Simulation Tools for the Study of Solar Energetic Particle Events

Neus Agueda
University of Barcelona, Spain

Bochum 12-16 September 2011

Workshop "Cosmic Rays and the Heliospheric Plasma Environment"

Outline

1. Solar Near-Relativistic Electron Events
2. Simulations of Interplanetary Particle Transport
3. Tools for the Investigation of SEP Events
4. Examples
5. SEPServer FP7 Project

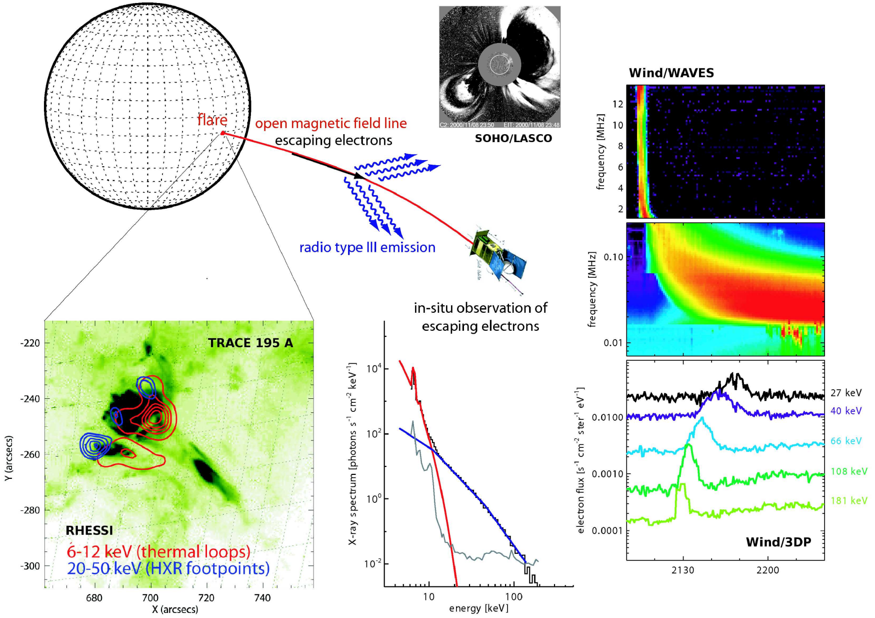
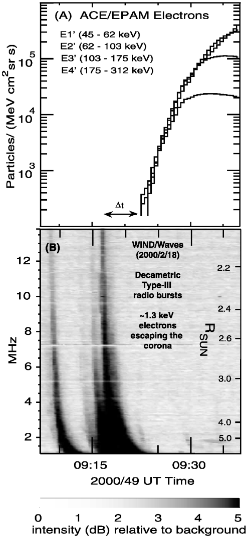


Figure Credit: Säm Krucker (SSL/UCB)

- Lin (1985) showed that electron events were nearly always accompanied by solar type III radio bursts:

  2-100 keV ISEE3 measurements, 326 electron events

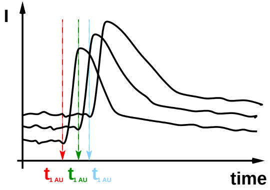
→ In-situ electron events are produced by solar flares



For **30-300 keV** electrons (speed 0.3-0.8c):

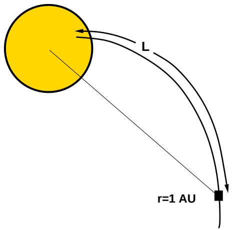
- Krucker et al (1999) ;
  58 events, $\Delta t_{\mathrm{max}} \simeq 30$ min
- Haggerty & Roelof (2002) ;
  79 events, $\langle \Delta t \rangle = 9.5$ min

→ Up to 30 min delays between t_{Sun} and t_{III}

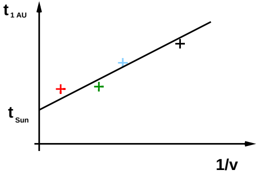


$$t_{1\ AU}(E) = t_{Sun} + \frac{L}{v(E)}$$

Assuming a nominal path length:



From a velocity dispersion analysis:



Assumptions:

