National Observatory of Athens (NOA)

INSTITUTE FOR ASTRONOMY, ASTROPHYSICS, SPACE APPLICATIONS & REMOTE SENSING

National Observatory of Athens

IAASARS

Solar Energetic Particle Origin, Acceleration and Transport in the Heliosphere

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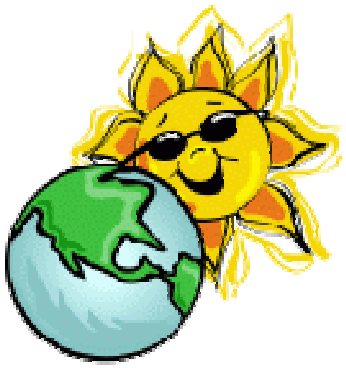


6th Workshop

" Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"

Collaborators

The SEPServer consortium
The COMESEP Consortium

A.J. Tylka, GSFC, NASA, USA
B.N. Dresing, B. Heber, A. Klassen, CAU, Germany
R. Gómez-Herrero, University of Alcala, Spain
W. Dröge and Y. Kartavykh, Universität Würzburg

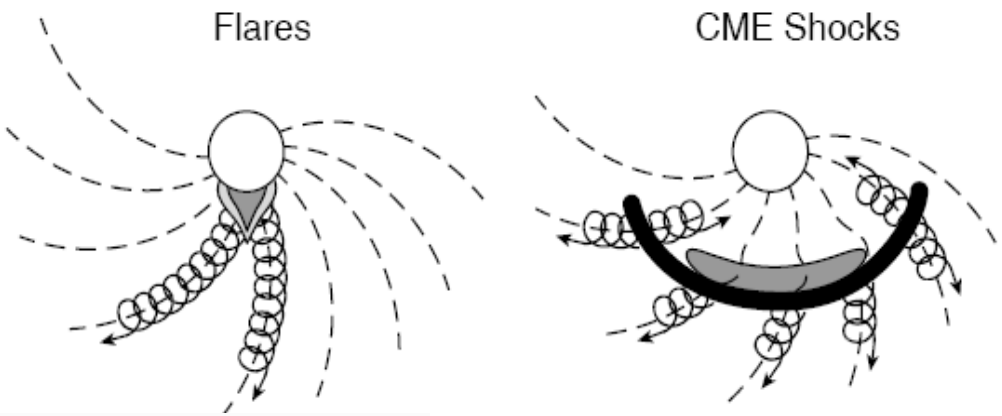
Outline

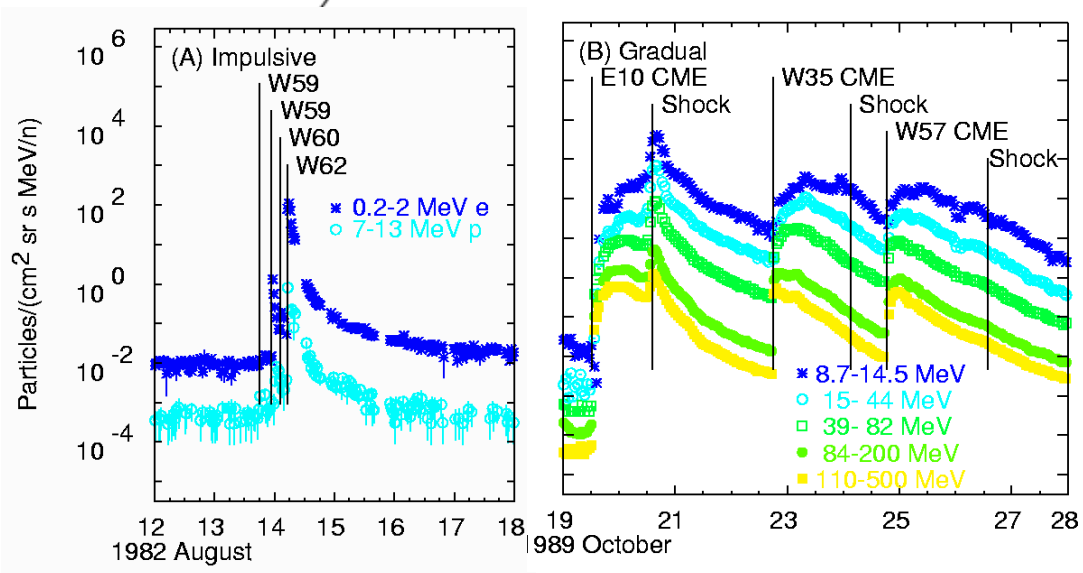
- **Solar Energetic Particles**

- **Research Results on the SEP Origin, Acceleration & Transport**

  - ***A Flare Contribution to Large Gradual SEP Events?***
  - ***Inconsistency of path lengths traveled by e and p***
  - ***Case study 13 July 2005 : First Comparative Results (SEPs, EM, Modeling) of the SEPServer project***
  - ***Release Timescales of SEPs in the Low Corona***
  - ***Statistical survey of wide-spread events in the Heliosphere (STEREO & ACE)***

Two Sources of SEPs





Impulsive events	Gradual Events
Flares	CMEs
e, ^{3}He, heavy ions	p
~10^2/yr at solar max	~10's/yr at solar max
~ hours	~ days

✓ This is the "standard" classification of SEPs with respect to their solar source.

Reames, 1999; 2013

Research Results on the

SEP Origin, Acceleration & Transport

A Flare Contribution to Large Gradual SEP Events?

A large body of evidence points to shocks driven by fast CMEs as the dominant accelerators in large, gradual SEP events.

In many of these events, Fe/O above a few MeV/nuc shows strong enhancements at the start of the event.

(1) Some researchers (e.g. Cane et al. 2003) attribute these initial enhancements to a direct flare contribution to gradual SEP events, similar to what is observed in small, impulsive events.

If this interpretation is correct, we expect to see enhanced Fe/O only when the observer is magnetically-connected to the flare site.

(2) Others (e.g., Tylka et al. 1999, Ng et al. 1999; Mason et al. 2006) attribute the initial enhancements to transport effects, i.e., Fe/O can show an initial enhancement provided that:

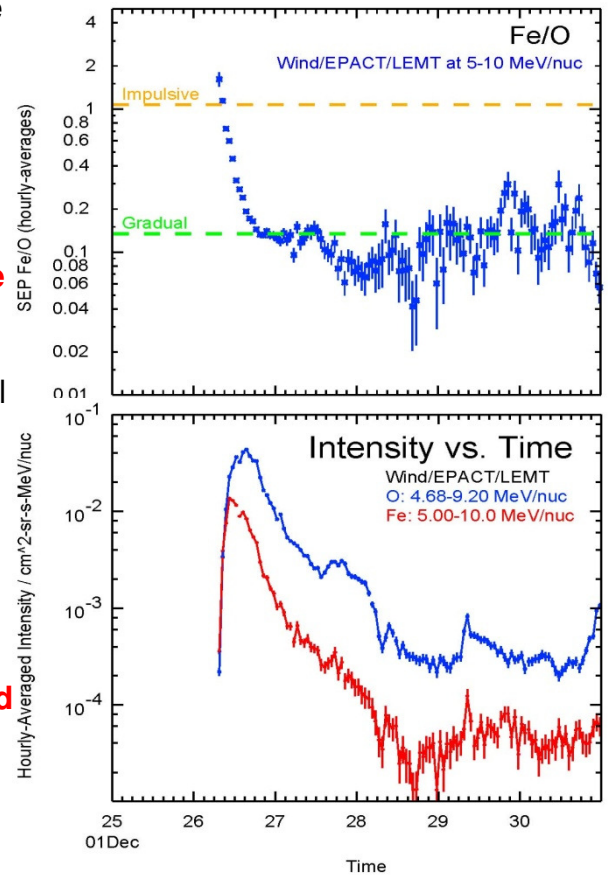
$$(M/Q)_{Fe} > (M/Q)_O$$
$$\lambda_{mfp} < L_{path}$$

If this interpretation is correct, we expect to see enhanced Fe/O even on widely-separated spacecraft, both of which cannot be magnetically connected to the flare site.

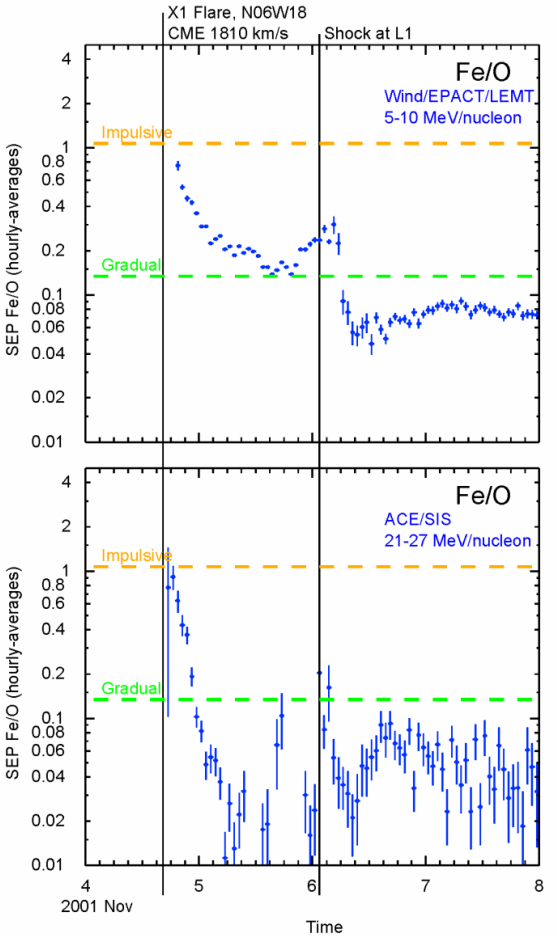
(3) Observation of the same event from widely-separated spacecraft thus provides a means of distinguishing between these two interpretations.

2001 December 26 GLE

Flare M7.1 at W54; CME speed 1406 km/s



Combination of Flare and Shock Population?



Cane et al., 2003

Based on O and Fe intensity-time profiles, Cane et al. 2003 divided large SEP events into three groups:

Group 1: Flare-dominated

Group 2: Shock-dominated

Group 3: Combination

"The November 4, 2001 event typifies … the third grouping. The profiles are basically a combination of those of the previous two groupings i.e., *an Fe-rich component at the time of the flare* and later, a shock-associated component with a lower Fe/O ratio."

Cane, Richardson and von Rosenvinge, 2010

A Flare Contribution to Large Gradual SEP Events?

A large body of evidence points to shocks driven by fast CMEs as the dominant accelerators in large, gradual SEP events.

In many of these events, Fe/O above a few MeV/nuc shows strong enhancements at the start of the event.

