Test Particle Simulations of Solar Energetic Particles using Parker Spiral and ENLIL Fields

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Thanks to: Markus Battarbee, Timo Laitinen, Mike Marsh.

Summary of Talk

- Motivation for modelling SEPs.
- The test particle approach to SEP modelling.
- Results using the Parker Spiral as input.
- The ENLIL solar wind model.
- Using ENLIL fields as input for test particle simulations.

Solar Energetic Particles

- Rapid reconfiguration of the magnetic field in the solar corona accelerates a population of energetic charged particles. SEPs can also be accelerated by shocks in CMEs.
- Produces a power-law distribution of particles.
- A fraction of these particles are able to propagate out into interplanetary space on “open” magnetic field lines.
- Events typically last from <1 day to several days. They can extend over a wide longitudinal range.

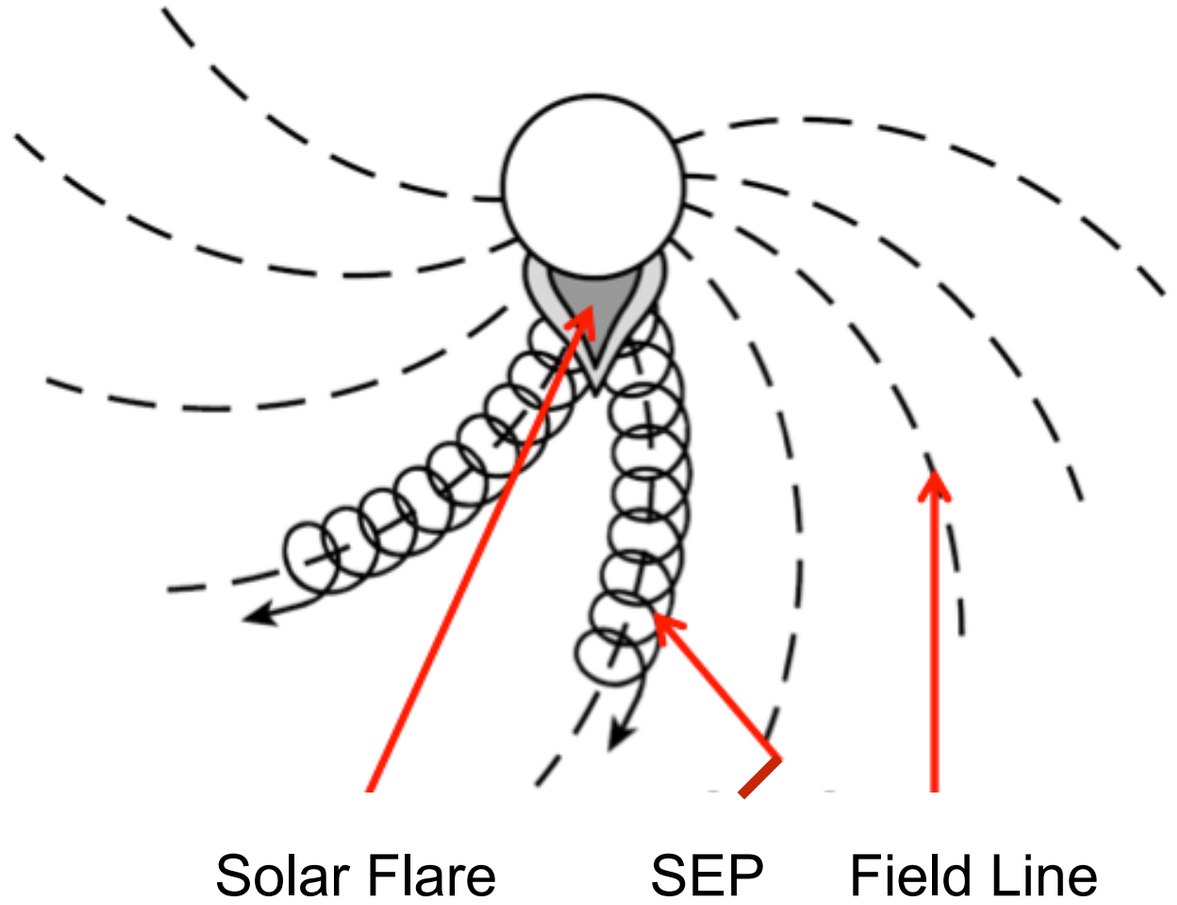
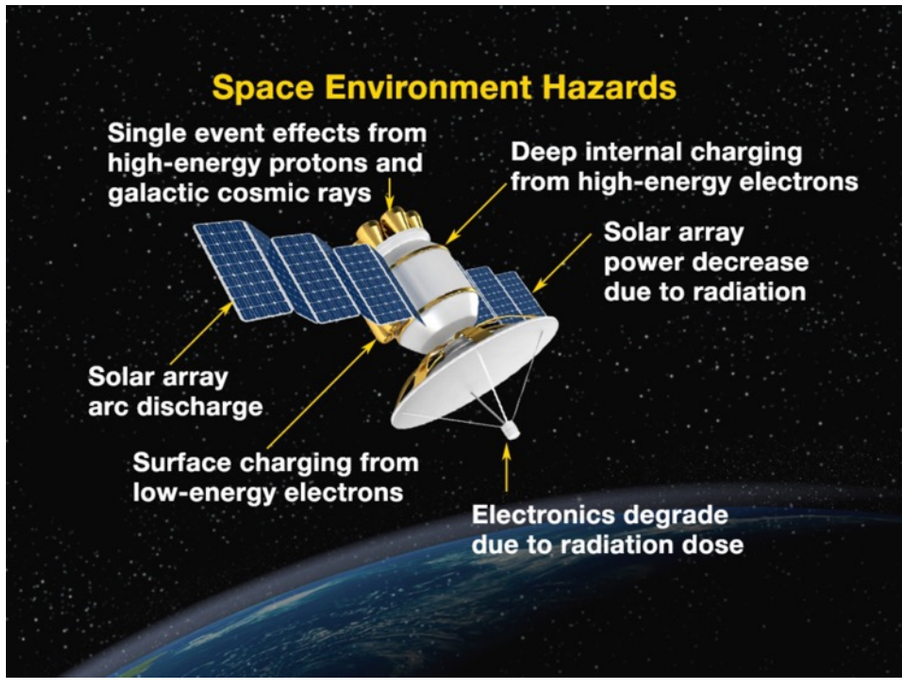