- Scatter-free transport
- $L = 1.2$ AU

- Simultaneous injection
- Energy-independent L

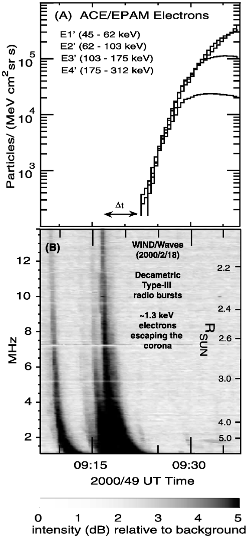
Problems:

(Kahler & Ragot 2006)

- High instrumental background
- Energy-dependent injection
- Interplanetary scattering → Numerical simulations have shown that the estimated injection times can be in error by several minutes (Sáiz et al. 2005; Lintunen & Vainio 2004)

Are in-situ electrons and the electrons at the origin of the type III emission the same?

1. Flares. Particle propagation effects along magnetic field lines (Cane 2003).
2. Coronal shocks (observed as type II radio bursts) and/or by large-scale coronal EIT waves in conjunction with CMEs (Krucker et al. 1999; Haggerty & Roelof 2002; Simnett 2002; Kahler et al. 2007)
3. Reconfiguration (reconnection) of the low corona behind the coronal shock/CME (Maia & Pick 2004; Klein et al. 2005).

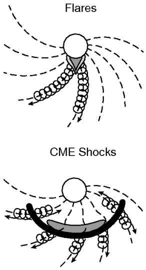


- Both solar flares and coronal shocks are possible candidates for sources of energetic heliospheric electron events:

  Miller (2000), Petrosian & Liu (2004), Dalla & Browning (2006), Drake et al. (2006)

  Burgess (2005), Giacalone (2005), Mann et al. (2001, 2003)

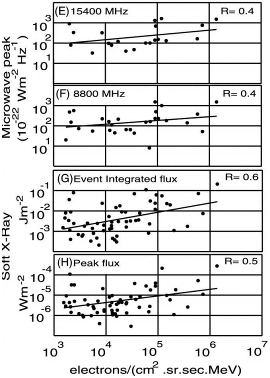
(Reames 1999)



	Flares	Coronal Shocks
1) Correlations with event parameters?	EM fluxes	CME speed
2) Injection timescales?	<hr	>hr
3) Extent of events?	narrow	broad

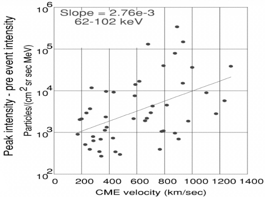
Correlations between electron peak intensities and

microwave peak fluxes	$r \sim 0.4$	(Haggerty & Roelof 2002)
SXR peaks	$r \sim 0.5$	(Haggerty & Roelof 2002)
SXR fluences	$r \sim 0.6$	(Gopalswamy et al. 2004)
HXR fluences	$r \sim 0.7$	(Kahler et al. 1994)
CME speeds	$r \sim 0.6$	(Haggerty & Roelof 2002)



Associations with fast ($\geq$1000 km s^{-1}) CMEs and solar type II radio bursts (Kahler et al. 2005):

- 37%/17% with m/dh type II bursts
- 67% of all type II burst can be associated with a NR electron event
- 50% of the NR electron events can be associated with fast CMEs



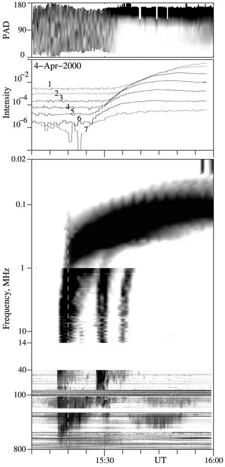


TABLE 2
NR ELECTRON PAD BEAMING DURATIONS AND TYPE II BURST ASSOCIATIONS

	Beam Duration		
Type II Burst Descriptor	Short[a]	Intermediate[b]	Long[c]
m/dh Type II	1	17	13
No Type II	13	27	3

[a] Beam durations ≤0.3 hr.
[b] Beam durations 0.4–1.7 hr.
[c] Beam durations ≥2 hr.