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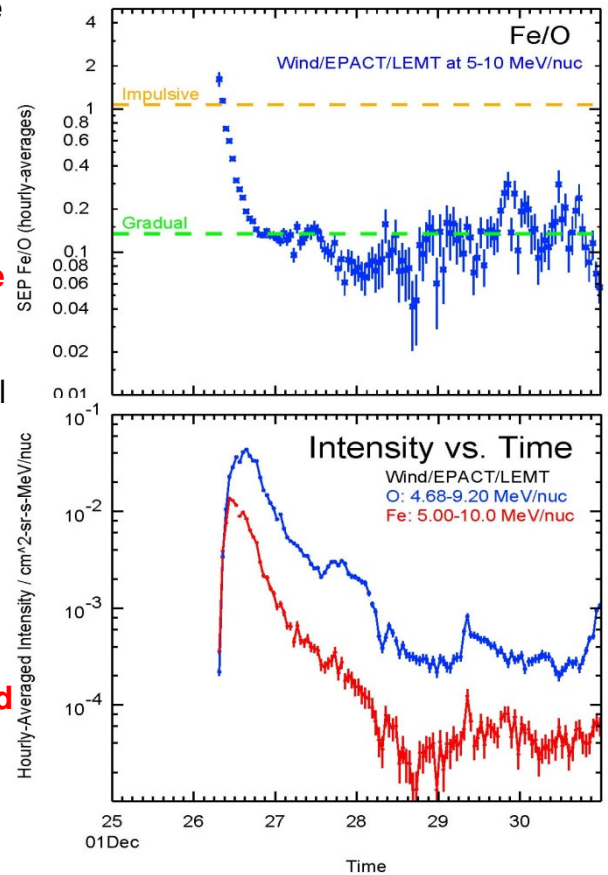
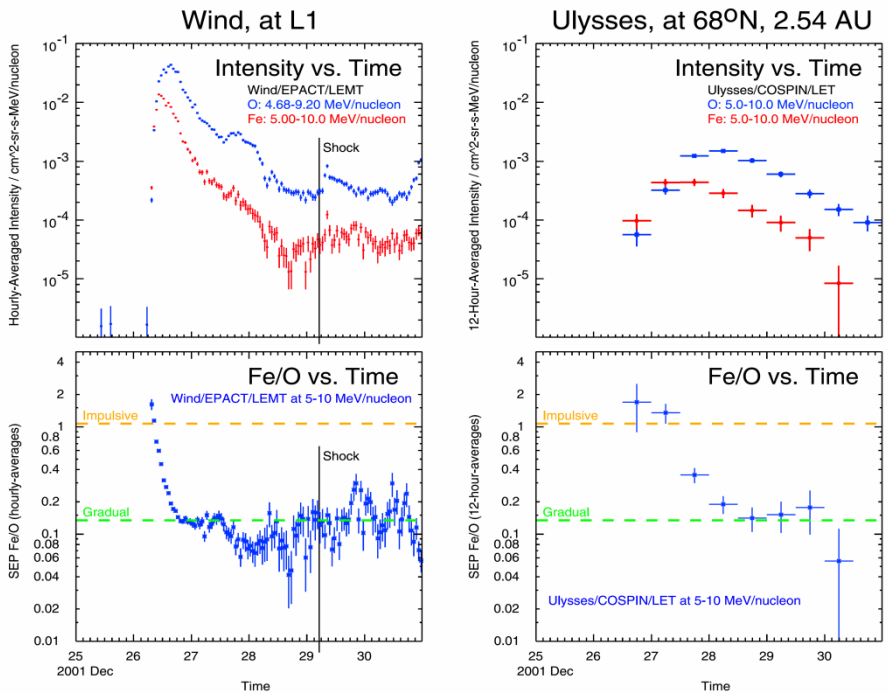
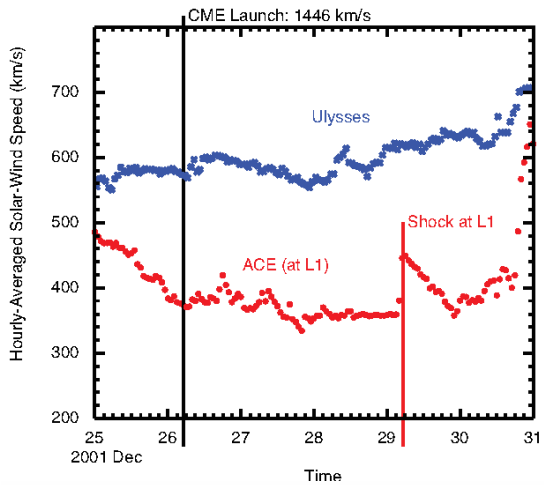
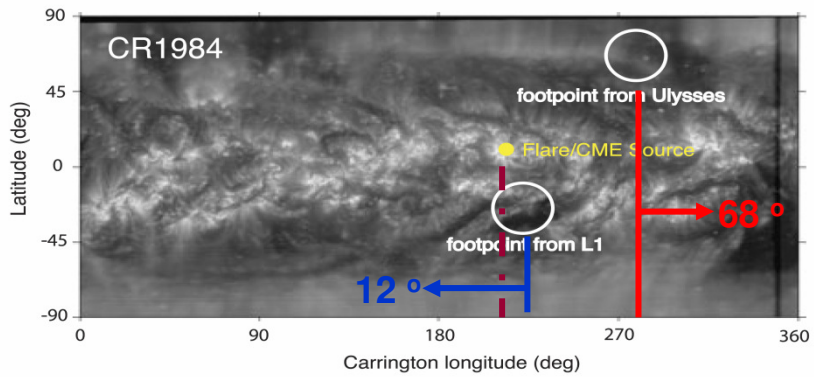


The December 26, 2001 case study





- Ulysses resides in a high speed stream whereas L1 is not.



- Associated flare at W54º heliolongitude → *see a direct flare component ?*

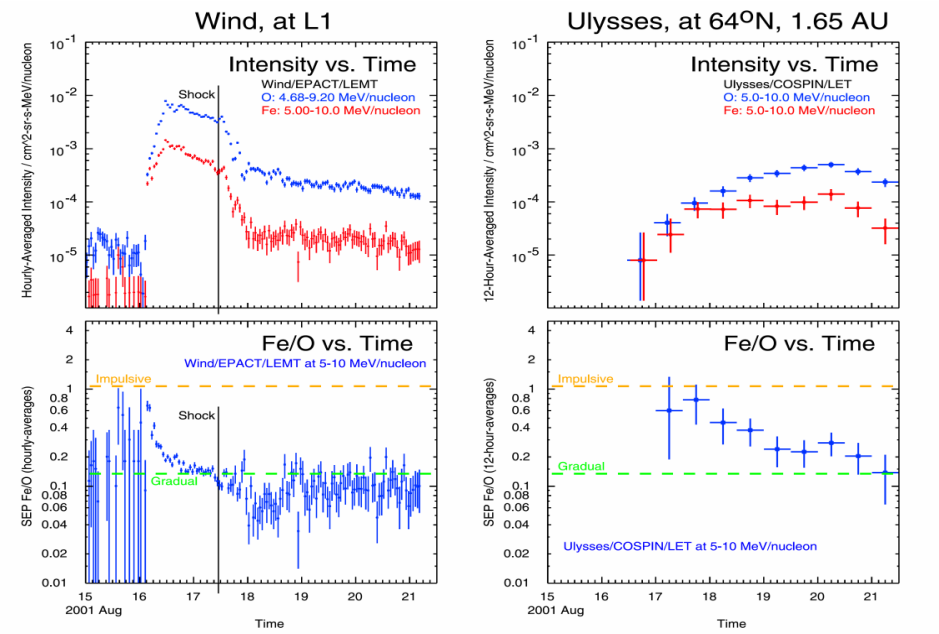
- Ulysses at R= 2.54 AU, N68º heliolatitude

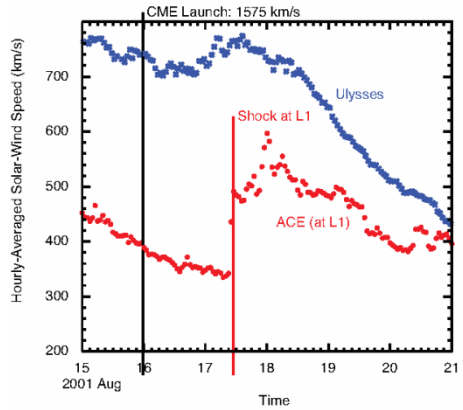
- Fe reaches its maximum before the O intensity just as observed at L1.

- Evolution in Fe/O like that at L1 evident.

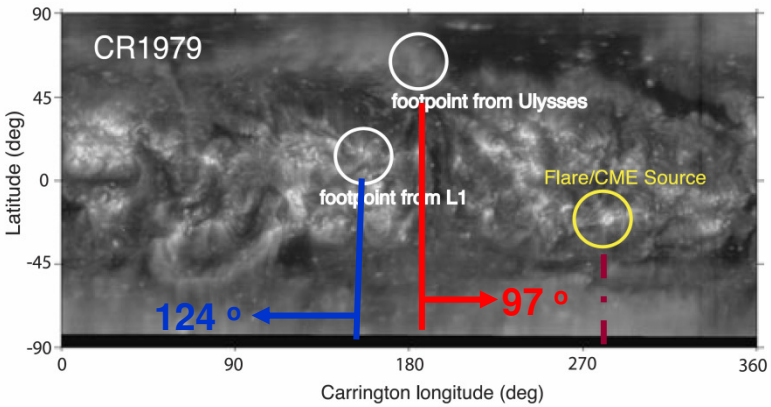
- Only ***L1*** is well-connected.

The August 16, 2001 case study





- Ulysses and L1 at different SW streams for at least 30 hrs.



- Well Known 'backside' event associated with a source region at W180-195 *[Cliver et al, 2005]*

- Ulysses at R= 1.65 AU, N64º heliolatitude

- Fe reaches its maximum before the O intensity just as observed at L1.

- Evolution in Fe/O like that at L1 evident.

- Neither L1 nor Ulysses well-connected.

Tylka, Malandraki et al., 2014

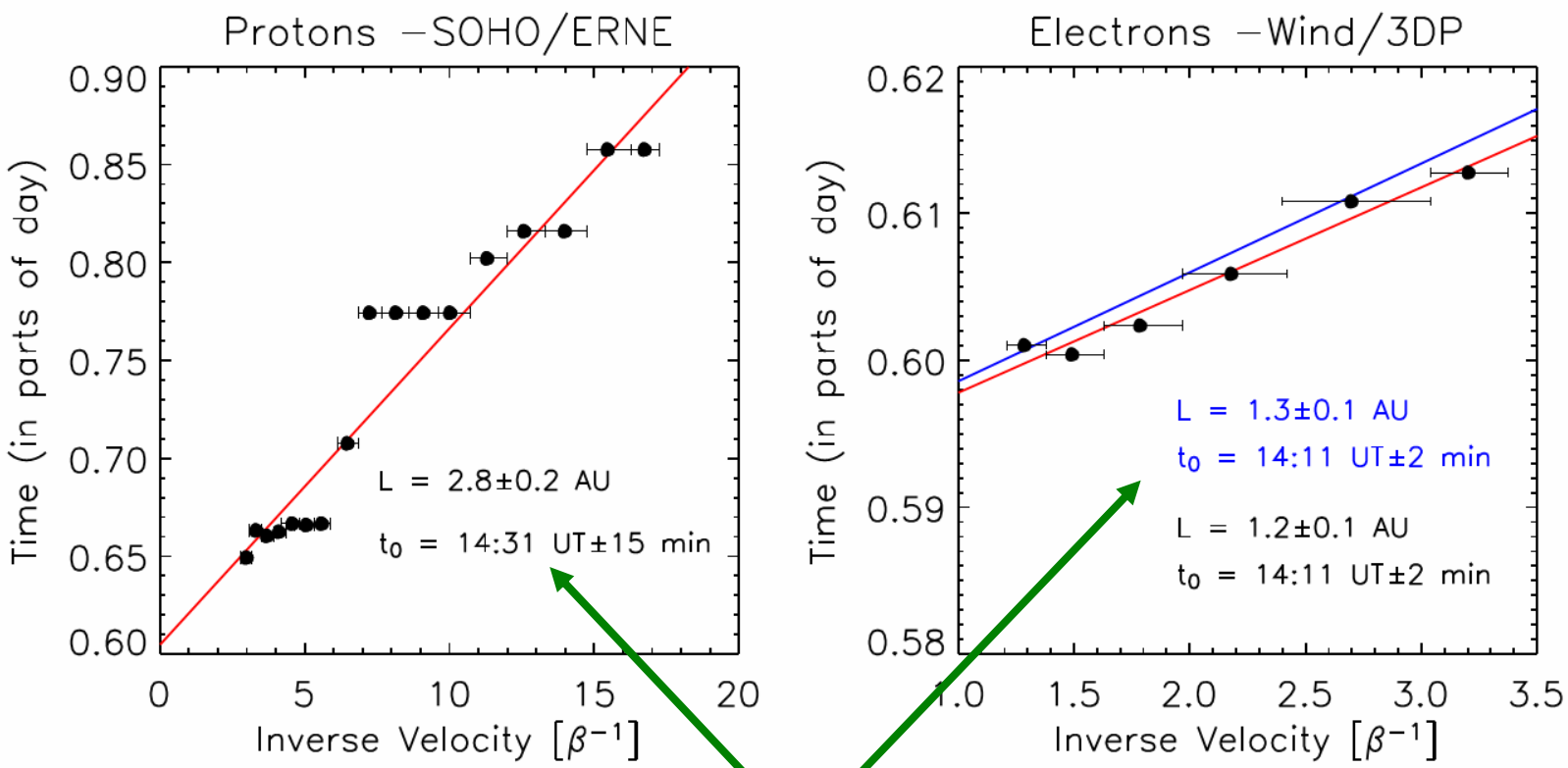
Initial Fe/O enhancements

Interpretation	Ref.
Direct Flare Origin – Hybrid Events	Cane et al., 2003; Cane et al., 2010
Rigidity Dependent Transport Effect	Ng et al., 1999 Mason et al., 2006 Tylka et al., 2013

✓**Future iron charge state measurements could be used to address the issue of a direct flare contribution component.**