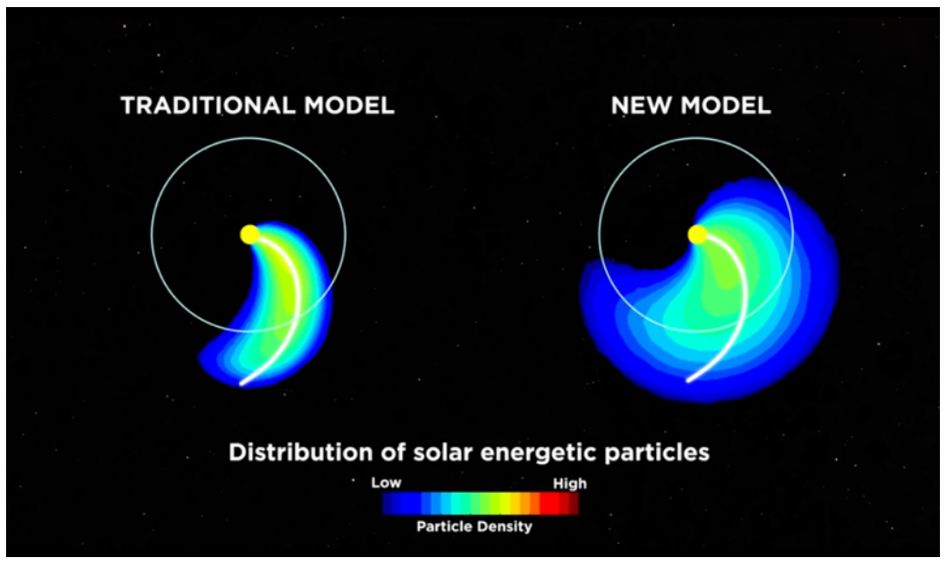
Figure courtesy of Reames (1999) & edited by Luke Barnard

Motivation for SEP Modelling

- SEPs are a key component of space weather.
- Radiation doses which are dangerous to humans in space or at high altitudes.
- Single particle events in satellite technology.
- Move towards operational space weather forecasting.



