Interplanetary transport simulations to infer SEP release timescales

Neus Agueda
University of Barcelona

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International School of Space Science
Heliospheric physical processes
for understanding Solar-Terrestrial Relations

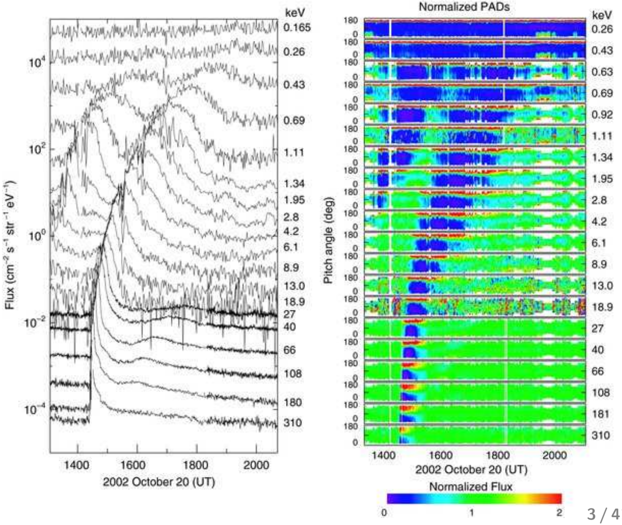
Outline

- What are SEP events?
  - and why do we care?
- How are they measured?
  - directional distributions
- How do they propagate in interpanetary space?
  - the interplanetary magnetic field
  - particle transport models
  - the power of convolution
- SEP release timescales
  - data-driven methods
  - forward/inverse modeling
  - SEPinversion software

What are SEPs?

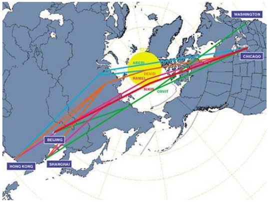
Solar Energetic Particles Seen as increases in counting rates of ions and/or electrons of energies usually above several keV and up to GeV in the most energetic cases

- *solar*: assumed to originate at the Sun
- *energetic*: above a few hundred keV
- *particles*: ions (mostly H, He like the Sun) + electrons

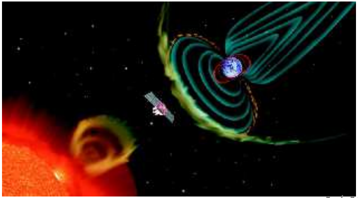


(Wang et al. 2011)

- Earth effects
    - SEPs hitting the Earth's atmosphere excite atoms and create aurora
    - radiation hazard for Earth-orbiting spacecraft: *degradation, onboard electronics malfunction, mission loss*
    - threat for astronauts on exploratory missions
    - part of geomagnetic storms which can cause black outs
    - major disturbances of radio communications in polar regions



- A sample of the Sun
    - one of the most accurately measured solar samples
    - if we can just figure out the details of creating them and getting them here



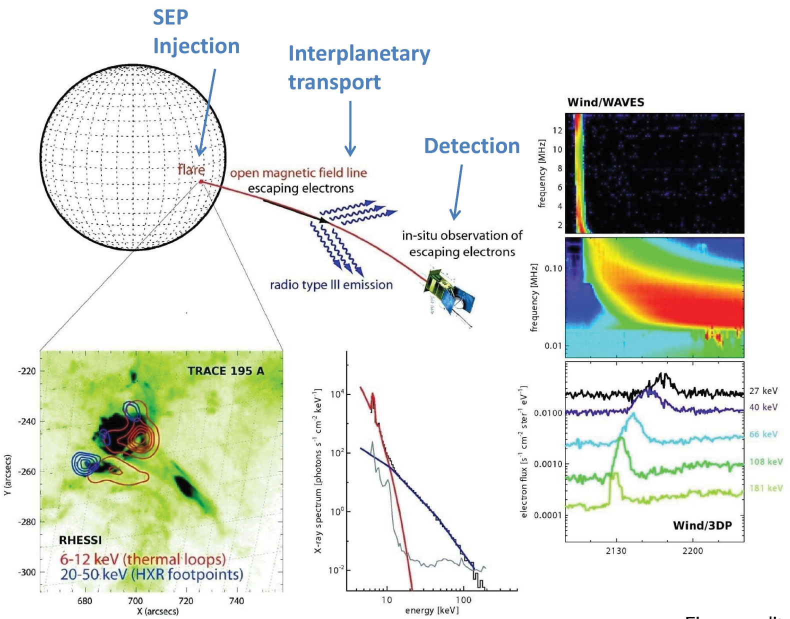
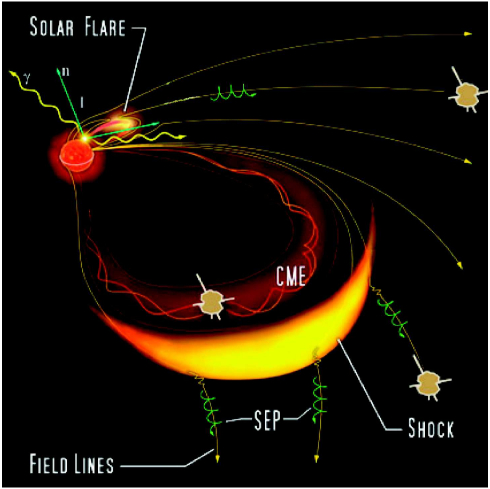


Figure credit: S. Krucker



Particle Release

↓

Interplanetary Transport

↓

In-situ Observation

- We need a link between SEP measurements at the S/C location and the Sun.