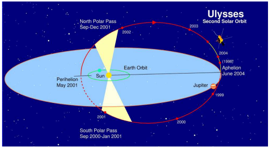
- Kahler et al. (2007) compared electron beam-like PAD times with type II burst associations:
  - 80 electron events
  - Wind/3DP measurements

- Only 1 of 14 short-duration (≤0.3 hr) beam-PAD events was associated with a m/dh type II burst.
- But 13 of 16 long-duration (≥2 hr) events were associated with a m/dh type II burst.

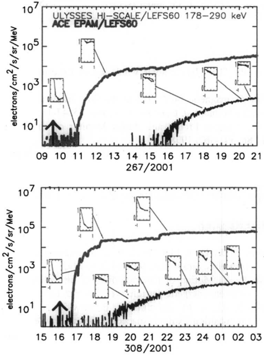
→ Two kinds of solar injection: one impulsive at well connected flare sites and the other extended at broad CME-driven shocks.

NR electron events observed when *ACE* and *Ulysses* were broadly ($\sim 80^\circ$) separated (e.g. Simnett 2003, Maclennan et al. 2003, Lario et al. 2004).

- Despite the latitudinal and longitudinal separations of the two S/C, all events seen at *Ulysses* were also seen at *ACE*.
  - Late particle injection (CME-driven shock)?
  - Different transport conditions?
  - Particle diffusion perpendicular to the mean IMF?

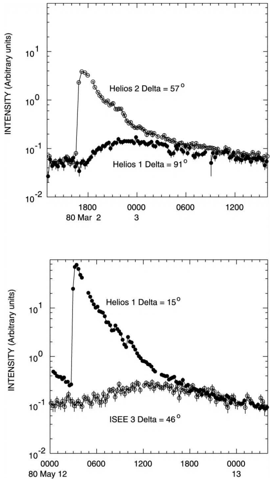


- Most of the small electron events observed by *ACE* were not observed *Ulysses*.

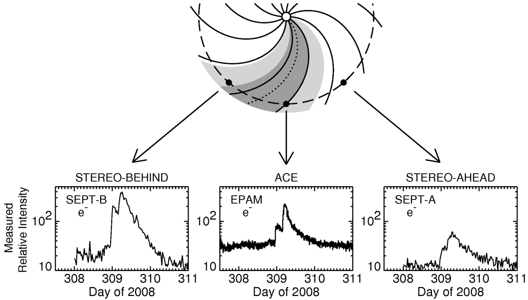


Lario et al. (2003)

Wibberenz & Cane (2006)



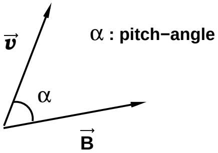
Wiedenbeck et al. (2010)



- AR W38, $\widehat{BEA} = 82^\circ$
- Mazur et al. (2000): Particles do not spread in large range of longitudes.
- PFSS model can not explain the spread

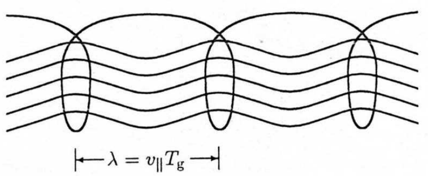
Focused transport equation (Roelof 1969)

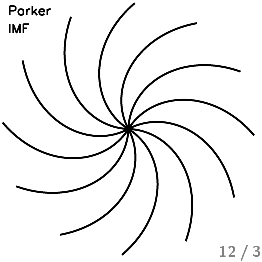
$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L}v\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = q(z,\mu,t) \qquad (1)$$



$\mu = \cos\alpha = \frac{v_{||}}{v}$

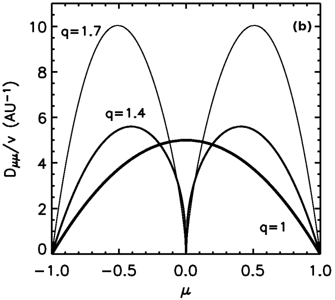
- Gyration around and streaming along the IMF
- Focusing and mirroring: $\frac{1-\mu^2}{B} = \mathrm{const.}$
- Diffusion in pitch-angle $\Longrightarrow$ spatial diffusion (scattering off magnetic irregularities)





- Diffusion coefficient (Jokipii 1966)