Above: www.nasa.gov.uk, Below: Timo Laitinen



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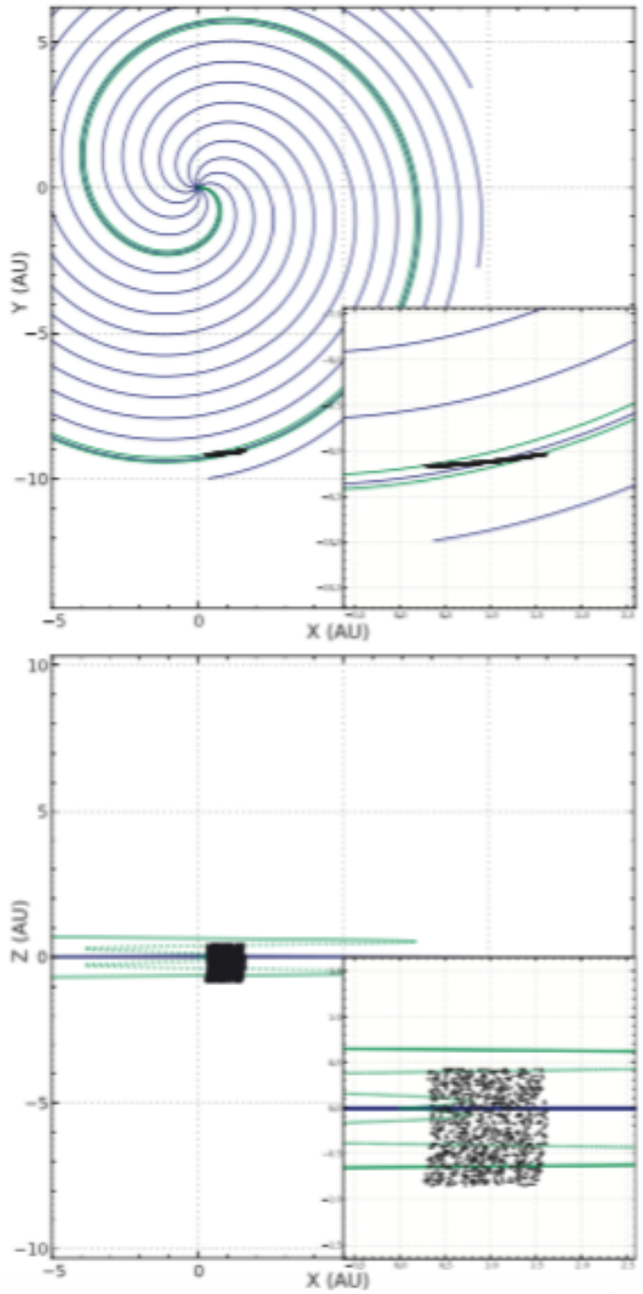
Test Particle Model - Inputs

Marsh et al. (2013)

- Model begins with an injection region of defined size at a given distance. The user can choose how many particles to begin in the region.

- The particles are injected into a Parker Spiral field. The solar wind speed and temperature is given by the user, as well as important parameters relating to diffusion (mean free path).

- It now also encompasses a heliospheric current sheet which can strongly influence the propagation of energetic particles (see Thomas, 2015).



Test Particle Model - How does it work?

- The particles from the injection region are propagated through the field according to the equation of motion on the right.

$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{1}{c}\frac{\mathbf{p}}{m_0\gamma} \times \mathbf{B}\right)$$

- Here p is the particle's momentum, t is time, q is charge, m0 is rest mass, and γ its Lorentz factor.