- SEP Transport Model + Detector Response
  ⟶ To unfold the release timescales of SEPs

Depending on the particle characteristics -their energy range and directional characteristics, their mass and charge, their intensities, and time variations- quite different measurement techniques and instrument designs must be employed. von Rosenvinge et al. (1995)

- **Dynamic range:** extends over 18 orders of magnitude in flux and 7 orders of magnitude in energy/nucleon.
- **Energy Ranges:** different instruments to cover the whole spectra
- **Time Resolution:** driven by science objectives, S/C location
- **Angular Coverage:** Rotating detector to scan different directions. A three-axis stabilized spacecraft is adequate as long as one field-of-view "faces" the Sun.

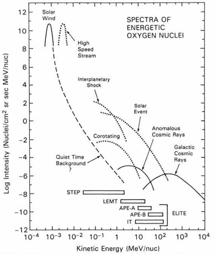
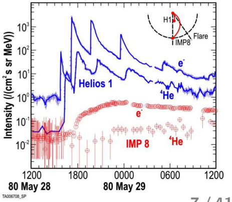


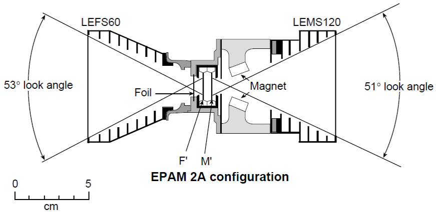
Fig. 2-1. Typical oxygen spectra for different populations of interplanetary particles. The energy ranges for each EPACT telescope are also shown.



Wibberenz & Kallenrode (2006)

Solid State Detectors

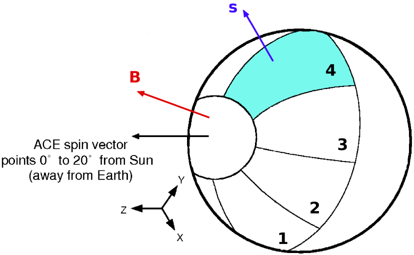
- They are used for electrons and ions with energies above about 20 keV.
- High sensitivity vs. resources



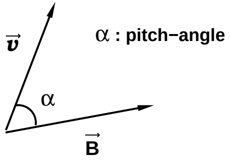
- The particle energy loss is related to the total energy of the incident particle
- Several SSD detectors can be used to achieve the desired energy range.

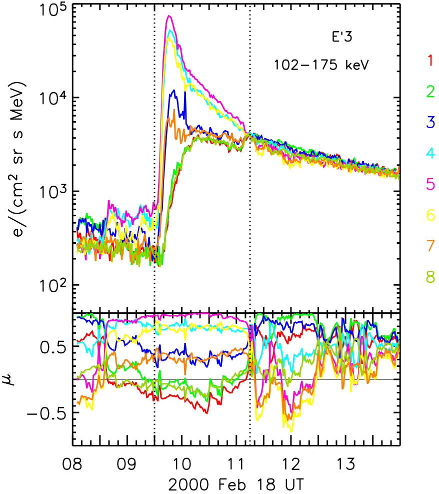
collimator
foil
stack of detectors
anti-coincidence
magnet

In-situ Sectored Intensities

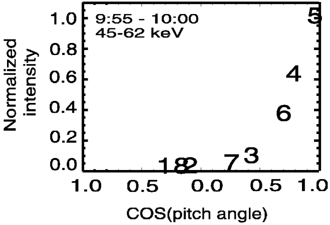


$$\boxed{\mu = \cos\alpha = -\mathbf{s}\cdot\mathbf{B}}$$





- Pitch-angle distribution

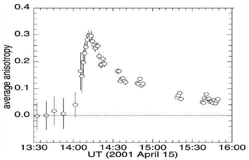


(Haggerty & Roelof 2002)

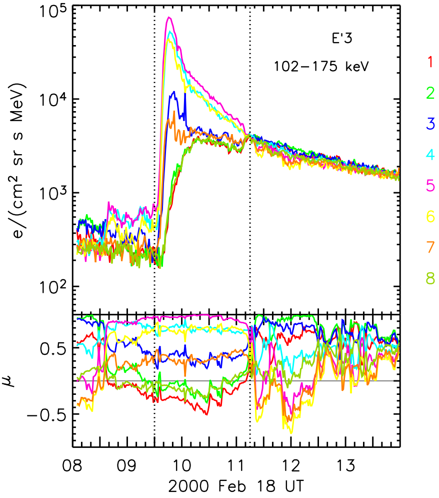
- First-order anisotropy

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

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



(Maia et al. 2007)



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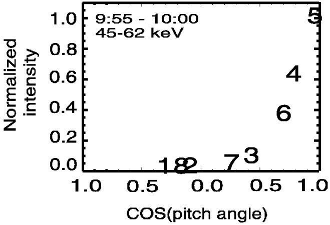

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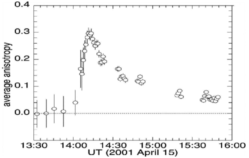
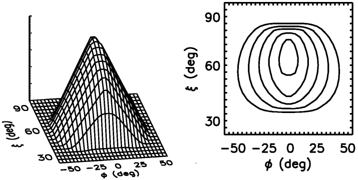
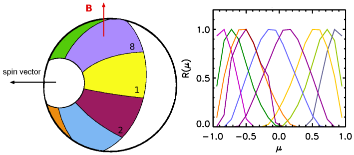


(Maia et al. 2007)

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

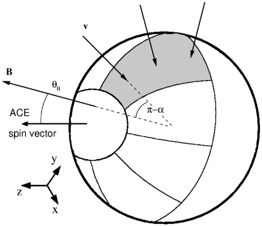


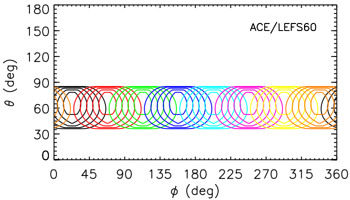
  - IMF vector → Telescope view boundaries

