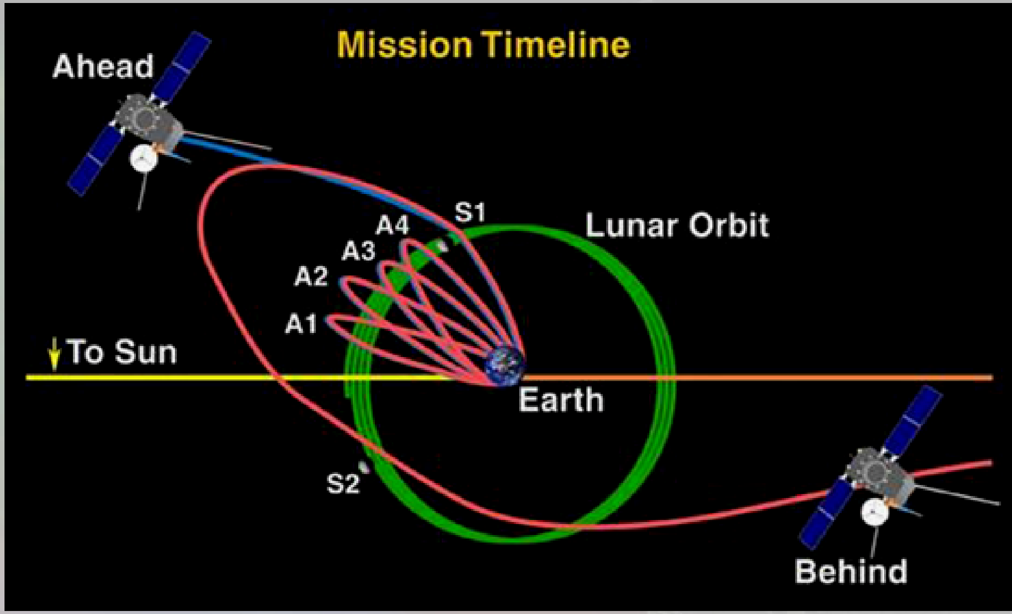


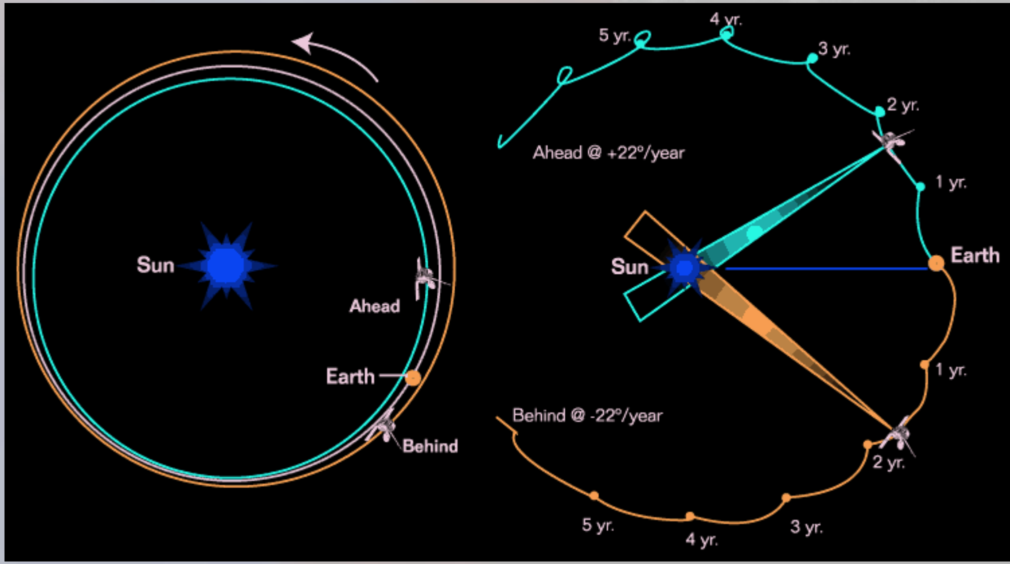




IGPP Univ. of California Riverside

- Launched on Oct 25, 2006
- SEPT B and A switched-on on Nov. 13 and 14, 2006
- Separation after lunar swingby S1 on Dec. 15, 2006
- SEPT-A doors opened on Dec. 14, 2006
- SEPT-B doors opened on Jan. 16, 2007
- Final orbit:
  - Near ecliptic, following Earth (0.95-1.09 AU)
  - Growing azimuthal separation 22°/year
  - Heliographic latitude from -7.3 to +7.3 degrees