- The equation of motion is numerically integrated for each particle in a population.

$$\mathbf{B} = \frac{B_0 r_0^2}{r^2}\,\mathbf{e}_r - \frac{B_0\, r_0^2\, \Omega}{v_{\mathrm{sw}}}\,\frac{\sin\theta}{r}\,\mathbf{e}_\phi$$

- Random scattering is implemented with the level of scattering being influenced by the inputted mean free path (mfp).

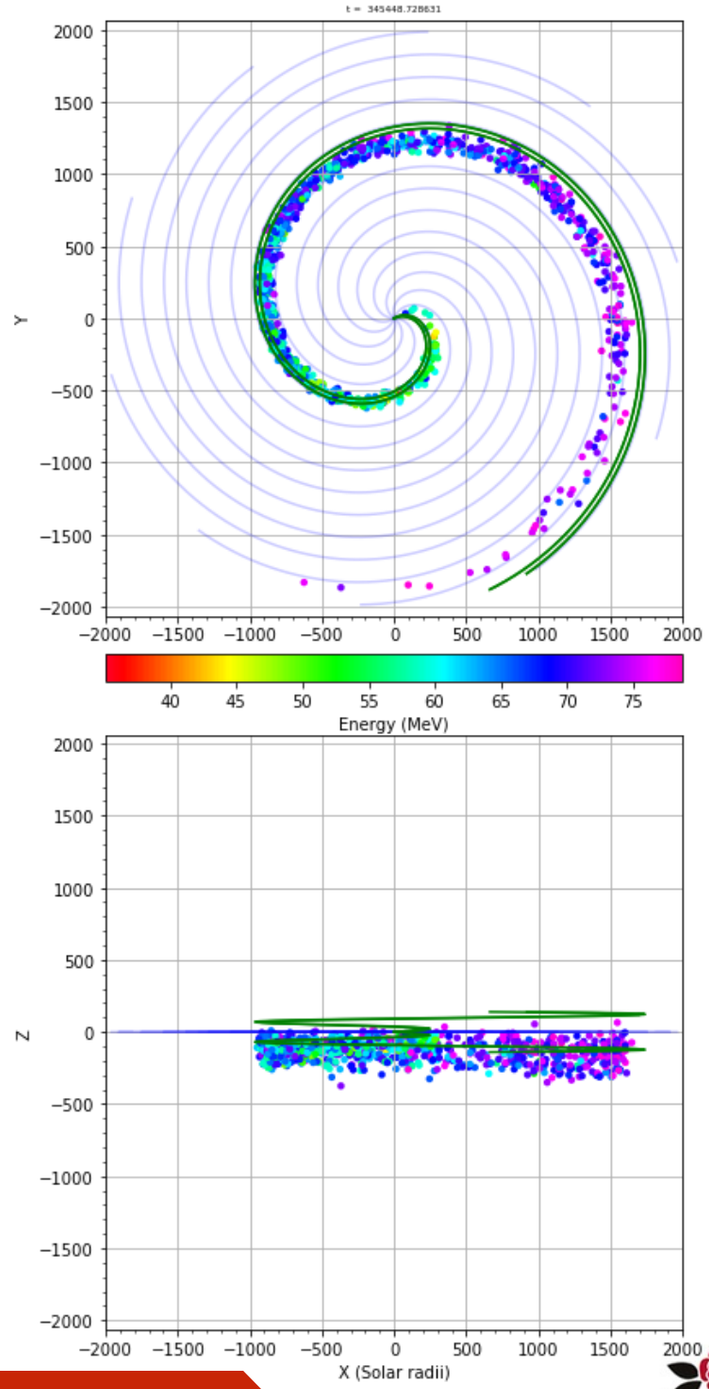
$$\mathbf{E} = -\frac{\Omega\, B_0 r_0^2}{c}\,\frac{\sin\theta}{r}\,\mathbf{e}_\theta$$

Test Particles in a Parker Spiral Field

- The trajectories of the particles are calculated at different time-steps up to a specified time, t.

- We can observe how the particles have been transported by the model in 3-dimensions.

- Out test case is shown on the right, with 500MeV particles, mfp of 0.3, v_{sw} of 500km/s and injection from 30 solar radii.