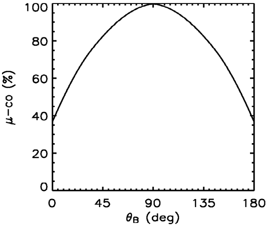


(Agueda et al. 2008)

ACE/LEFS60 (Ulysses/LEFS60) → Sectors







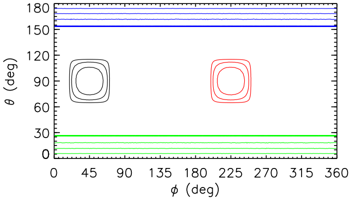
STEREO/SEPT → Fields of View

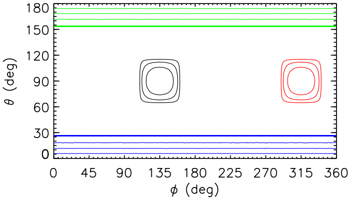
1: Sun

2: Anti-Sun

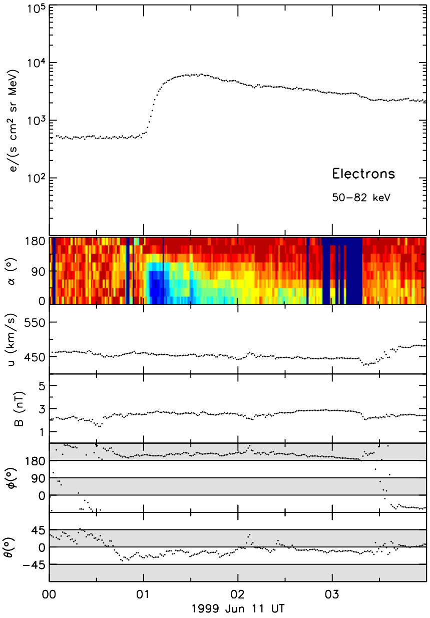
3: North

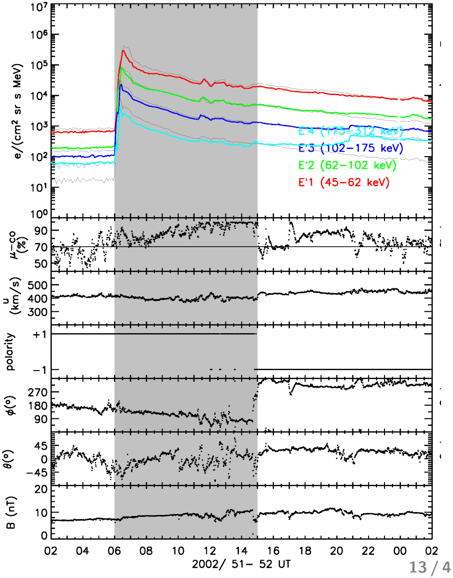
4: South

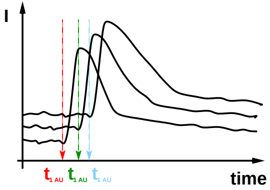




Wind/3DP → 4π: Pitch-Angle Distributions!

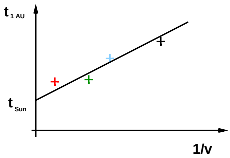

e/(s cm² sr MeV)
Electrons
50−82 keV
α (°)
u (km/s)
B (nT)
φ(°)
θ(°)
00
01
02
03
1999 Jun 11 UT


e/(cm² sr s MeV)
E'4 (175−312 keV)
E'3 (102−175 keV)
E'2 (62−102 keV)
E'1 (45−62 keV)
μ−co (%)
u (km/s)
polarity
φ(°)
θ(°)
B (nT)
2002/ 51− 52 UT

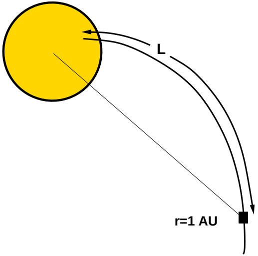


$$t_{1\ \mathrm{AU}}(E) = t_{\mathrm{Sun}} + \frac{L}{v(E)}$$

From a velocity dispersion analysis:



Assuming a nominal path length:



Assumptions:

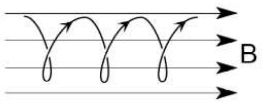
- Simultaneous injection
- Energy-independent L

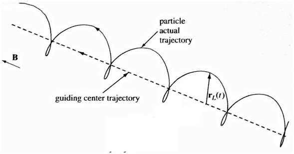
- Scatter-free transport
- $L = 1.2$ AU

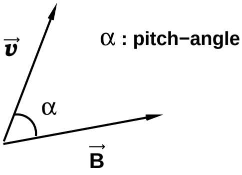
Problems:

(Kahler & Ragot 2006)

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







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

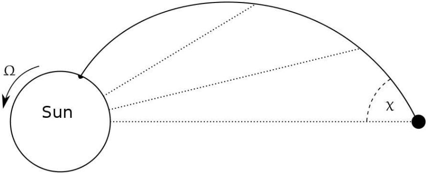
- **Colisionless plasma:** SEPs can travel through the heliosphere with a negligible chance of hitting each other or even hitting one of the much more numerous particles of thermal energy which constitute the solar wind.
- Their trajectories are shaped by the **interplanetary magnetic field** (IMF): smooth average Archimedean spiral (Parker 1958) with superimposed irregularities
- **Guiding center approximation:** The motion of the GC is the effective motion of the particle averaged over many gyrations