- standard model of particle scattering
    - Small irregularities (QLT)
    - Transverse and axially symmetric fluctuations
- $P(k) \propto k^{-q}$



$$D_{\mu\mu} = \frac{\nu(\mu)}{2}(1-\mu^2) \quad ; \quad \nu(\mu) = \nu_0 |\mu|^{q-1}$$

- Parallel mean free path (Hasselmann & Wibberenz 1968,1970)

$$\lambda_{||} = \frac{3v}{8}\int_{-1}^{1} \frac{(1-\mu^2)^2}{D_{\mu\mu}} d\mu = \frac{3v}{4}\int_{-1}^{1} \frac{(1-\mu^2)}{\nu(\mu)} d\mu$$

isotropic scattering $(\nu = \nu_0) \Rightarrow \lambda_{||} = \frac{v}{\nu_0}$

$\lambda_r = \lambda_{||} \cos^2 \psi = \mathrm{const.}$ (Palmer 1982, Kallenrode et al. 1992, Ruffolo et al. 1998)

- Finite-difference numerical method:

  Heras et al. 1992, Ruffolo 1995, Lario et al. 1998, Hatzky & Kallenrode 1999, Dröge 2000

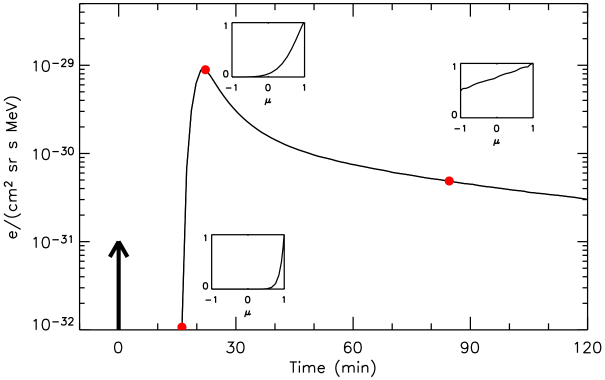
  $\uparrow$ Advantages: computationally fast

- Monte Carlo method:

  Kocharov et al. 1998, Zhang 2000, Li et al. 2003, Maia et al. 2007, Agueda et al. 2008

  $\uparrow$ Advantages: track of individual particles

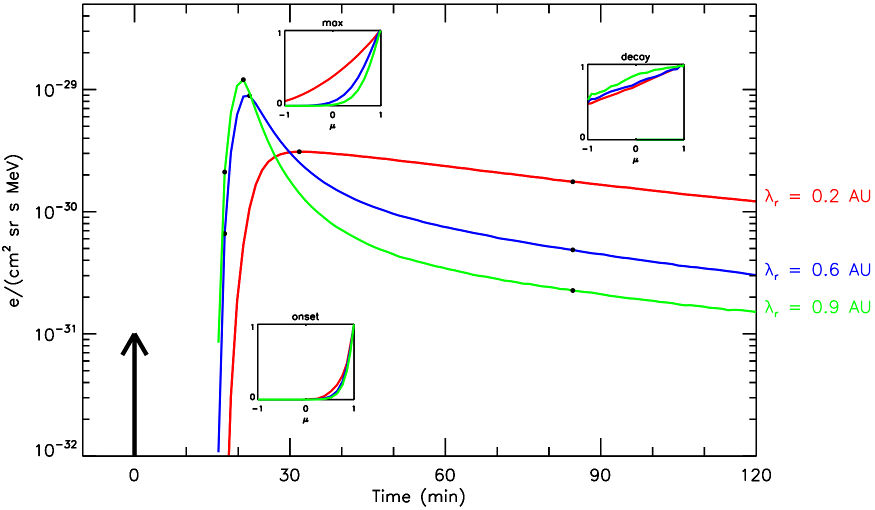
- The results of the simulations are expressed in terms of
  - differential intensities at 1 AU
  - resulting from a delta injection close to the Sun
  - normalized to one particle injected per steradian

