Numerical simulations of the propagation of SEPs

Applications to the Study of the SEP Release Mechanisms in the Low Corona

Neus Agueda

University of Barcelona, Spain

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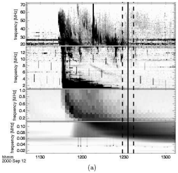
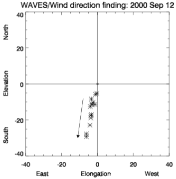
Electron Release → IP Transport → In-situ Observation





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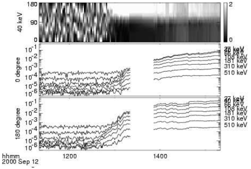
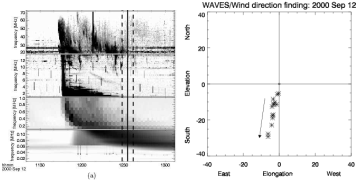
Simulations



Solar Sources

- Radio emission provides information about the location and temporal evolution of the source and it reveals a complex structure (Klein et al. 2005)
- Interacting particles vs. released particles (Krucker et al. 2007)
- Rapid expansion of open magnetic flux tubes (Klein et al. 2008)

Electron Release → IP Transport → In-situ Observation



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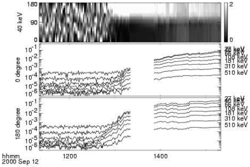
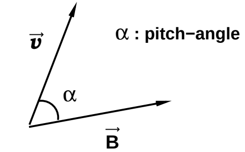
Simulations

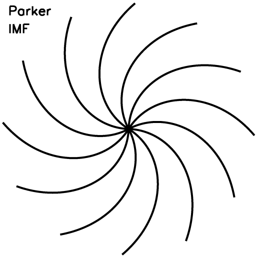


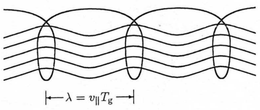
In-situ Observations

- From *Helios*, *Ulysses* and *STEREO* missions: Large events are seen at remote longitude/latitudes (Wibberenz & Cane 2006, Lario et al. 2003, Dresing et al. 2012)
- Release times inferred from VDA or TSA suggest up to half an hour delay with respect to the type III burst (Krucker et al. 1999, Haggerty & Roelof 2002)



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





Focused transport equation (Roelof 1969)

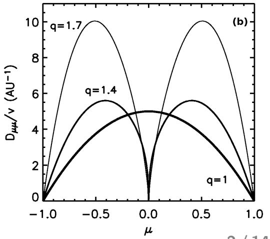
$$\frac{\partial f}{\partial t} + v\mu \frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) = q(z, \mu, t)$$

- 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)

Standard QLT (Jokipii 1966)

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

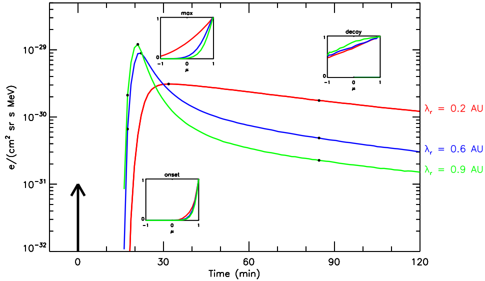
$$\lambda_{||} = \frac{3v}{8} \int_{-1}^{1} \frac{(1-\mu^2)^2}{D_{\mu\mu}} d\mu$$



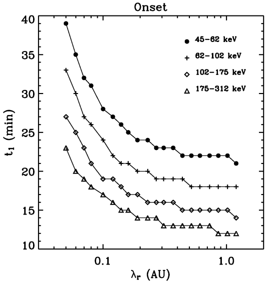
The results of the simulations are

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

→ **Green's functions of particle transport**



(Agueda et al. 2012)



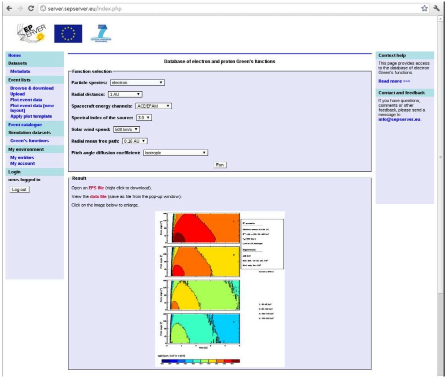
- Onset time: 12 and 23 min (175-312 keV), for $\lambda_r \in [0.05, 1.20]$ AU → IP scattering can delay the onset time by up to 11 min; 18 min (for 45-62 keV).
- FWHM @onset: 86° to 25° for $\lambda_r \in [0.05, 1.20]$ AU
  FWHM @peak: 180° to 36° for $\lambda_r \in [0.05, 1.20]$ AU