✓**Given that initial Fe/O enhancements are seen at widely-separated s/c even when one or both is not magnetically well-connected to the flare site it is likely that the initial Fe/O enhancement is generally a transport effect!**

(In) Consistency of Path Lengths Travelled by *e* and *p*

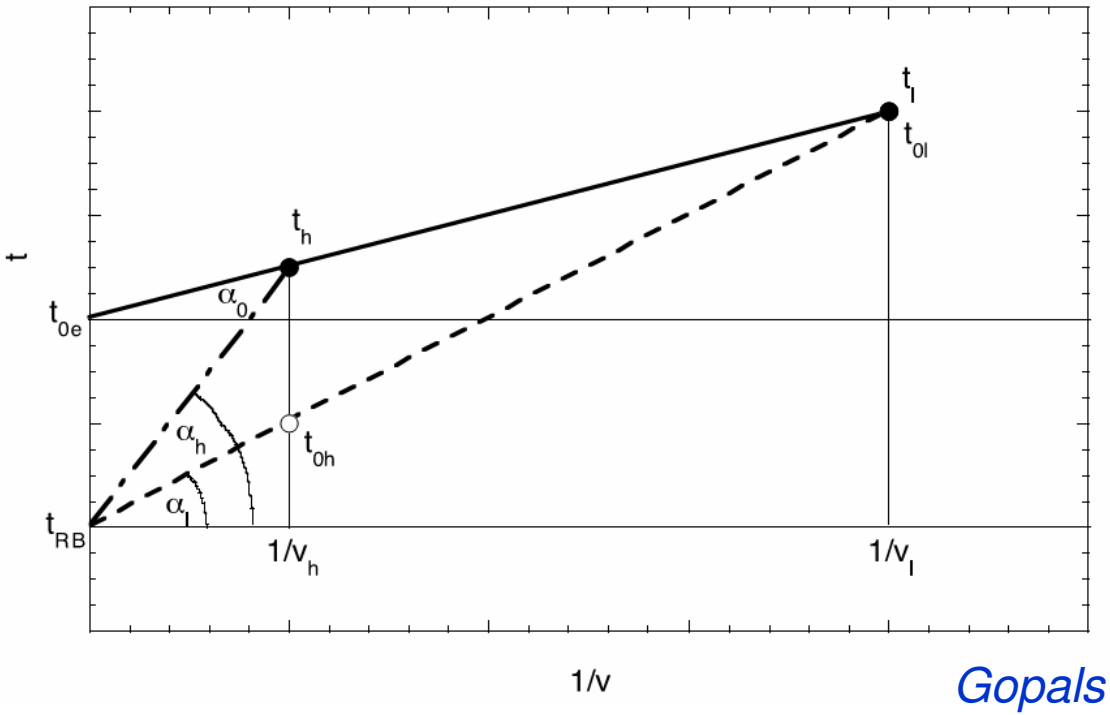


Protons clearly show turbulence
Electrons seem not to feel the effect of turbulence

Malandraki et al , 2012

Comparison of Path Lengths traveled by Solar Electrons and Ions in GLE events

Improved Velocity Dispersion Analysis (VDA)
Electron Path Length Calculation assuming $SRT_e = t_{RB}$

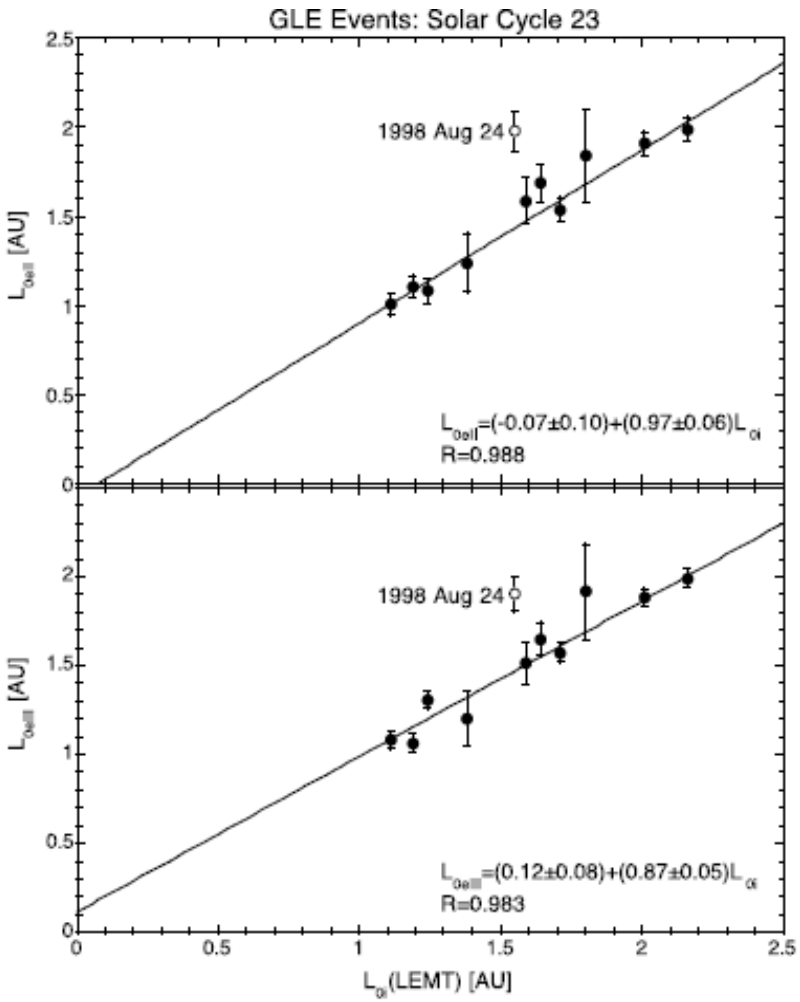


Gopalswamy et al., 2012
Radio Burst (RB) data

Tan, Malandraki et al. , 2013

Reames, 2009

Consistency of Path Lengths Travelled by *e* and *p*



Electron Path Length Calculation assuming $SRT_e = t_{RB}$

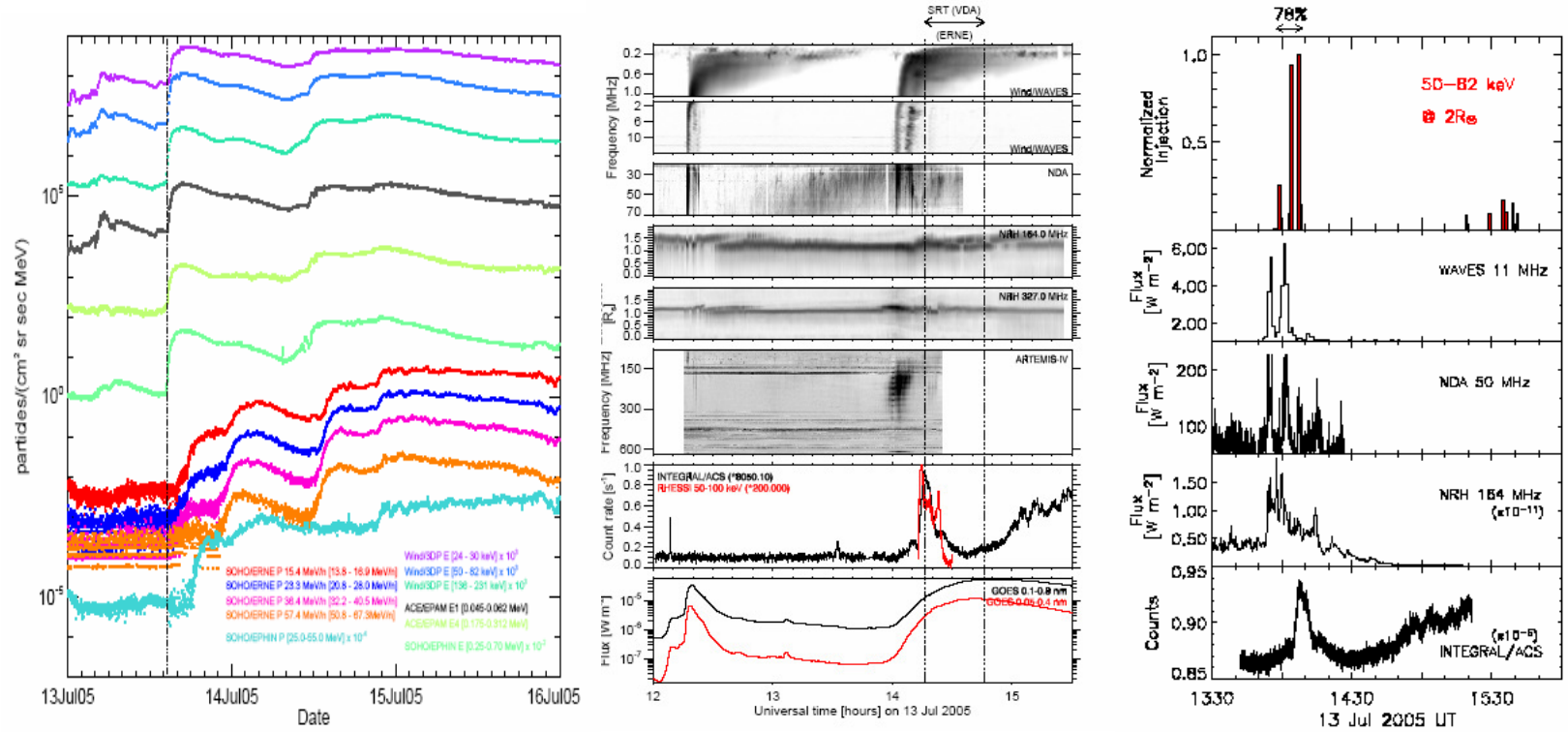
Assuming that the onset time of metric tII or DH tIII radio burst is the SRT of N-R electrons: the deduced path lengths of ~27 keV electrons is consistent (within and error range of 10%) with the ion path length deduced by Reames (2009) from the onset time analysis

Tan, Malandraki et al. , 2013

(!) First comparative results of SEPServer

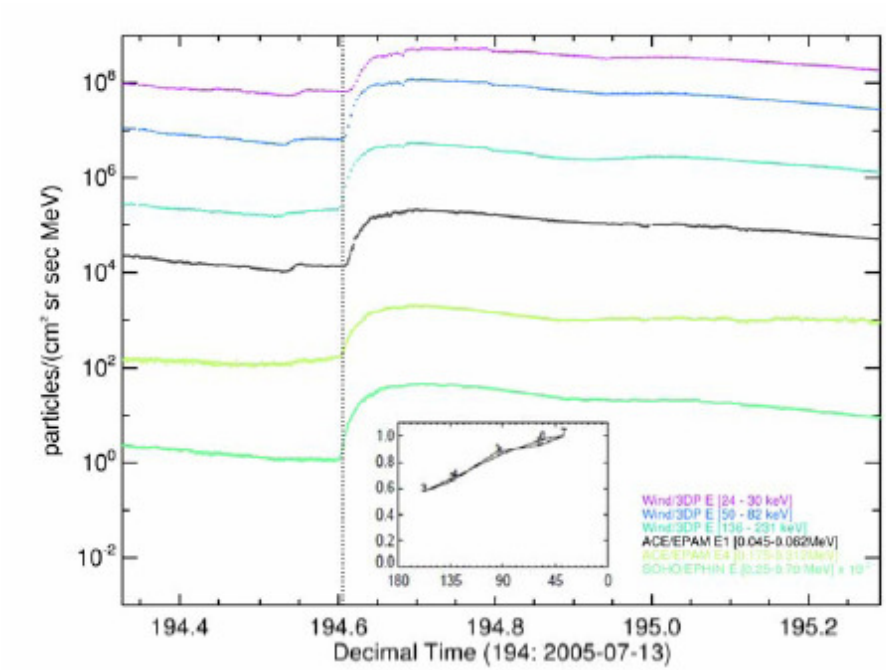
Case Study:
The SEP event of 13 July 2005

Particle Observations + EM Observations + Simulations



Malandraki et al., 2012

Pitch-Angle Distributions (PADs)



✓ PADs were calculated for all E's channels of ACE/EPAM. Moderate anisotropic characteristics was revealed and sector 7 of E'4 was directed along the magnetic field.