Length of the field line

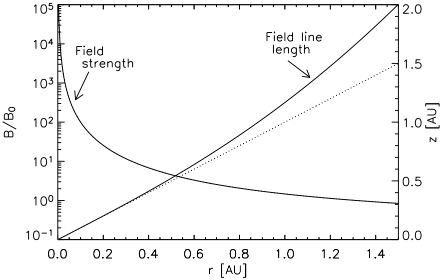
$$z(r) = \frac{a}{2}\left[\ln\left(\sqrt{1+\frac{r^2}{a^2}}+\frac{r}{a}\right)+\frac{r}{a}+\frac{r}{a}\sqrt{1+\frac{r^2}{a^2}}\right]$$

where $a = u/\Omega$

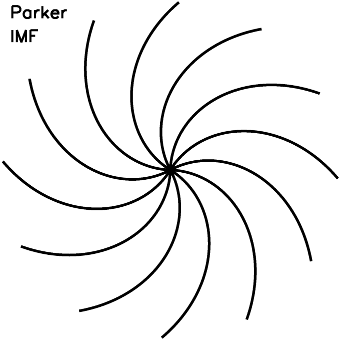
$$\begin{array}{ll} z \simeq r & \text{for } (\frac{r}{a})^2 \ll 1 \\ z \simeq r^2/2a & \text{for } (\frac{r}{a})^2 \gg 1 \end{array}$$



$\chi \sim 30^\circ$ at 0.5 AU
$\chi \sim 45^\circ$ at 1.0 AU
$\chi \sim 87^\circ$ at 5.0 AU



Magnetic field strength



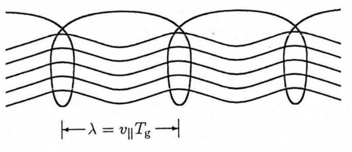
$$B(r) = B_0 \left(\frac{r_0}{r}\right)^2 \sqrt{1 + \left(\frac{r}{a}\right)^2}$$

where $a = u/\Omega$

$$\begin{array}{ll} B(r) \propto 1/r^2 & \text{for } (\frac{r}{a})^2 \ll 1 \\ B(r) \propto 1/r & \text{for } (\frac{r}{a})^2 \gg 1 \end{array}$$

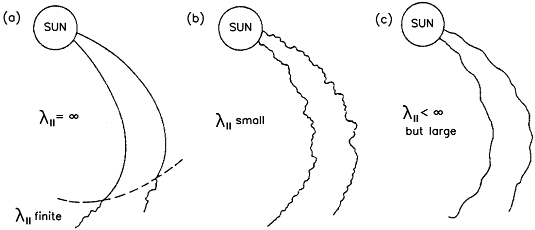
- 1st adiabatic invariant: $\frac{\sin\alpha}{B} = \text{const.}$
- Pitch angle α decreases when a particle moves in a weaker B $\longrightarrow$ The particle motion becomes more focused in the field direction (**focusing effect**)
- Particles released with $\alpha = 90^\circ$ at the Sun appear to come in a narrow cone only $\sim 1^\circ$ wide at 1 AU

- Particles are scattered by magnetic irregularities which are in resonance with the particle gyration.



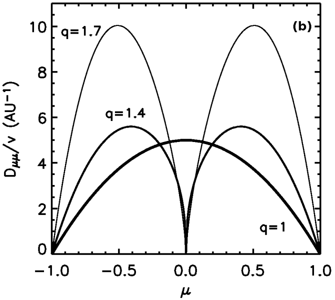
- As a cumulative result of many small random changes in pitch-angle, SEPs experience a macroscopic change in direction.

- An important special case which has been studied extensively is the quasilinear theory (QLT) of pitch-angle scattering and various modifications.



- Diffusion coefficient (Jokipii 1966)

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



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

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

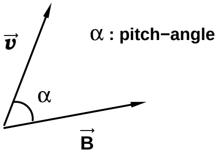
$$\boxed{\lambda_{||} = \frac{3v}{8}\int_{-1}^{1} \frac{(1-\mu^2)^2}{D_{\mu\mu}} d\mu = \frac{3v}{4}\int_{-1}^{1} \frac{(1-\mu^2)}{\nu(\mu)} d\mu}$$

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)

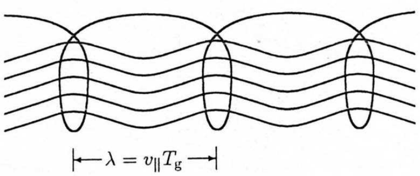
Focused transport equation (Roelof 1969)

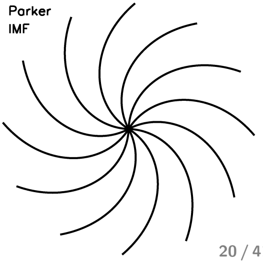
$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L}v\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = q(z,\mu,t)$$



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

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





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- Finite-difference numerical method:

  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

Model Assumptions:

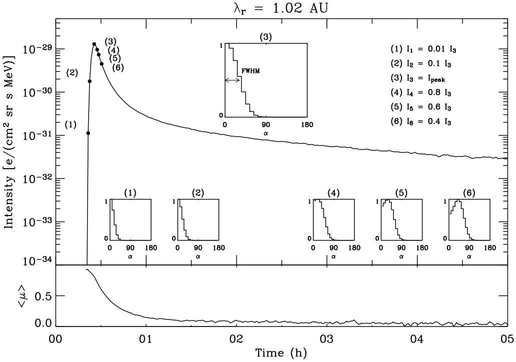
- Static source at $2R_\odot$
  Power spectra $\propto E^{-\gamma}$
- Archimedean IMF
- Scattering model

Model Parameters:

- Source spectral index (γ)
- Solar wind speed
- Diffusion coefficient ($D_{\mu\mu}$)
- Mean free path (λ_r)