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)

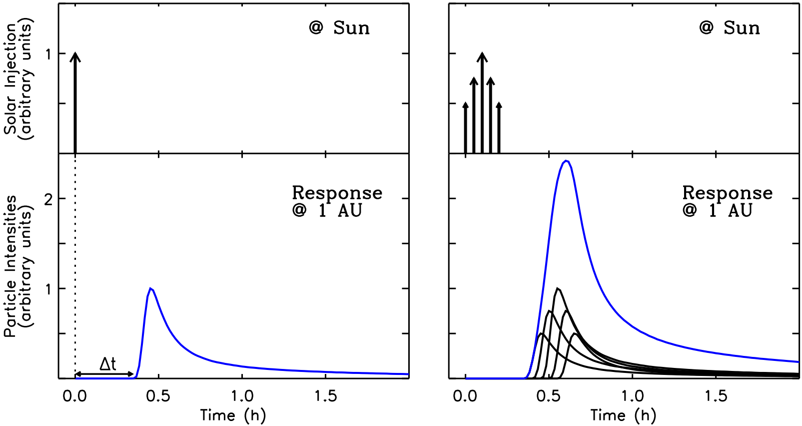
`http://server.sepserver.eu`



Download:

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

The Power of Convolution



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

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

- **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 priory assumption about the injection profile.

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

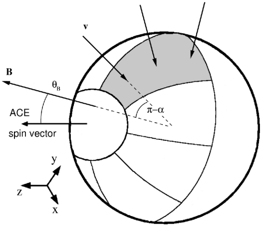
$$||\vec{J} - \mathbf{g} \cdot \vec{q}|| \sim 0$$

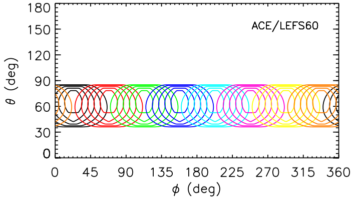
Observations — Modeled intensities

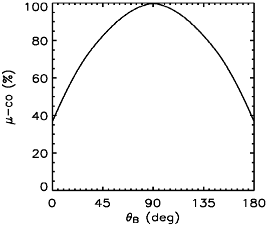
subject to the constraint that $q_j \geq 0 \; \forall j$

- The problem is ill-posed if $\vec{J}$ are omni-directional intensities ($n_{\text{unk}} = n_{\text{cns}}$)
- The problem is **well-constrained** if $\vec{J}$ are directional intensities ($n_{\text{unk}} \ll n_{\text{cns}}$)

ACE/LEFS60 (Ulysses/LEFS60) → Sectors

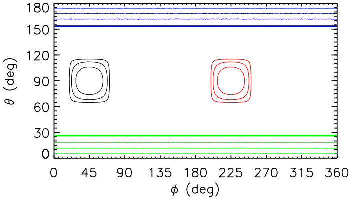


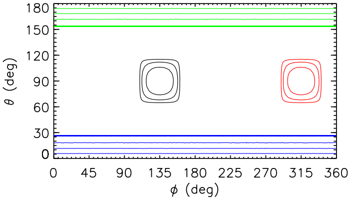




STEREO/SEPT → Fields of View

1: Sun
2: Anti-Sun
3: North
4: South





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

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.

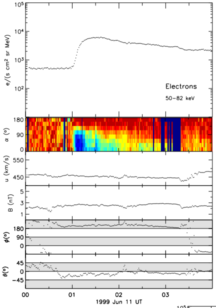
- Written in IDL and designed to run in a Linux platform
- Free software under GNU General Public License
- It requires access to:
  1. Measurements (directional intensities + Field components)
  2. Simulations (Green's functions)

Initial sample: 115 events from the SEPServer Catalog (Vainio et al. 2013)