Onset Time Determination

$$\langle I \rangle + n \cdot \sigma_I$$

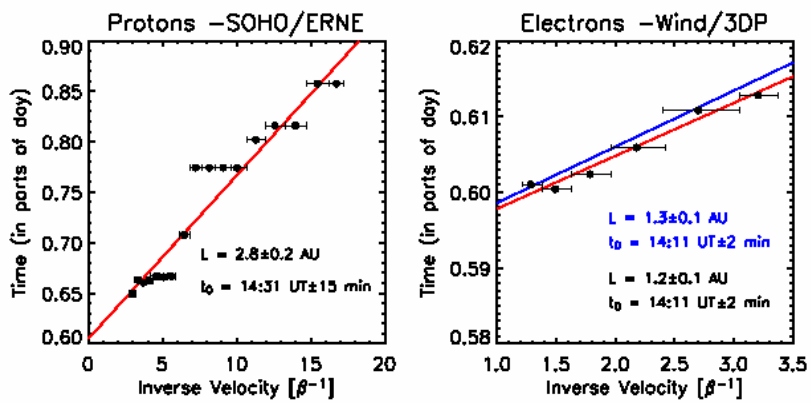
Instrument	Channel	Onset time	Sector
ACE/EPAM	E'4 (0.175-0.312 MeV)	14:33	7
Instrument	**Channel**	**Onset time**	
SOHO/EPHIN	Electrons (0.25-0.70 MeV)	14:27	

✓ Onset times for ***ACE/EPAM*** and ***SOHO/EPHIN*** have been determined based on the criterion of ***> I+3σ*** or ***>I+4σ***

Velocity Dispersion Analysis (VDA)

$$t_{onset}(E) = t_0 + 8.33 \frac{[\mathrm{min}]}{[\mathrm{AU}]} \cdot s \cdot \beta^{-1}(E)$$

✓ ***Wind/3DP*** and ***SOHO/ERNE*** onset times have been determined by the *Poisson-CUSUM* method. VDA has been applied to these results.



Anticipated Release Time Determination

✓ The SOHO/ERNE VDA presents, based on onset times determined by the Poisson-CUSSUM method, a path length of ***2.84 AU*** and an Anticipated release time of ***14:31 ± 15 min*** based on onset times determined by eye, a path length of ***2.32 AU*** and an Anticipated release time of ***14:40 ± 17 min***

✓ The Wind/3DP VDA presents an anticipated release time ***14:11 ± 2 min*** when the path length is considered to be ***1.2 AU***

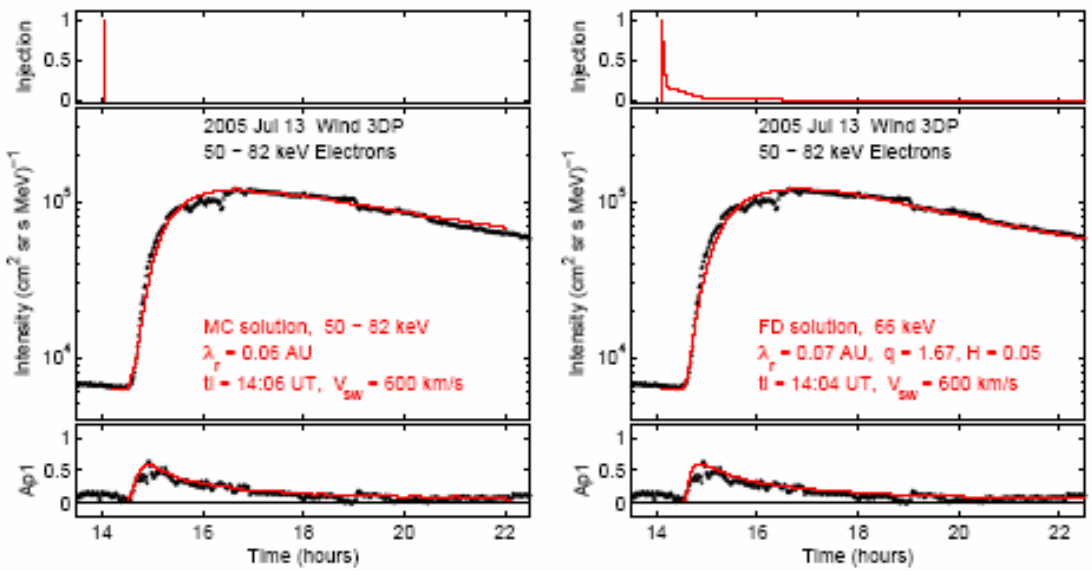
Instrument	Path length (AU)	Release time (UT)
Wind/3DP Electrons (0.025-0.65 MeV)	**1.2**	**14:11 ± 2 min**
SOHO/ERNE Protons (1.58-67.30 MeV)	**2.84** **2.32**	**14:31 ± 15 min** **14:40 ± 17 min**

Modeling results

$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L}v\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = q(z,\mu,t)$$

Numerical Methods Applied

Monte Carlo (MC) Finite Differences (FD)



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INSTITUTE FOR ASTRONOMY, ASTROPHYSICS, SPACE APPLICATIONS & REMOTE SENSING
(formerly INSTITUTE OF ASTRONOMY & ASTROPHYSICS)
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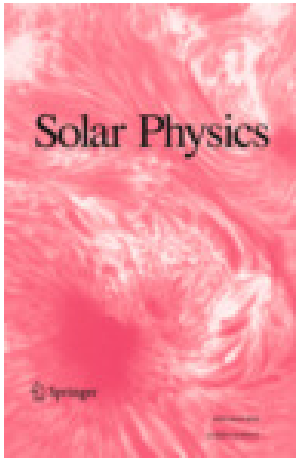
Please register @ http://server.sepserver.eu

Comparative analysis and DDA of various datasets available via SEPServer

Malandraki et al., Solar Phys., 281, 333-352, 2012



Solar Phys
DOI 10.1007/s11207-012-0164-9

THE SUN 360

Scientific Analysis within SEPServer – New Perspectives in Solar Energetic Particle Research: The Case Study of the 13 July 2005 Event

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Received: 23 March 2012 / Accepted: 10 October 2012

Abstract Solar energetic particle (SEP) events are a key ingredient of solar–terrestrial physics both for fundamental research and space weather applications. Multi-satellite observations are an important and incompletely exploited tool for studying the acceleration and the coronal and interplanetary propagation of the particles. While STEREO uses for this diagnostic two identical sets of instrumentation, there are many earlier observations carried out with different spacecraft. It is the aim of the SEPServer project to make these data and analysis tools available to a broad user community. The consortium will carry out

The Sun 360
Guest Editors: Bernhard Fleck, Bernd Heber, and Angelos Vourlidas

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K.-L. Klein

The Release of Near–Relativistic Electrons in the Low Corona

Aim

Study timing+duration of the release processes of NR electrons in the low corona

The inversion methodology

The IP transport model used is based on the Monte-Carlo IP transport model (Agueda et al., 2008)

Assumptions

✓Static particle source at 2 Rs
✓Archimedean spiral + a turbulent component
✓Parametrize the pitch-angle diffusion coefficient as in standart QLT, imposing for the spectral slope of the magnetic field power spectrum the value q=1.66.

The radial mean free path is the only free parameter that describes the amount of pitch-angle scattering!

The IP transport model results (for delta injection function) in the Green function of particle transport. Temporal convolution of Green function+source function ⇒ particle intensity as a function of time, energy and direction.
***The inverse procedure:* the SEP sources are obtained from deconvolution of the in-situ measurements**

Observations

ACE/EPAM: NR electrons 40-400 keV (0.4-0.7c)+**B**
WIND/3DP: energetic electrons in similar energy ranges+**B**+PADs
GOES: SXRs
RHESSI: HXRs
SOHO/LASCO: CME white-light obs.
WIND/WAVES: dm-km radio spectra
Ground-based obs.: radio data

Event Selection

Initially: 115 proton events observed by SOHO/ERNE in SEPServer catalogue (Vainio et al., 2013)

Criteria

✓Quietness in the IP medium (no ICME near the s/c within ±3 days of the SEP event onset)

✓ Peak near-relativistic electron intensity: at least one order of magnitude higher than background

✓ Velocity dispersion at the event onset

✓ Good observational coverage of the PADS

⇒11 near relativistic electron events fulfilled the criteria

BUT

Change of the magnetic topology in 4 events

⇒ 7 near-relativistic electron events were studied

	Date	DOY	ACE $t_\oplus$ (UT)	ACE Rise (min)	ACE $\langle u \rangle$ (km s^{-1})	ACE Foot. (°)	ACE IMF Pol.	Wind $t_\oplus$ (UT)	Wind Rise (min)	Wind $\langle u \rangle$ (km s^{-1})	Wind Foot. (°)	Wind IMF Pol.	S/C Separation ($R_\oplus$)
Group I	1999 Jun 11	162	00:50	45	445	W55	−1	00:59	37	455	W53	−1	60
	2002 Feb 20	51	06:00	24	398	W61	+1	06:09	22	412	W59	+1	340
	2002 Dec 19	353	21:55	24	530	W46	+1	22:05	16	550	W44	+1	132
	2004 Nov 1	306	06:05	29	419	W58	+1	06:14	27	431	W56	+1	42
Group II	2000 Sep 12	256	12:30	619	372	W65	−1	12:44	589	370	W66	−1	274
	2002 Jul 7	188	11:44	286	415	W59	−1	11:58	378	424	W57	−1	282
	2002 Aug 14	226	01:49	35	430	W57	+1	02:00	35	443	W55	+1	208

Observational characteristics of the selected NR electron events measured by ACE(62-102 keV) and WIND (50-82 keV)

Two groups, based on the time over which the event PADs remained highly anisotropic → clear antisunward beaming of electrons

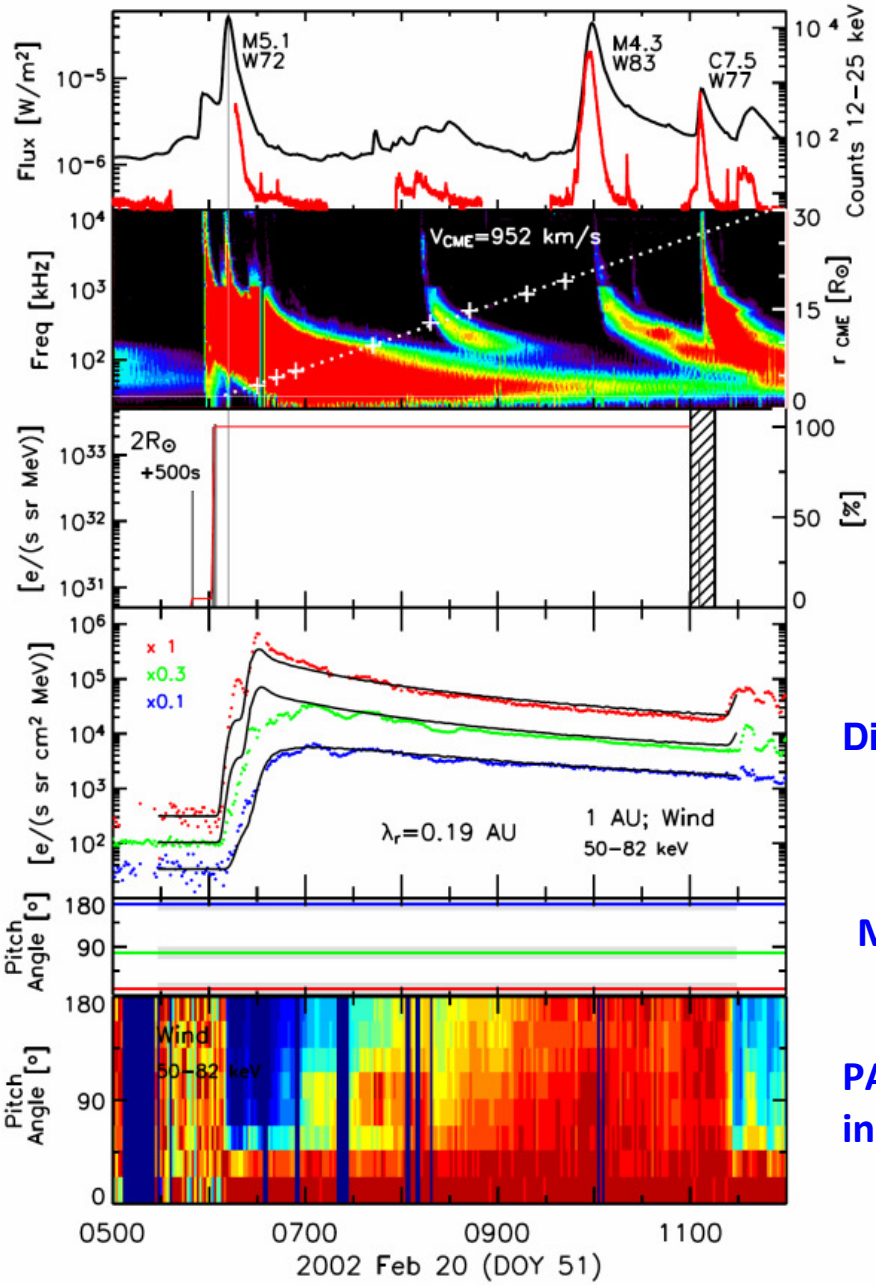
	Event	γ	Electron Radial Mean Path (AU) — *ACE* observations: 175-312 keV	102-175 keV	62-102 keV	Total	*Wind* observations: 135-230 keV	82-135 keV	50-82 keV	Total
Group I	1999 Jun 11	2.5	0.16	0.16	0.16	0.16	0.14	0.14	0.16	0.14
	2002 Feb 20	2.5	0.23	0.27	0.37	0.27	0.16	0.19	0.23	0.19
	2002 Dec 19	2.5	0.10	0.10	0.12	0.12	0.10	0.12	0.14	0.12
	2004 Nov 1	2.5	0.14	0.19	0.27	0.23	Long data gaps			
Group II	2000 Sep 12	2.5	0.12	0.14	0.16	0.14	Long data gaps			
	2002 Jul 7	2.0	0.12	0.14	0.19	0.14	Long data gaps			
	2002 Aug 14	3.5	0.31	0.44	0.52	0.44	Long data gaps			

Electron Radial mean free path providing the best fit for each event, using ACE and Wind observations.