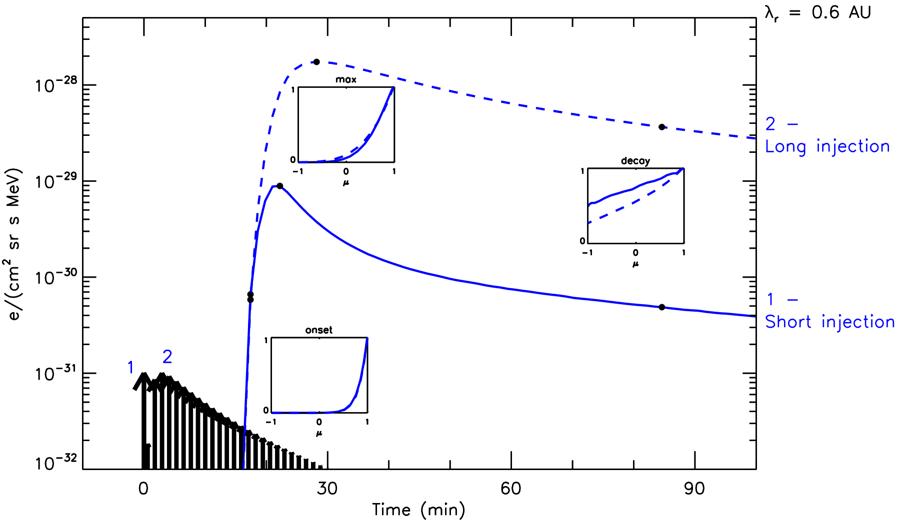


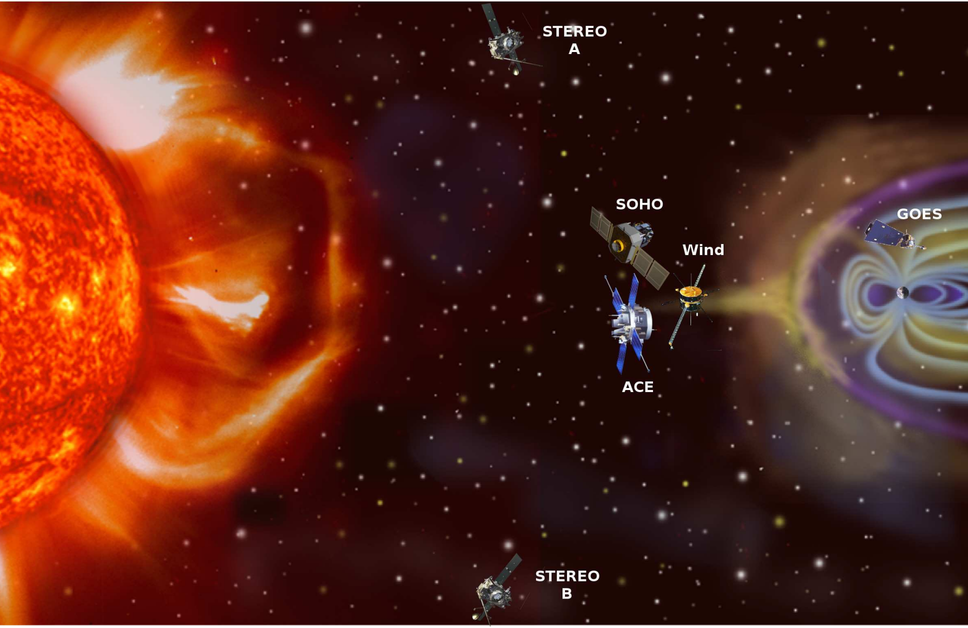
62–102 keV

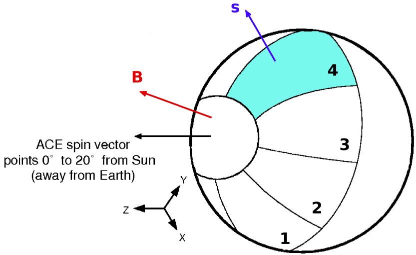
λ_r=0.6 AU

isotropic scattering

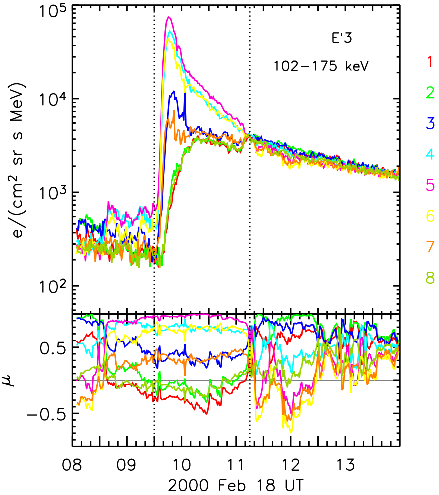

max
decay
onset
μ
10^{-29}
10^{-30}
10^{-31}
10^{-32}
e/(cm² sr s MeV)
0
30
60
90
120
Time (min)
λ_r = 0.2 AU
λ_r = 0.6 AU
λ_r = 0.9 AU


λr = 0.6 AU
e/(cm2 sr s MeV)
Time (min)
max
onset
decay
μ
1
2
2 –
Long injection
1 –
Short injection

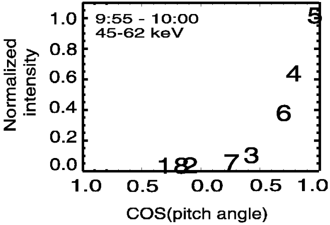

STEREO
A
SOHO
GOES
Wind
ACE
STEREO
B



$$\mu = \cos\theta = -\mathbf{s} \cdot \mathbf{B}$$



- Pitch-angle distribution

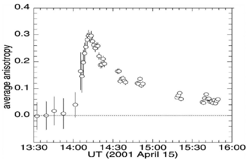


(Haggerty & Roelof 2002)

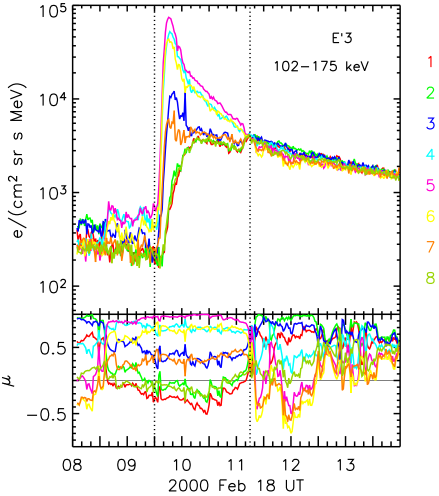
- First-order anisotropy

$$F(\mu) = A_0 + A_1\mu + \ldots$$

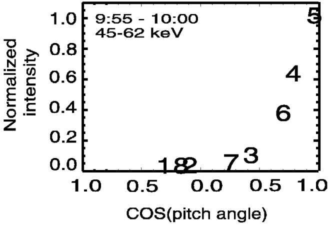
$$\frac{A_1}{A_0} = 3\langle\mu\rangle$$