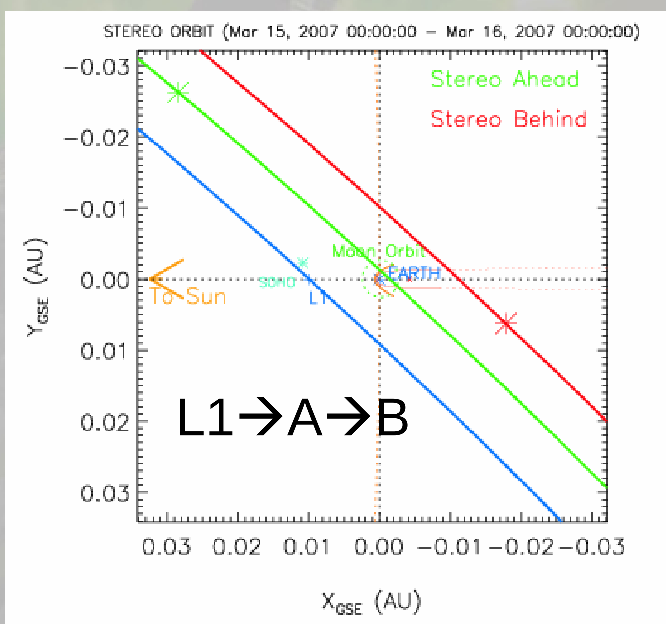


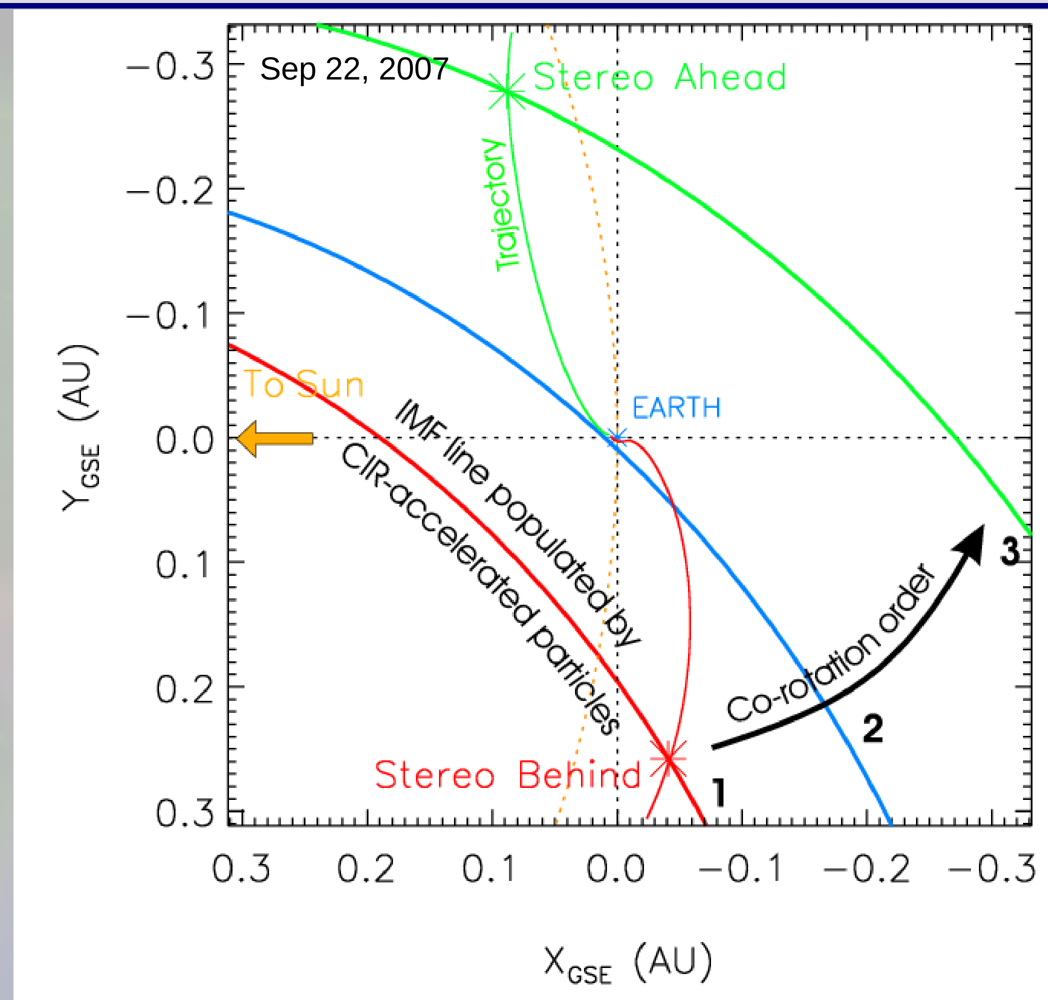


- Co-rotation time:

$$t_B - t_A = \frac{\phi_B - \phi_A}{\Omega^S_{SUN}} + \frac{r_B - r_A}{V_{SW}}$$

- Most of the time the sequence is B→L1→A
- For the early phase of the orbit, the western s/c can be earlier than the eastern s/c





Ballistic Backmapping

- The progressive delay A-B is consistent with the corotating nature of the events. Overall reconstruction is possible using Ballistic backmapping:

$$\Delta\phi = \frac{\Omega(r - r_0)}{V_{SW}}$$