	Date	Proton VDA t_0 (UT)	Proton VDA L (AU)	Electron VDA t_0 (UT)	Electron VDA L (AU)	Inversion of in-situ electron obs. *ACE* 62–102 keV t_0 (UT)	*ACE* Δt (min)	*ACE* Released Part. (e sr^{-1} MeV^{-1})	*ACE* λ_r (AU)	*Wind* 50–82 keV t_0 (UT)	*Wind* Δt (min)	*Wind* Released Part. (e sr^{-1} MeV^{-1})	*Wind* λ_r (AU)
Group I	1999 Jun 11	00:32±07	1.81±0.09	00:58	0.6	00:39	8	6.8×10^{33}	0.16	00:40	3	1.5×10^{34}	0.14
	2002 Feb 20	05:44±06	1.62±0.08	06:12	0.3	05:51	30	1.1×10^{35}	0.27	05:49	14	3.5×10^{35}	0.19
	2002 Dec 19	21:36±6	1.61±0.07	22:01	0.7	21:26	24	3.4×10^{34}	0.12	21:43	4	8.7×10^{34}	0.12
	2004 Nov 1	05:42±6	1.60±0.07	06:02	1.2	05:47	53	7.7×10^{34}	0.23	-	-	-	-
Group II	2000 Sep 12	12:29±09	1.76±0.12	12:41	0.7	12:25	137	5.2×10^{34}	0.14	-	-	-	-
	2002 Jul 7	11:26±04	1.77±0.05	11:54	0.7	11:34	187	3.1×10^{35}	0.14	-	-	-	-
	2002 Aug 14	02:01±07	1.29±0.08	02:04	0.2	01:46	195	1.7×10^{35}	0.44	-	-	-	-

Release times inferred from the VDA of proton ERNE observations and Wind/3DP electron observations together with the results of the inversion of in-situ electron directional intensities. All times have been shifted by +500 s to allow comparison with EM emissions.

Example of an event



SXR flux by GOES (black) + HXR flux by RHESSI (red; when available)

Radio flux by *Wind*/WAVES (white horizontal ine: 30 kHz) and time-height plot of the CME leading edge (dotted curve; right axis).

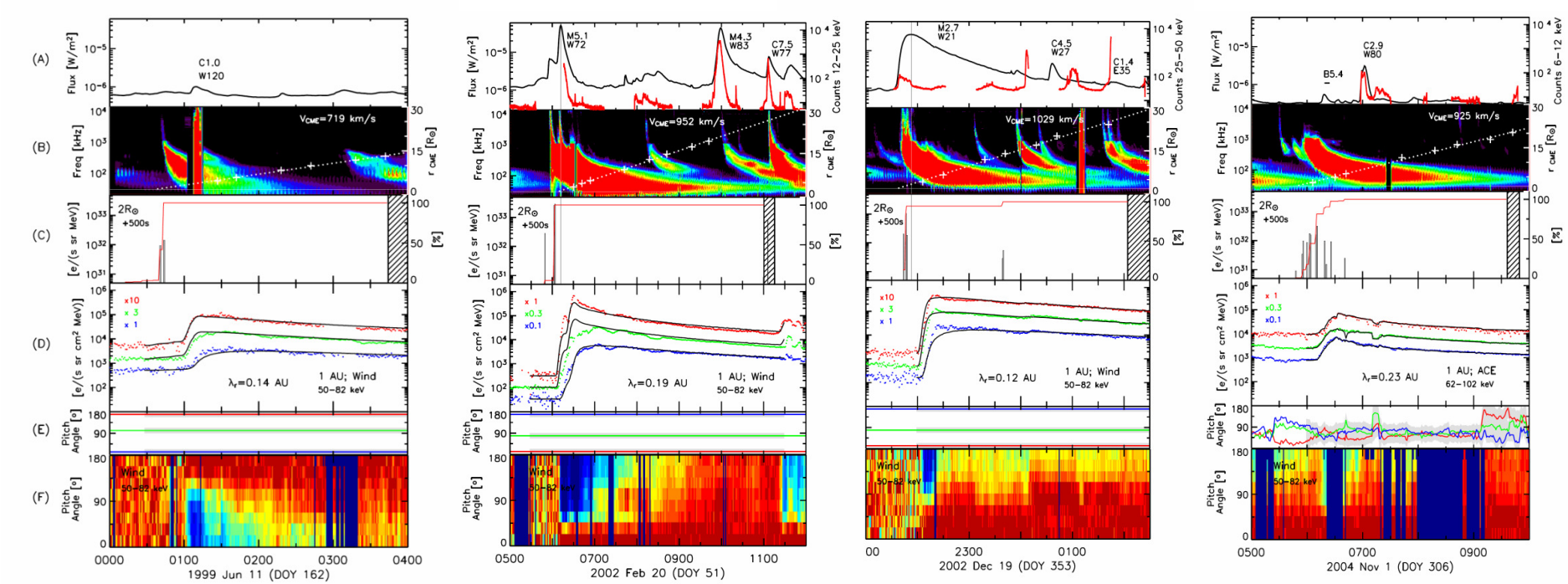
Electron source profile deduced at 2*R* (gray histogram) and total electron ratio (red curve; right axis). Profile shifted by +500 s to compare with EM emissions.

Directional NR electron intensities measured near 1 AU

Mean pitch-angle and range (gray area) scanned by each sector.

PADs measured by *Wind*/3DP normalized to unity in each time interval.

Group I (4 events): nearly isotropic PADs in <1 h



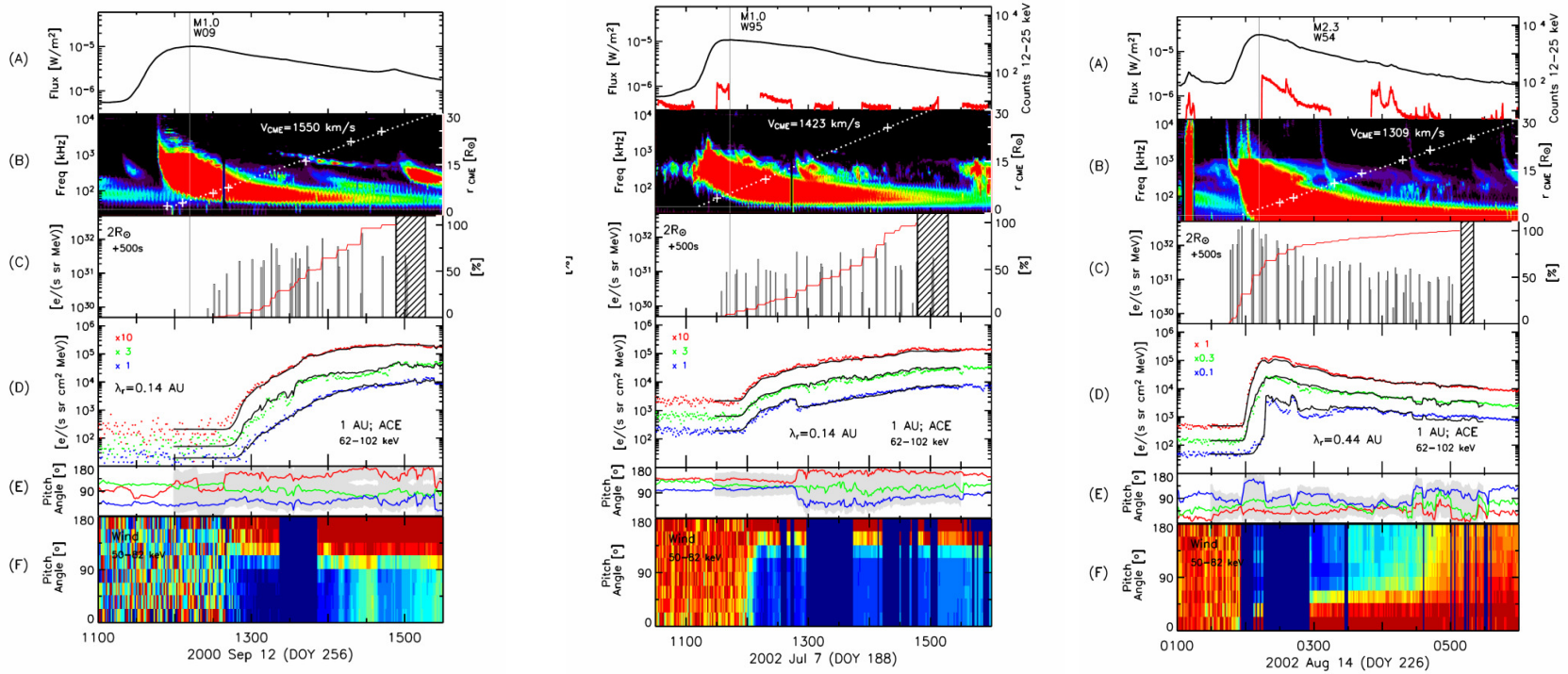
✓ **Associated with impulsive SXR flares, with rise times ≤ 20 min. Location: 2 behind the west limb and 2 at the western hemisphere.**

✓ **Prompt release (< 60 min)**

✓ **At low energies the timing of the release agrees with the timing of the type III radio bursts within 5 minutes, while the duration is also the same.**

✓ **A CME observed in all cases (in 2 events: halo)**

Group II (3 events): highly anisotropic PADs for > 2 h



✓ Associated with gradual SXR flares, with risetimes >25 min and long SXR decay times

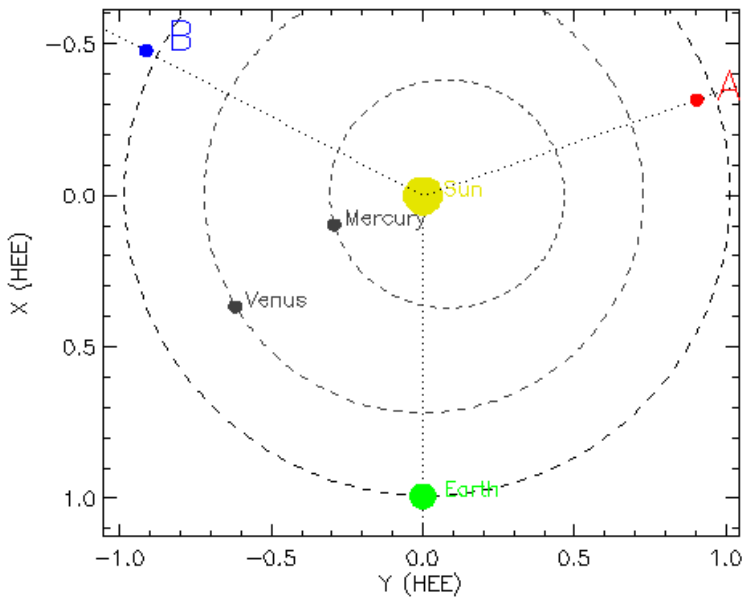
✓Long release time histories (several hours)

✓The electron release started in coincidence with the tIII radio bursts on 2002 Aug 14, but the duration of the particle release appeared to be sustained during > 3h, well after the end of the tIII radio emission

✓Signatures of long-duration acceleration processes in the corona were observed: long decay microwave emission (5 GHz) on 2002 Aug 14, a type IV burst was observed by the Nançay Radioheliograph on 2000 Sep 12 and tII radio bursts were reported

✓CMEs were observed for all the 3 events, with larger speeds than the CMEs in Group I.