The results of the simulations are

- differential intensities at the S/C location
- resulting from an instantaneous injection
- normalized to one particle injected per steradian



45-62 keV

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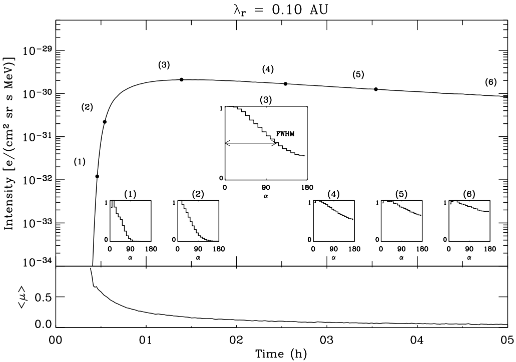
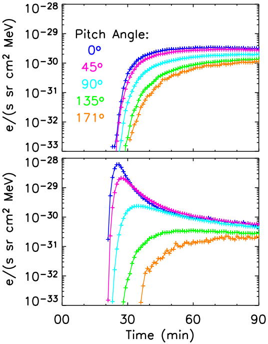
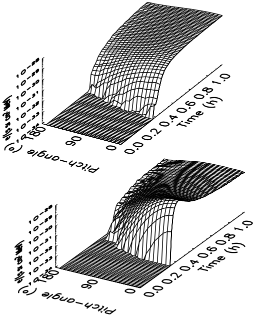


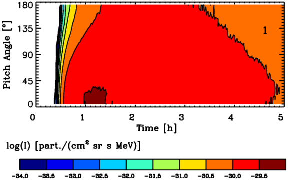
45-62 keV

$\lambda_r = 0.10$ AU

$\lambda_r = 1.02$ AU



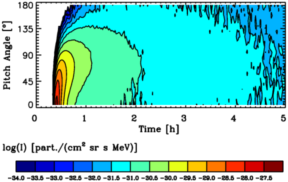




IP scenario:

Electron source at 0.01 AU,
$E^{-\gamma}$ with γ=3.0, 24–400 keV
V_{sw}=400 km/s
λ_r=0.10 AU; Isotropic

Generated by SEPServer



IP scenario:

Electron source at 0.01 AU,
$E^{-\gamma}$ with γ=3.0, 24–400 keV
V_{sw}=400 km/s
λ_r=1.02 AU; Isotropic

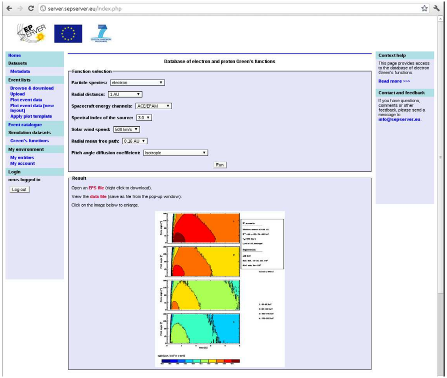
Generated by SEPServer

Database of Green's functions available through the SEPServer website!

Selection:

1. Particle specie (electron, proton, relativistic particle)
2. Transport scenario (γ, u, λ_r, $D_{\mu\mu}$)
3. Registration bins (or S/C)

`http://server.sepserver.eu`



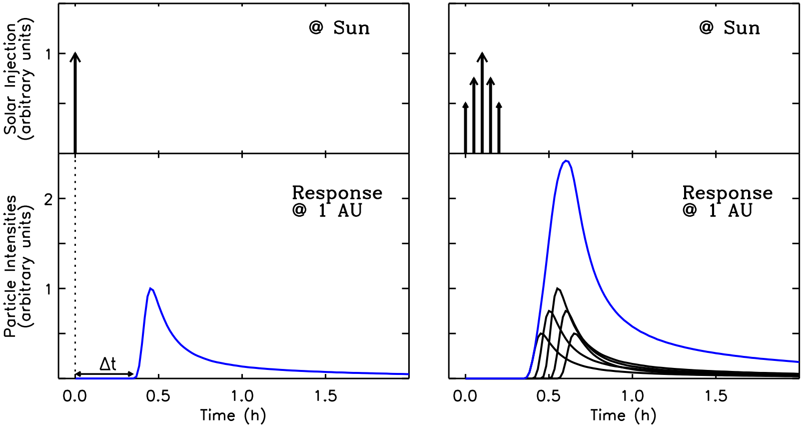
Download:

- Results (text data file or EPS plot)
- Documentation

Computed for

- different **species**
  - Near-relativistic electrons (>24 keV)
  - Protons (1-11 MeV)
  - Relativistic particles ($v = c$)
- a total of 2000 **source and transport scenarios**
- different spacecraft **locations**
- different **energy channels**, **time** and **pitch-angle resolution**

Specie	**Experiment**	**Location**	**Channels**	δt **(min)**	$\delta\alpha$ **(°)**
e	ACE/LEFS60	1 AU	45–312 keV	1	9
e	Ulysses/LEFS60	>1 AU; 3 loc	42–290 keV	4	9
e	STEREO/SEPT	1 AU	45–375 keV	1	9
e	Wind/3DP	1 AU	24–400 keV	1	22.5
p	Wind/3DP	1 AU	1–11 MeV	1	22.5
-	—	1 AU	$v = c$	0.5	9



$$\boxed{I(t) = \int_0^{\infty} q(t')g(t-t')dt'}$$

Green's function

λ_r; (t,α,E)

Injection Function

- **Forward Modeling:** Prediction of the measurements with a given set of model parameters. Inductive.
  - ↓ Trial and error. Difficult to scan all the parameter's space