(Maia et al. 2007)



- Pitch-angle distribution



(Haggerty & Roelof 2002)

- First-order anisotropy

$$F(\mu) = A_0 + A_1\mu + \dots$$

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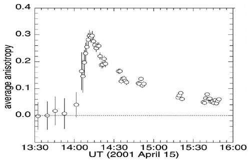
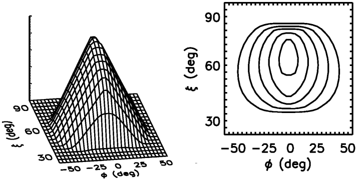
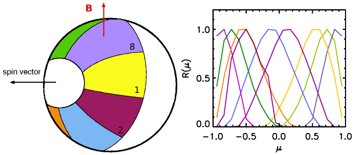


(Maia et al. 2007)

- Angular response of a sector
  - Isotropic distr. seen by a rotating conical aperture



  - IMF vector → Telescope view boundaries



(Agueda et al. 2008)

- Modeled sectored intensities $M_l^s(t;\lambda_r)$ in sector s and energy interval l can be expressed as

$$\boxed{M_l^s(t;\lambda_r) = \int_{T_1}^{T_2} dt'\; g_l^s(t,t';\lambda_r)q(t')}$$

where

$$g_l^s(t,t')=\int_0^\pi d\xi \int_0^{2\pi} d\phi R^s(\xi,\phi)\frac{1}{\Delta E_l}\int_{E_l}^{E_l+\Delta E_l} dE\;\; G(\mu(\xi,\phi,t),t-t',E)$$