Statistical survey of wide-spread events in the Heliosphere (STEREO & ACE)



Multi-spacecraft - Wide Spread Event

Event Date	Ref.	Interpretation	Other events
03.04.2010	Rouillard et al., 2011	**Shock Evolution**	**21.03.2011** Rouillard et al., 2012
17.01.2010	Dresing et al., 2012	**Perpendicular Diffusion**	**17.05.2012** Heber et al., 2013
07.02.2010	Wiedenbeck et al., 2013 Wiedenbeck et al., 2011	**Cross-Field Transport**	Reames, 2013 Tan, Malandraki et al., 2013

Statistical survey of wide-spread events in the Heliosphere (STEREO & ACE)

Goal

- Investigate a set of near-relativistic solar electron events with a remarkable longitudinal distribution (2009-mid 2013)

- Statistical approach: investigate the longitudinal variation of event properties: Maximum intensities, Onset delays, Rise times, ANISOTROPIES observed at different viewpoints

- We discuss the role and importance of the different transport and injection mechanisms leading to the large longitudinal spread.

Statistical survey of wide-spread events in the Heliosphere (STEREO & ACE)

A list of wide-spread events were selected – 21 electron events. **Criteria:**

- ***A 55-105 keV e increase above bkgd detected by at least 2 of the 3 s/c***
- ***The widest separated s/c must have a flare to s/c footpoint longitudinal separation of at least 80 deg.***

Longitudinal Separation – Flare & STB foot point 18º

Longitudinal Separation – Flare & ACE foot point -94º

Longitudinal Separation – Flare & STA foot point 163º

LONGITUDINAL CONFIGURATION SHOWN:

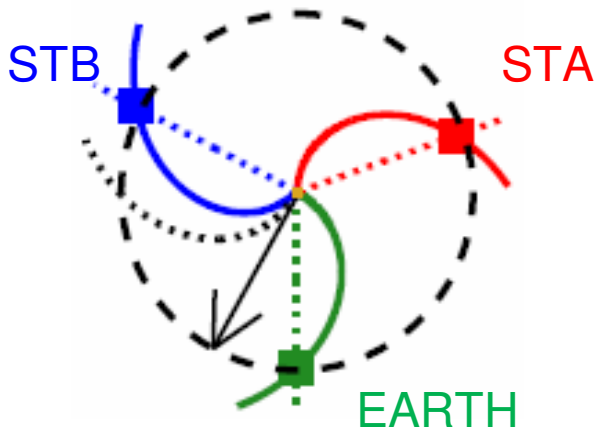
ARROW: The longitude of the flaring region

DOTTED BLACK LINE: Nominal Parker field line connecting to AR

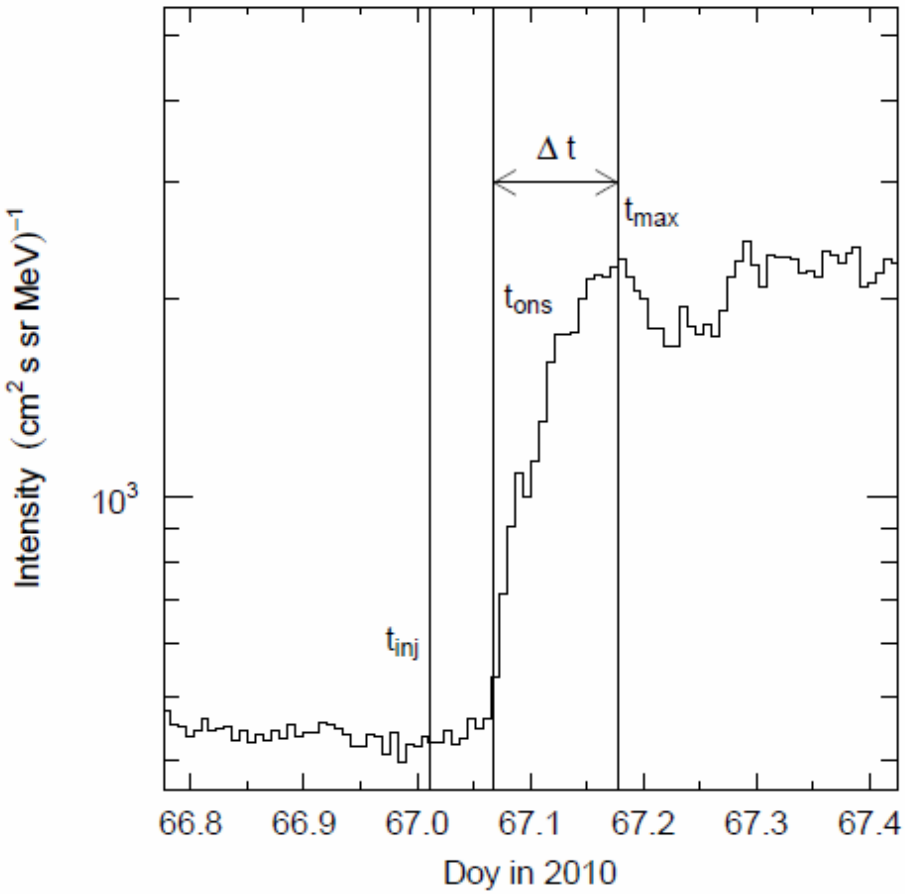
BLUE, RED, & GREEN:

field lines connecting the 3 s/c back to the Sun

2012-03-07

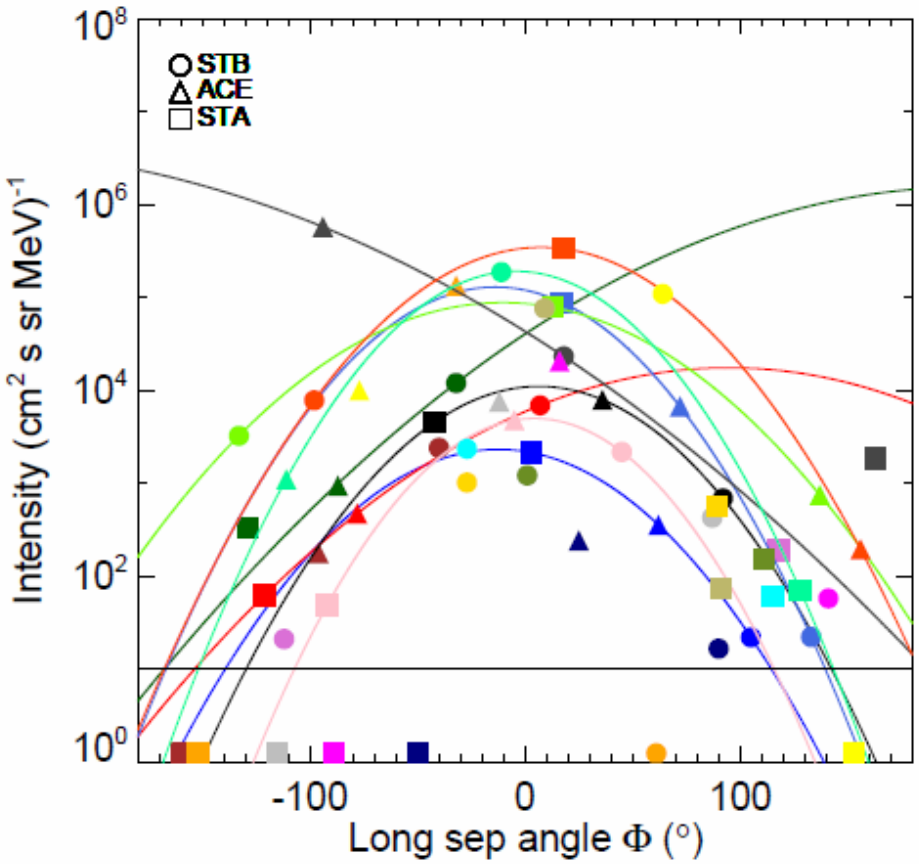


Onset & Time to Max determination



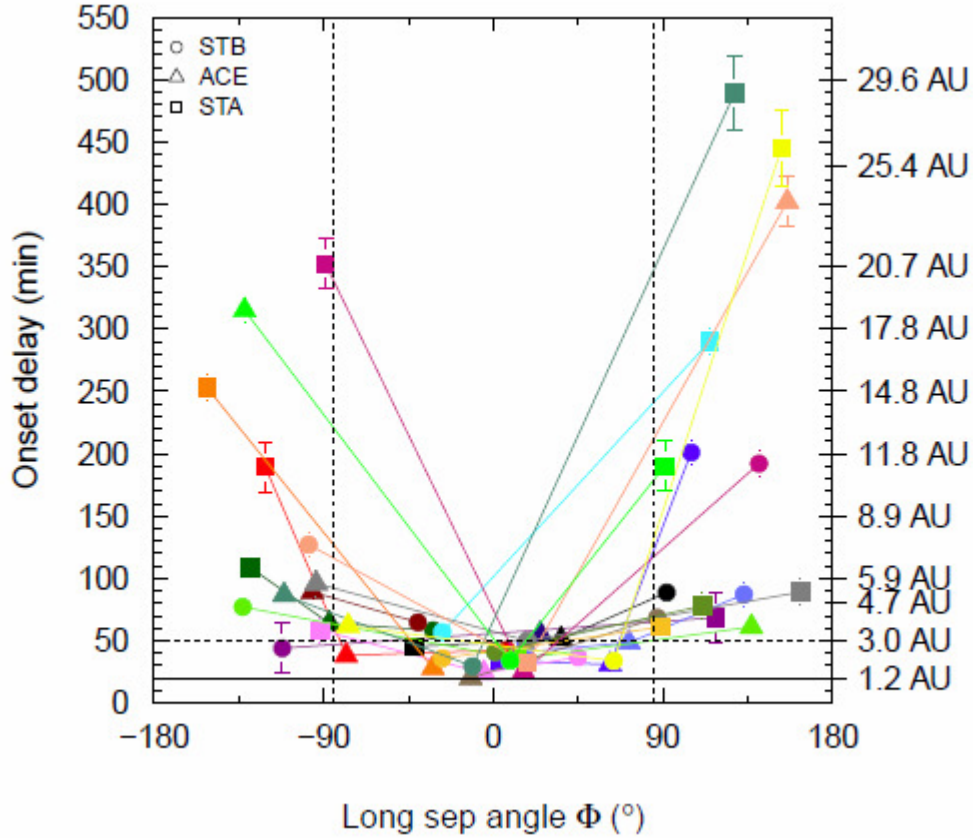
Longitudinal variation of Max Intensities