Selection Criteria

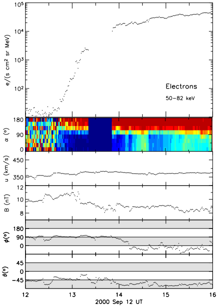
- No ICMEs in nearby IP medium
- Prominent event (>1 om above bkg)
- Velocity dispersion at the onset
- Good directional coverage
- No flux tube variations

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



Isotrop. in $\leq$2 h

Anisotr. PADs for >4 h



- We used SEPinversion to model each event

  1. Download from SEPServer Green's functions; assuming the solar wind speed measured in-situ, estimating the spectral index of the source

     20 values of $\lambda_r \in [0.05, 1.20]$ AU
     Anisotropic pitch-angle diffusion coefficient

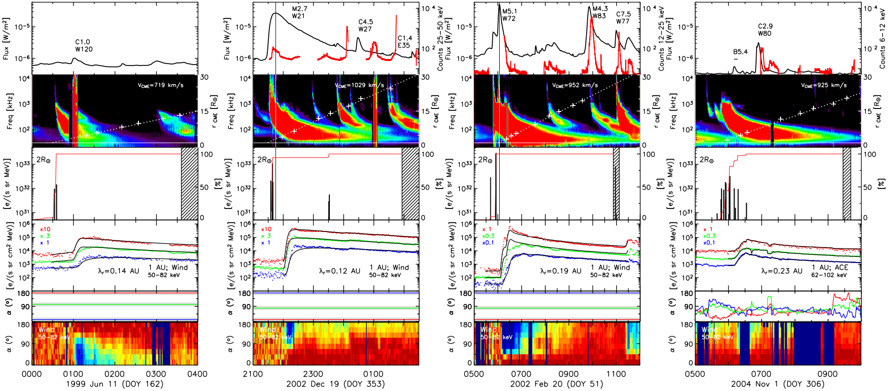
  2. Solve inversion problem for each transport scenario $\rightarrow$ Infer release time profile

  3. Determine the best fit scenario by comparing the data with the model results. Best fit = minimum squared differences between log(data) and log(model)

- *Wind* and *ACE* directional distributions can be explained. λ_r-values are very similar!

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

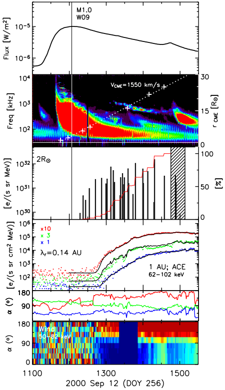
- The largest release of particles agrees with the timing and duration of the type III radio bursts reaching the local plasma frequency.

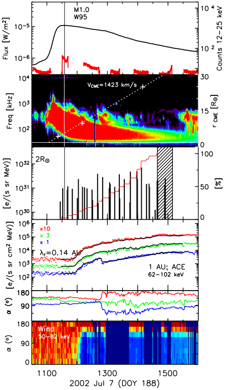


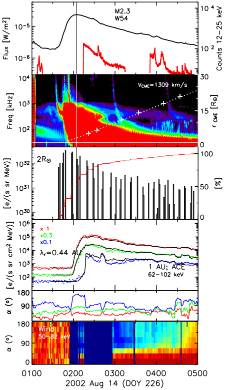
- Only *ACE* observations can be inverted.
- Electron release extends for several hours.

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 a type IV (NRH, 2000 Sep 12), long decay microwave emission (5 GHz, 2002 Aug 14) and type II radio emission.

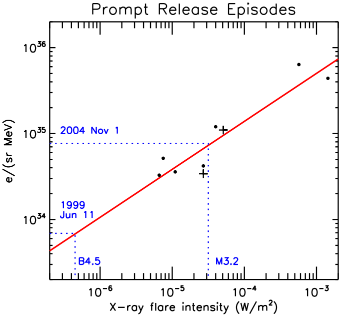






- **Sources**
  - Flare reconnection processes $\leftarrow$ Prompt events

    Obs. magnetic connection through field excursions in the corona?
  - Coronal shock, reconnection behind the CME? $\leftarrow$ Extended events
  - $V_{CME} \leq 1000$ km/s (prompt), $V_{CME} > 1300$ km/s (extended)



• *Agueda et al. (2009)*
+ *this study*

- **Rigidity dependent transport**
  - 50–80 keV electron release time histories are consistent with the onset of radio emission.
  - Fitting method suggests lower values of λ_r for higher energies.
  - If so, release timing in better agreement for prompt events.