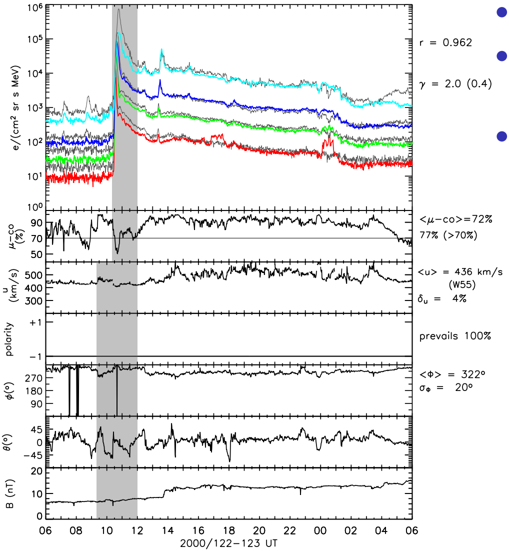
- We determine the injection function of NR electrons solving the equation

$$||\vec{J} - \mathbf{g}\cdot\vec{q}|| \sim 0$$

subject to the constraint that $q_j \geq 0\; \forall j$

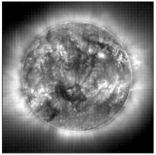
- We use the non-negative least squares (NNLS) method of Lawson & Hanson (1974).

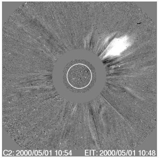
Assumptions	Parametrized injection profile	Obtain it from the fit
Data	Spin-averaged intensities and $<\mu>$	Pitch-angle distributions
Best fit	Eye ball	Define an objective goodness-of-fit estimator
	Dröge (2000), Bieber et al. (2001) Kartavykh et al. (2007), Maia et al. (2007)	Maia et al. (2007) Agueda et al. (2008,2009)

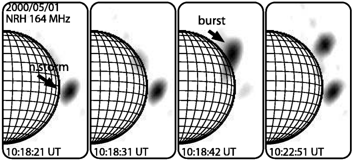


- **Flare:** M1.1, N20W54
- **CME:** $v_{\mathrm{CME}} = 1360\ \mathrm{km\ s^{-1}}$, $\Delta = 20^{\circ}$
- Outward moving radio source

(Pick et al. 2003)





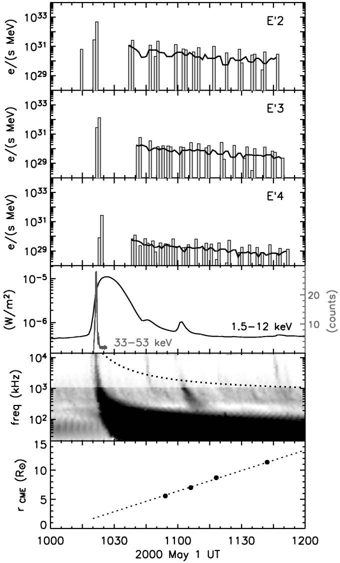


Best-fit parameters:

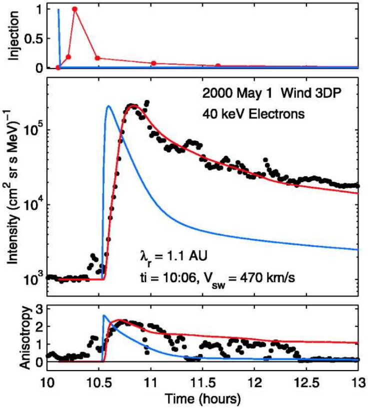
- $\lambda_r = 0.9$ AU
- The injection profile shows two components

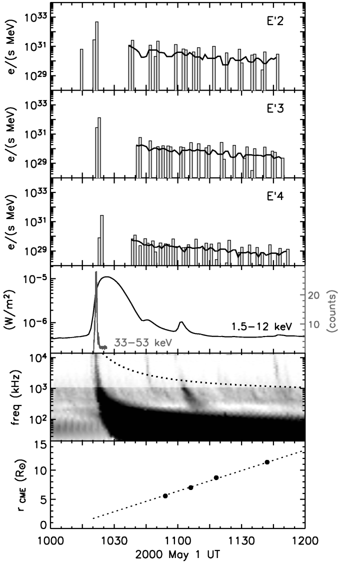
Short	~2.5 min	~75%	hard-X ray type III radio burst
Extended	~80 min	~25%	white-light CME radio emission