$$I(\varphi) = I_o \exp\left[-(\phi-\phi_0)^2/2\sigma^2\right]$$



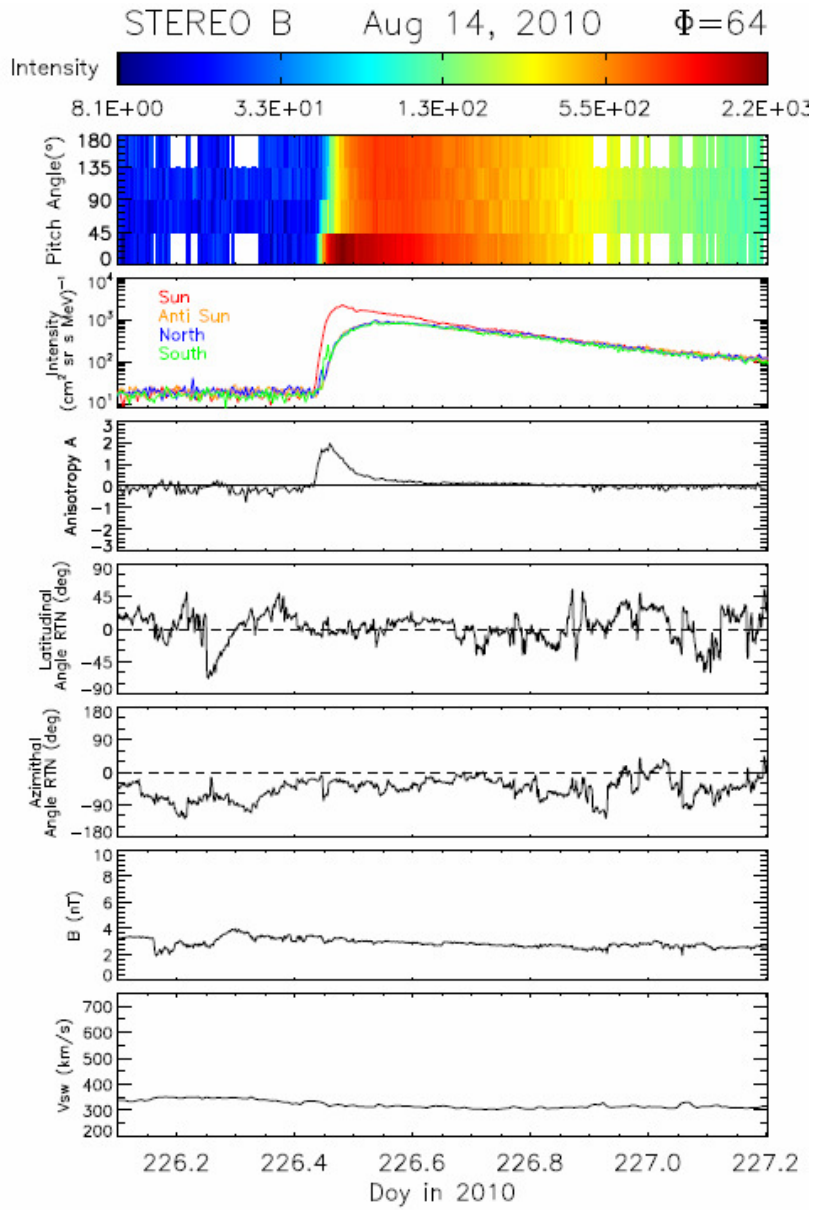
σ = 32° - 48° deg, mean 37.3°

Longitudinal variation of Onset Delays



- **The particles arrive delayed in the spacecraft**
- **Remarkable that several well-connected events show delays of up to 30 min.**

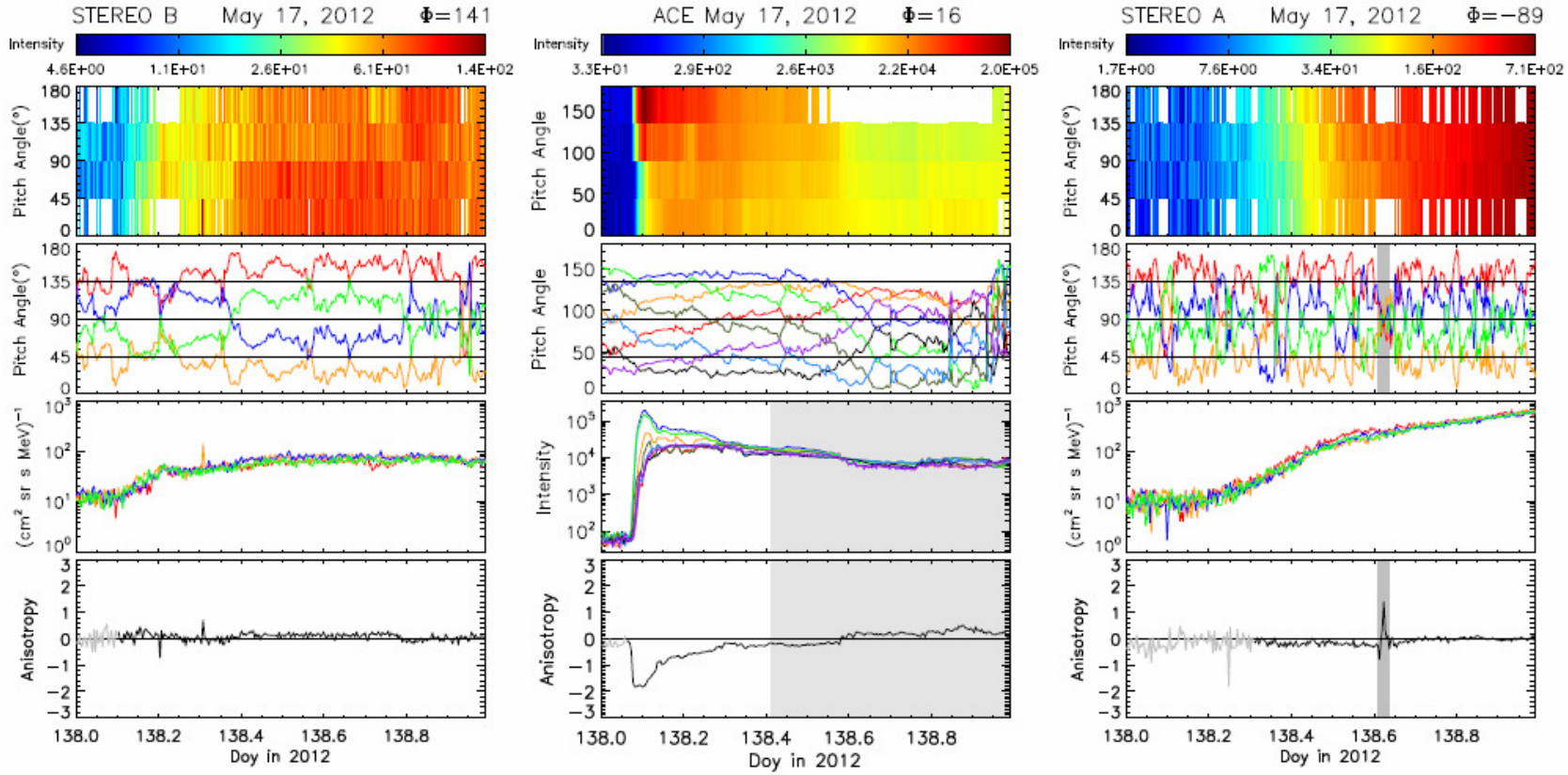
$$A = \frac{3\int_{-1}^{+1} I(\mu)\cdot\mu\cdot d\mu}{\int_{-1}^{+1} I(\mu)\cdot d\mu}$$



SUN
ANTI-SUN
NORTH
SOUTH

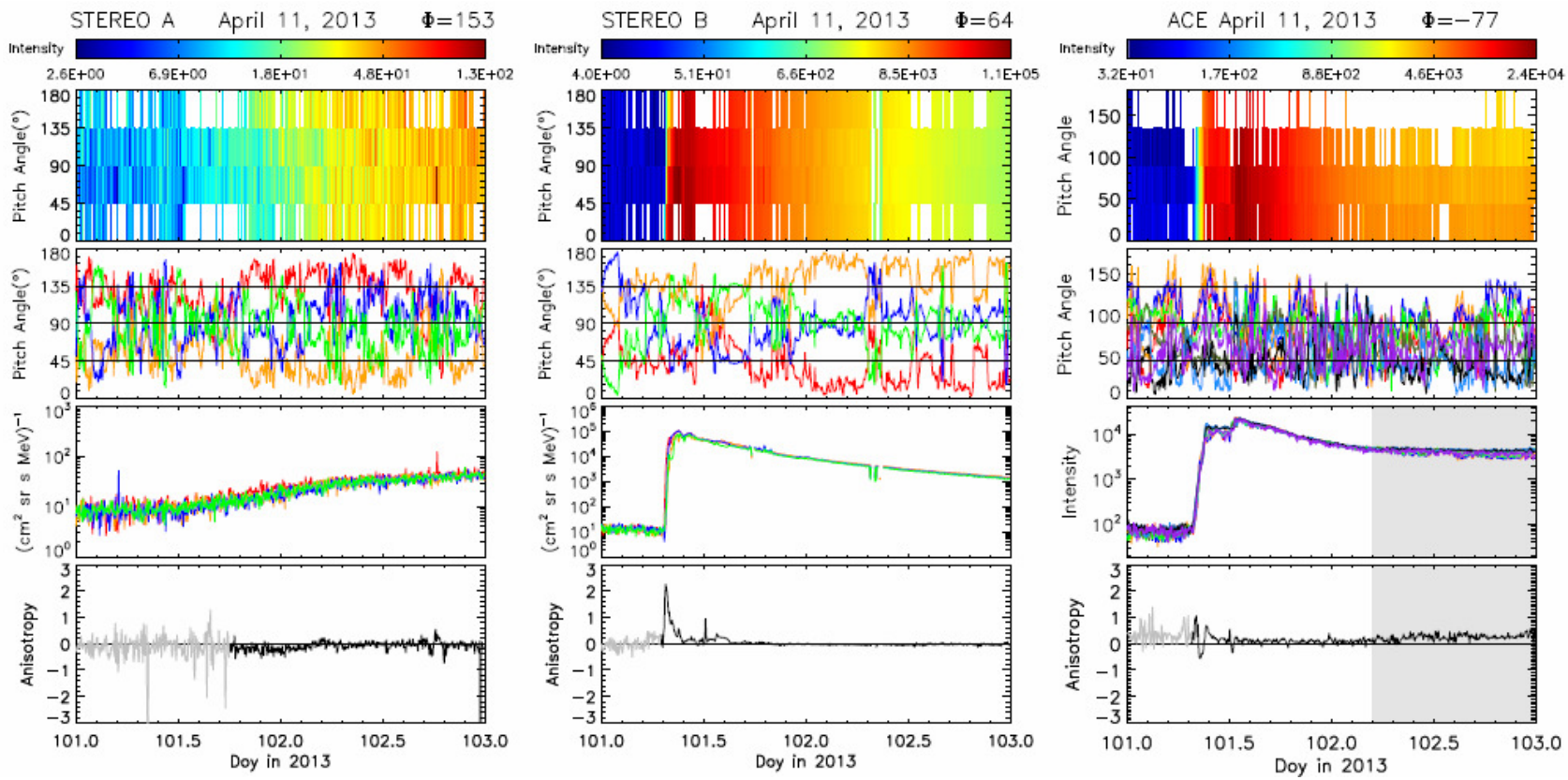
Class 1

Significant anisotropy is observed at a well-connected s/c (φ < 50°) Almost no anisotropy at a far separated s/c (A<0.6, at φ > 60°)



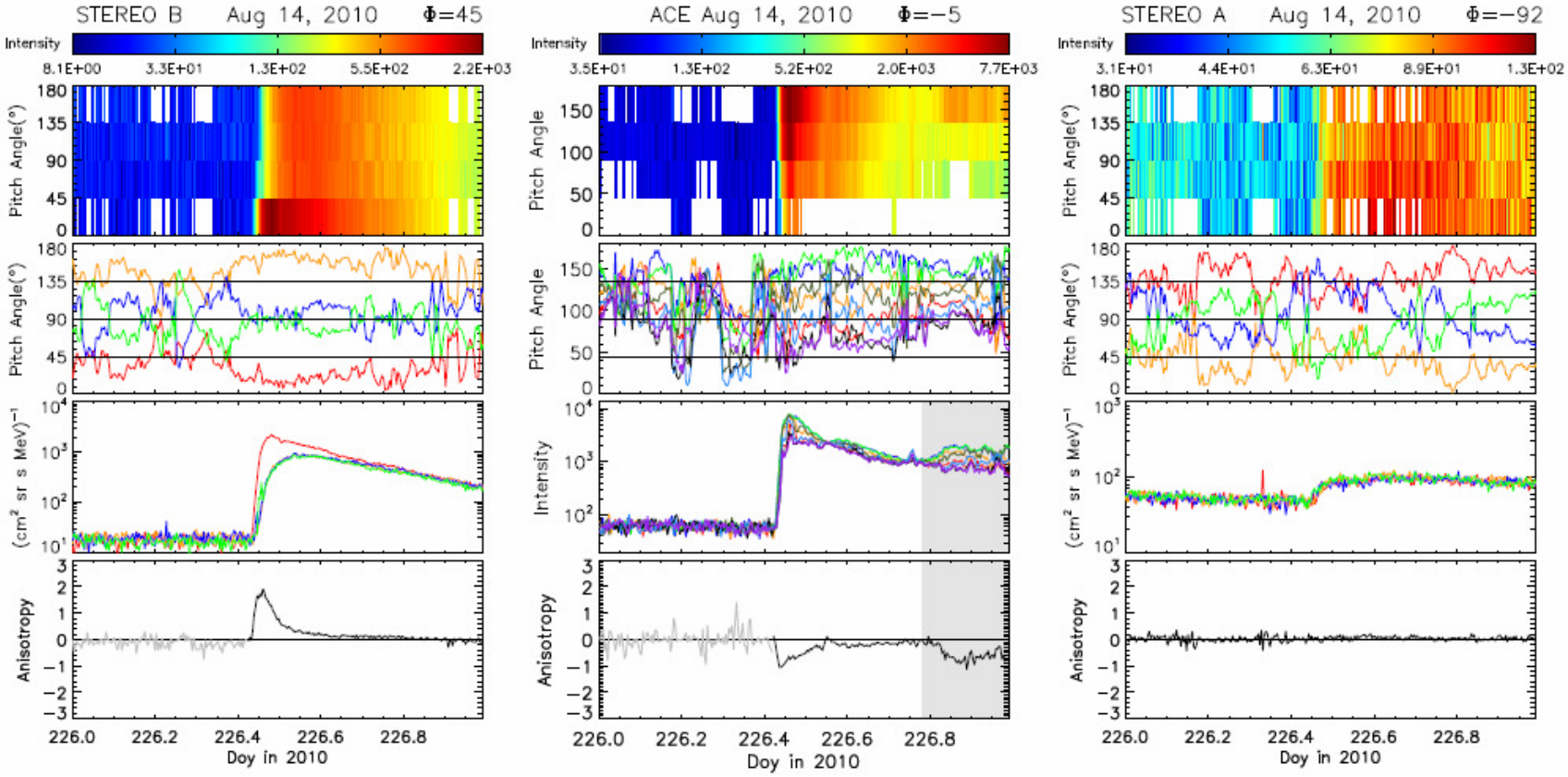
Class 2

Highest anisotropy observed by best-connected s/c but… Significant anisotropy (A>0.6) still observed at far separated positions (φ> 60°)