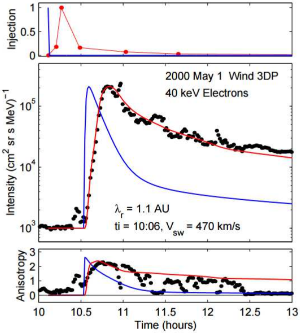
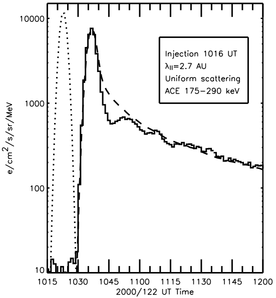
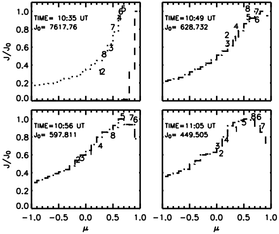


Figure 1: Fits to the time-intensity and anisotropy profiles of 40 keV electrons observed on Wind after the 2000 May 1 flare, assuming a constant $\lambda_r = 1.1$ AU.



Kartavykh et al. (2008)



Agueda et al. (2008)

- **Inverse Modeling:** Use of the measurements to infer the actual values of the model parameters. Deductive.
  - ↑ Systematic exploration of the parameters space. Reproducible.
  - ↑ No a priori assumption about the injection profile.

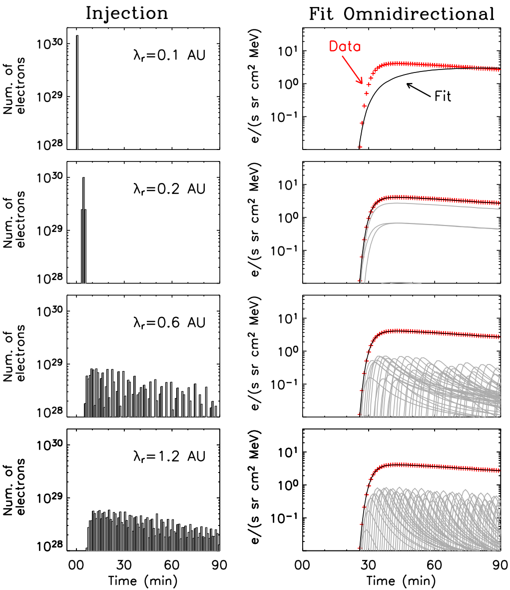
The injection function can be determined by solving the least squares problem

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

Observations   Modeled intensities

subject to the constraint that $q_j \geq 0 \ \forall j$ (NNLS; Lawson & Hanson 1974)

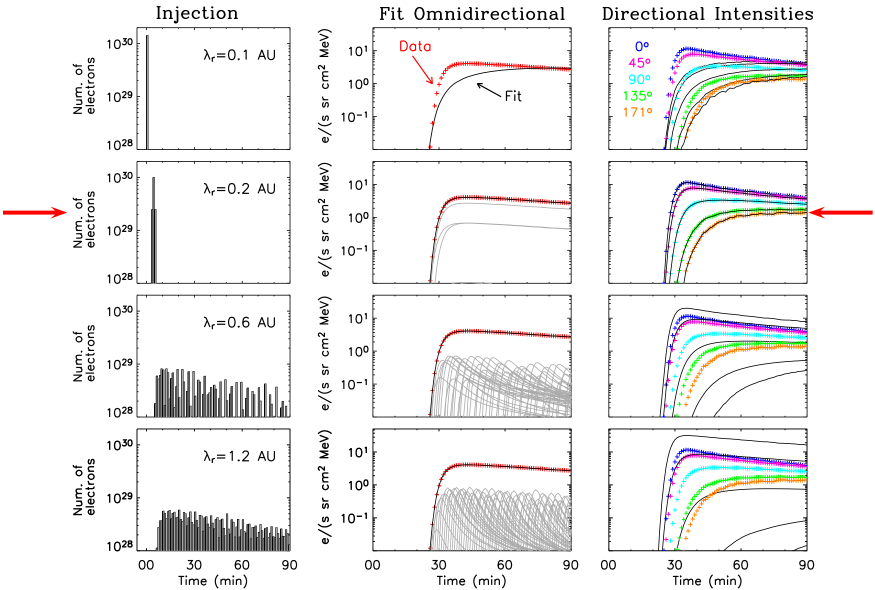
The problem is ill-posed if $\vec{J}$ are omni-directional intensities
The problem is well-constrained if $\vec{J}$ are directional intensities



Too much freedom!

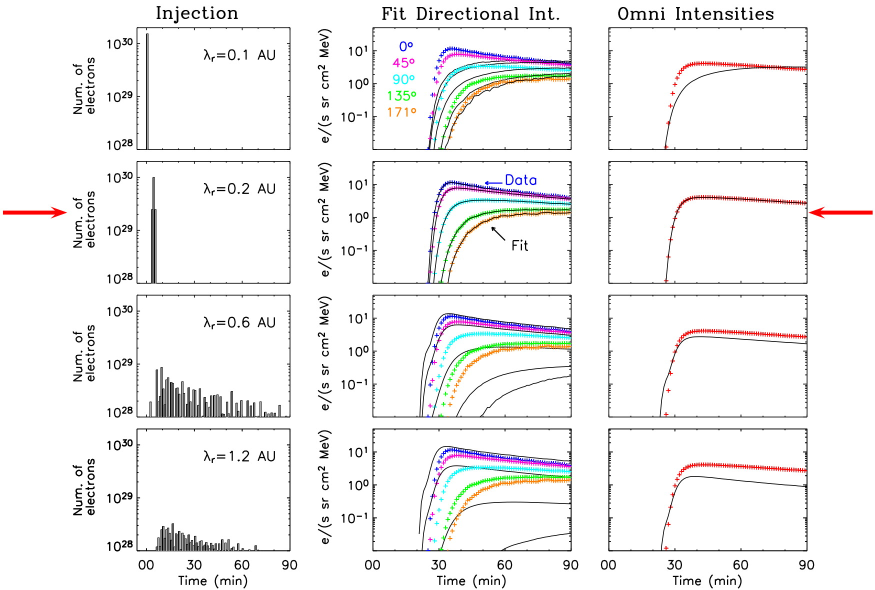
More constraints:

a) 1st order anisotropy
b) Directional Intensities



Injection
Fit Omnidirectional
Directional Intensities
Num. of electrons
λr=0.1 AU
λr=0.2 AU
λr=0.6 AU
λr=1.2 AU
e/(s sr cm² MeV)
Data
Fit
0°
45°
90°
135°
171°
Time (min)

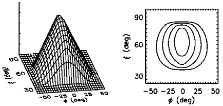
Inversion of Directional Intensities



Simulated Green's Functions of particle transport

$\otimes$

Sectors' Response



Sectored Green's Functions of particle transport

Sectored intensities measured by the S/C

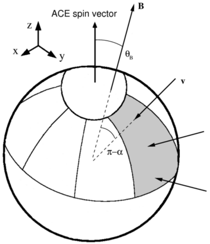
Deconvolution

Injection Profile for each λ_r

Goodness of fit ?

Best fit λ_r and Injection Profile

$$\zeta(\lambda_r) = \sum_{i=1}^{n} \left(\log \frac{I_i}{M_i^*(\lambda_r)+b} \right)^2$$



SEPinversion

IDL Software for Analyzing Solar Energetic Particle Events

Last Revised: 03/07/2013

FAQ

1. **What is this software for?**

   This software is intended to facilitate the study of the sources of solar energetic particle (SEP) events observed by spacecraft in the heliosphere, as well as the conditions under which SEPs propagate in interplanetary space, from the source to the spacecraft.

2. **What does this software do?**

   It fits SEP observations by the *ACE*, *Ulysses*, *Wind* and *STEREO* spacecraft. It makes use of a database of simulation results of a transport model to fit the observations. The problem is constrained by using the most direct form of directional SEP intensities provided by each spacecraft, such as sectored intensities for *ACE* and *Ulysses*, fields of view intensities for *STEREO* and pitch-angle distributions for *Wind*.

3. **What do I need to run this software?**

   You need a Linux machine and a non-ancient version of IDL (i.e., at least IDL Version 6.0).

4. **Where can I get this software?**

   The software is available through SEPServer.

5. **What do I get with the package?**

   You get a set of IDL routines for reading observational data and simulations results, solve the inversion problem (taking into account the instrument angular response, if necessary), and plot the results. The software consists of 39 routines, of which 33 were developed at the University of Barcelona while the remaining six are external to SEPServer. These include two routines from the IDL Astronomy User's Library (ydn2md.pro and ymd2dn.pro) and four routines from the IDL NNLS package developed to solve the non-negative least squares problem.

6. **Are there examples available to show how to use this software?**

   Yes! An input file template and directions on how to run SEPinversion are distributed with the package. Four test cases/examples (including *ACE*, *Ulysses*, *Wind* and *STEREO* observations) are available here.

7. **I found a bug. What should I do?**

   Please send me an e-mail (`n.agueda@ub.edu`) with a minimal sequence of commands that reproduces the error, and I will try to fix it.

✓ Source code

✓ User's Guide

✓ Examples

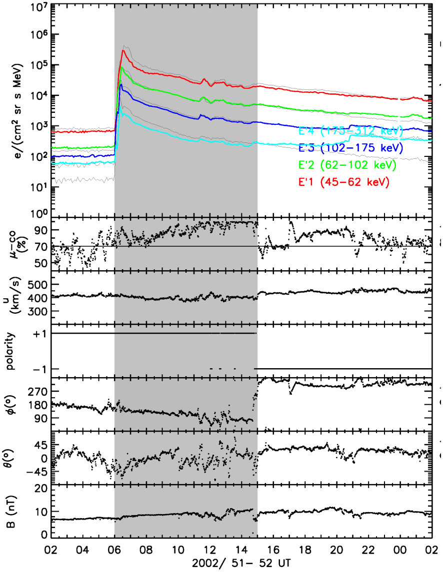
Goal: To invert in-situ SEP observations by *ACE*, *Ulysses*, *STEREO* or *Wind* to obtain information about the SEP release time profile and the IP transport conditions.

- Written in IDL
- It requires access to:
  1. Measurements (directional intensities + Field components)
  2. Simulations (Green's functions)

1. Timescales of NR Electron Release Processes in the Low Corona?
   Large sample of NR electron events observed at 1 AU
   (Agueda et al. 2008, 2009, 2014)
   Short ($<$15 min) flare-related vs. extended ($>$1 h) episodes

2. Angular Extent of these Processes?
   Four multi-spacecraft events observed by ACE and Ulysses and the two STEREOs
   (Agueda et al. 2012, Gomez-Herrero et al. 2015)
   Extent can be wide ($> 70^\circ$)

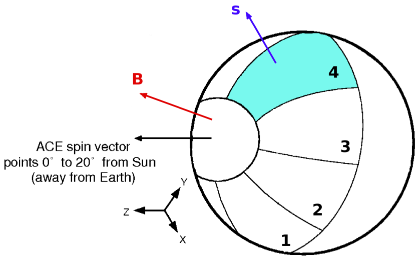
3. Effects of Interplanetary Structures?
   "Strange" events
   (Agueda et al. 2010)
   Interplanetary structures can shape SEP events (bidirectional PADs)