(Agueda et al. 2008)



Kartavykh et al. (2007)





Agueda et al. (2009):

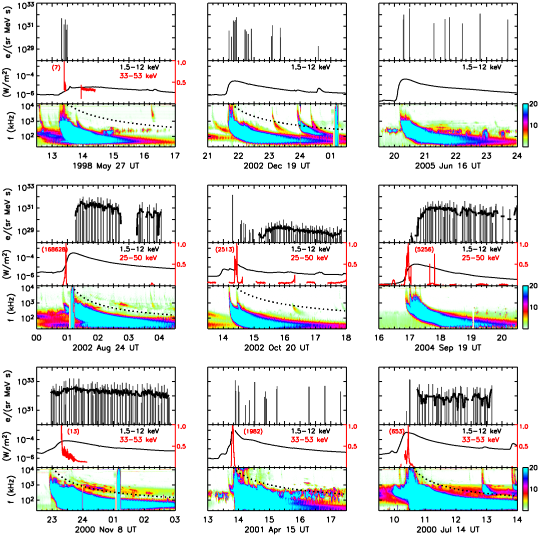
Transport conditions:

$\lambda_r = 0.9$ AU; 2/11

$\lambda_r < 0.2$ AU; 9/11

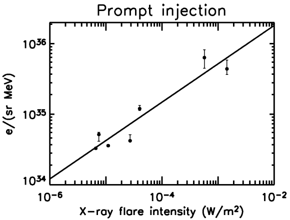
Injection components:

Short (< 15 min)	Extended (> 1 h)	
✓	×	4/11
×	✓	4/11
✓	✓	3/11



Prompt

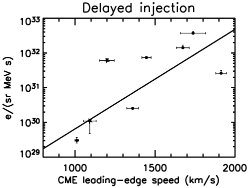
- beginning within the rise phase of the soft X-ray flux
- at low energies, within 10 min of the type III radio emission
- accompanied by hard X-ray emission



$$\log N_e = 0.54(\pm 0.08) \log I_x + 37.3(\pm 0.4)$$

Delayed

- beginning after the peak of the soft X-ray flux
- associated with intermittent radio emissions at the height of the CME leading edge or below
- in some cases, also with type II radio bursts



- Simulation-based analysis have provided conclusive evidence that the injection of heliospheric NR electrons is related to both flares and coronal shocks.
- The derived injection profiles show two types of injection episodes: short (< 15 min) and extended (> 1 h).
- The timing of the short injection episodes agrees with the timing of the hard X-rays and radio type III bursts.
- Extended injection episodes seem to be related to intermittent radio emissions at the height of the CME leading edge or below, and type II bursts.
- We conclude that there is a continuous spectrum of scenarios that allow for either flare or coronal shock injection, or both, and that this can occur both under strong scattering conditions and under almost scatter-free propagation conditions.

SEPSERVER: Data Services and Analysis Tools for Solar Energetic Particle Events and Related Electromagnetic Emissions

Start date: January 2011, **Duration:** 3 years

- Collaborative Project funded through the European 7th Framework Programme.
- It is coordinated by the University of Helsinki.
- 11 European partners: UH, CAU, CNRS, UB, U. Turku, UO,UNI WUE, NOA, UOI, AIP, DHC
- Several collaborating partners from Europe and the US.

SEVENTH FRAMEWORK PROGRAMME

SEPServer FP7 Project

The SEPServer project will produce an Internet server for the investigation of the origin and transport of SEPs.

It will provide:

- in-situ SEP and plasma data for several missions (SOHO, ACE, Wind, Ulysses, STEREO and Helios)
- related electromagnetic observations and state-of-the-art analysis methods
- a comprehensive catalog of SEP events observed over solar cycle 23
- numerical simulation results and inversion methods for SEP event analysis

SEVENTH FRAMEWORK PROGRAMME