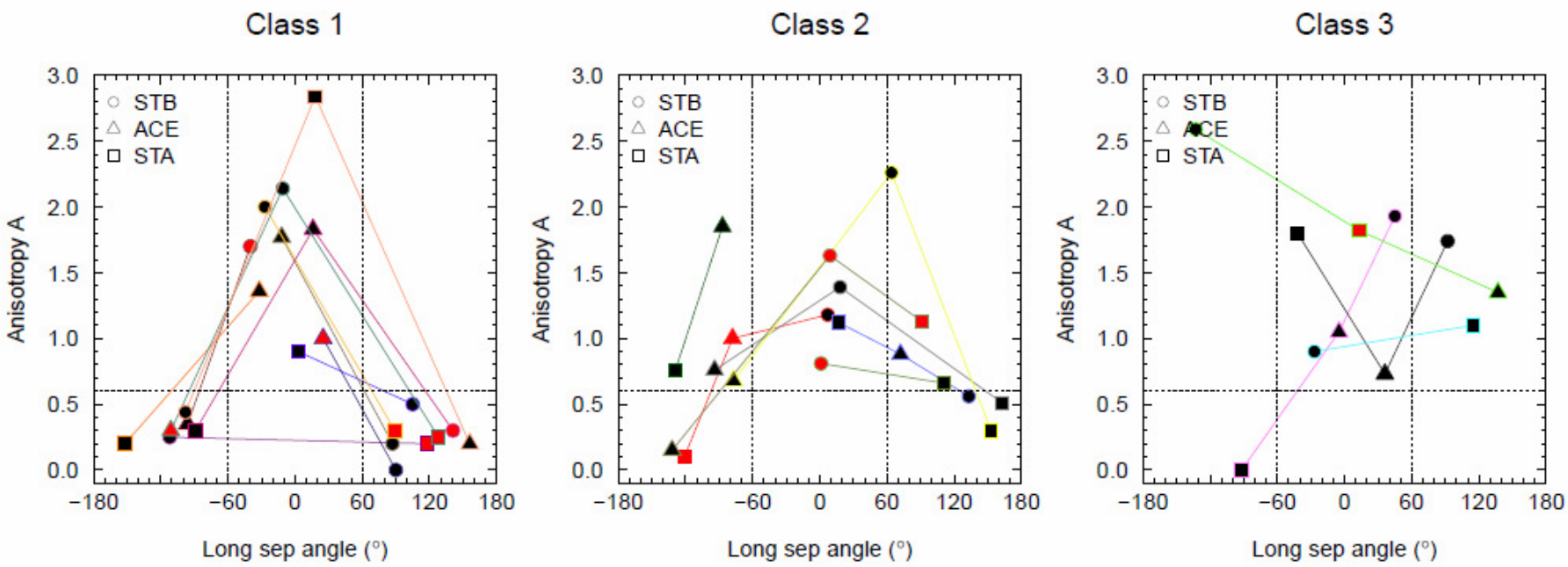


Class 3

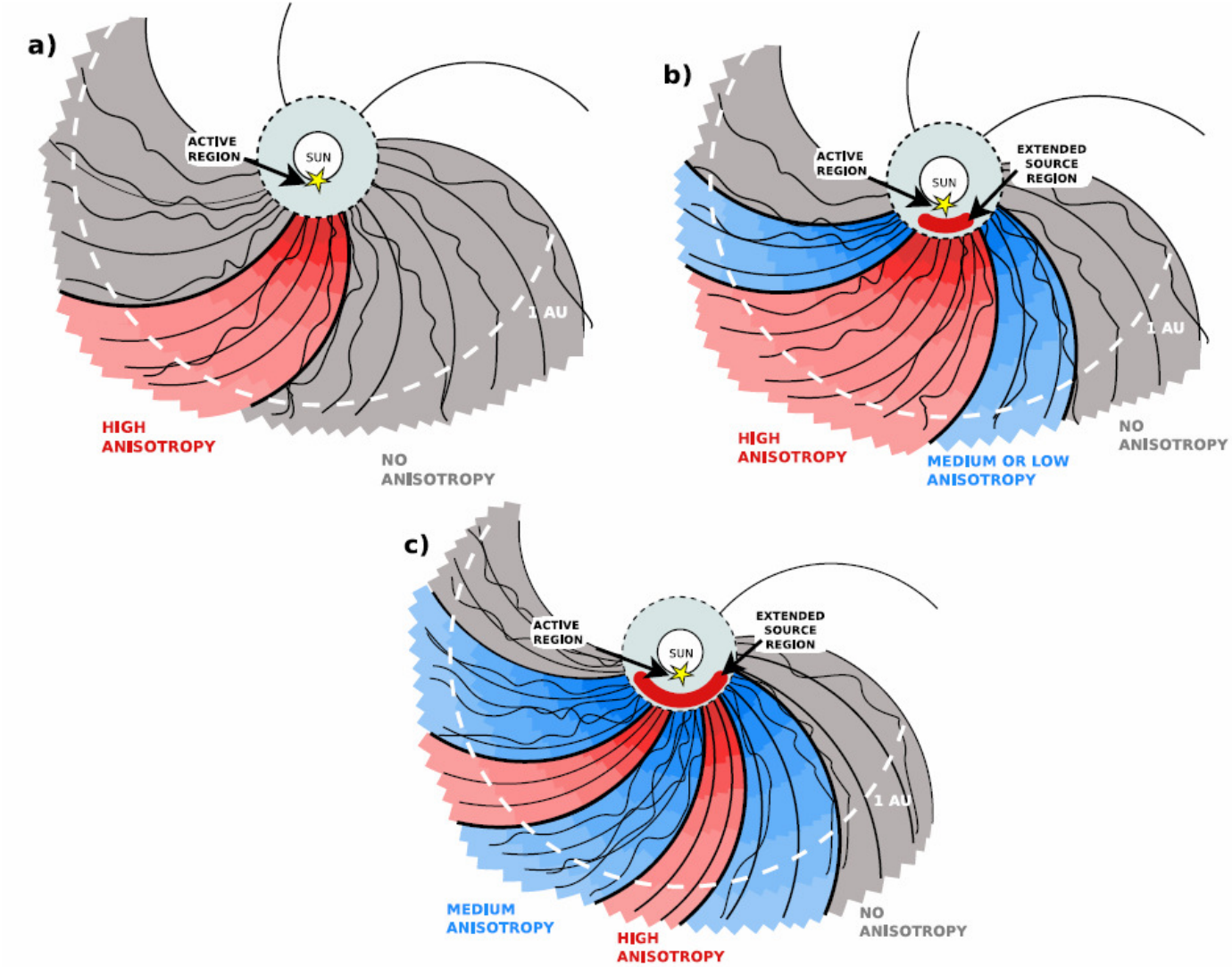
The highest anisotropy is not observed by the best-connected s/c but by a further–separated one



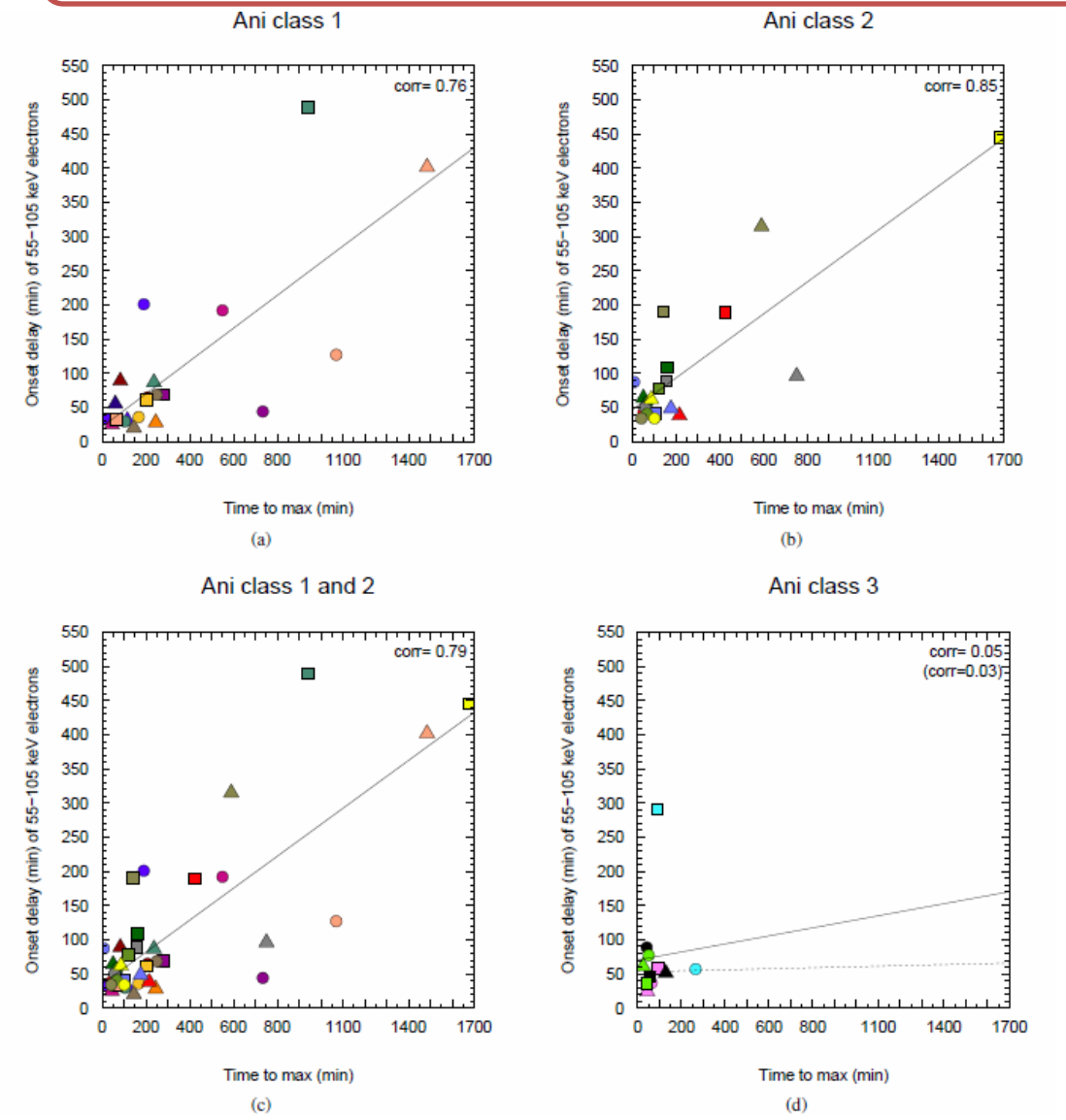
Statistics of the A maxima observed by the 3 S/C as a function of longitudinal separation angle



Conclusions on the source and transport processes for the wide-spread events under study



Correlation Results – Onset delay vs. Rise time



Both an extended source region at the Sun and perpendicular transport in the IP medium are involved for the majority of these widely-spread events!