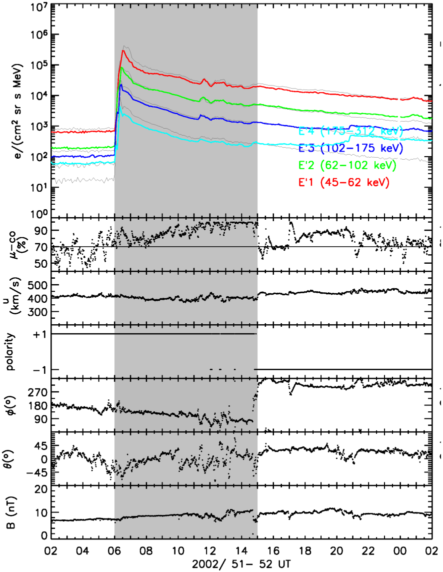


In-situ SEP data

- electrons
- 40–300 keV (0.4–0.7c)
- *Wind*/3DP (complete PADs)

  and/or
- *ACE*/EPAM (sectored intensities)





In-situ SEP data

- electrons
- 40–300 keV (0.4–0.7c)
- *Wind*/3DP (complete PADs)

  and/or
- *ACE*/EPAM (sectored intensities)

Remote EM data

- SXRs by *GOES*
- HXRs by *RHESSI*
- white-light by *SOHO*/LASCO
- radio by *Wind*/WAVES + NRH

Initial Sample

SEPServer Event Catalogue

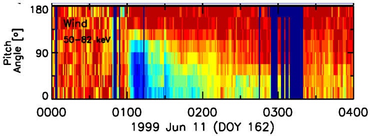
(Vainio et al. 2013)

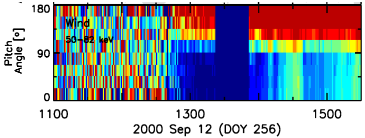
Selection Criteria

- No ICMEs in nearby IP medium
- Prominent event (>1 order of magnitude above background)
- Velocity dispersion at the onset
- Good observational coverage of the PADs
- Monotonic PAD evolution

→ Seven >50 keV electron events

Year	Date	DOY	Onset
1999	Jun 11	162	00:54
2000	Sep 12	256	12:30
2002	Feb 20	051	06:00
2002	Jul 07	188	11:49
2002	Aug 14	226	01:55
2002	Dec 19	353	21:55
2004	Nov 01	306	06:10

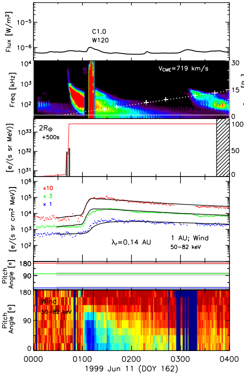


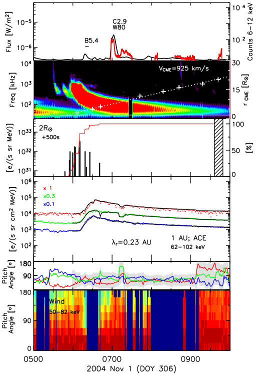


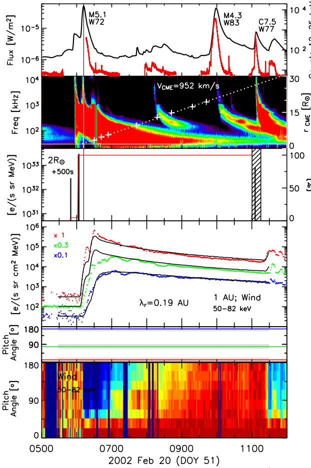
Inversion Results: Group I

- ✓ Good fits of the directional intensities
- ✓ λ_r-values are very similar for both S/C
- ✓ Short (<60 min) release of particles that agrees with the timing and duration of the type III radio bursts **reaching the local plasma frequency**

Event	λ_r (AU)
1999 Jun 11	0.16
2002 Dec 19	0.12
2002 Feb 20	0.27
2004 Nov 1	0.23





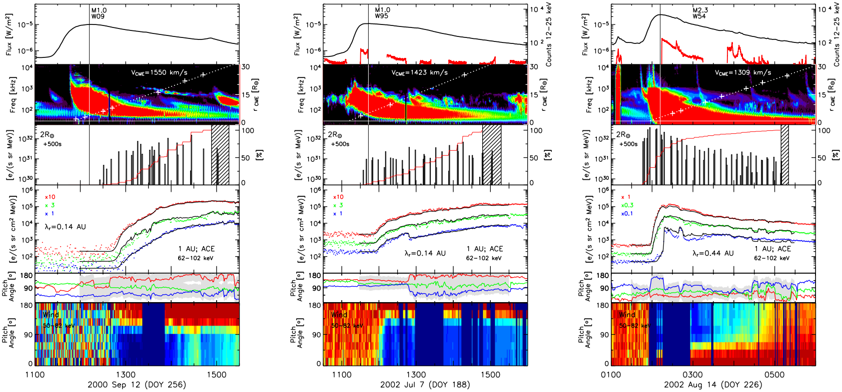


Inversion Results: Group II

- Only *ACE* observations can be inverted.
- Electron release extends for several hours.

Event	λ_r (AU)
2000 Sep 12	0.14
2002 Jul 7	0.14
2002 Aug 14	0.44

- Time extended acceleration in the corona revealed by type II radio emission and long decay radio and microwave emission.



Take away message

- SEP events are observed by particle detectors in space
- We can infer from in-situ observations characteristics of their interplanetary transport conditions and disentangle the release timescales at the Sun
- It's a double deconvolution problem: IP effects, detection
- Needs to be improved (denoising!!, Solar Orbiter)