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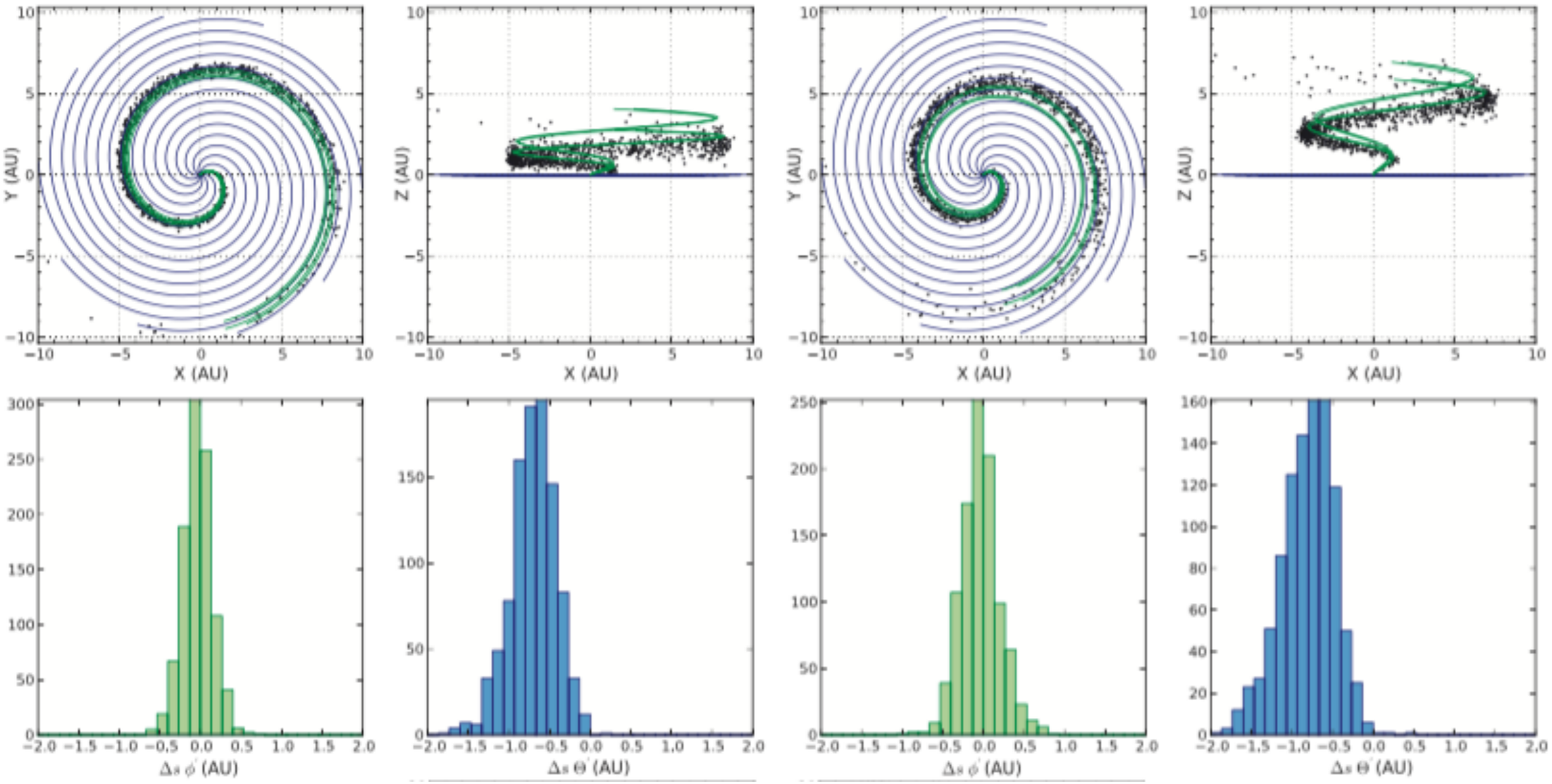
Test Particles in a Parker Spiral Field



Marsh et al. (2013)

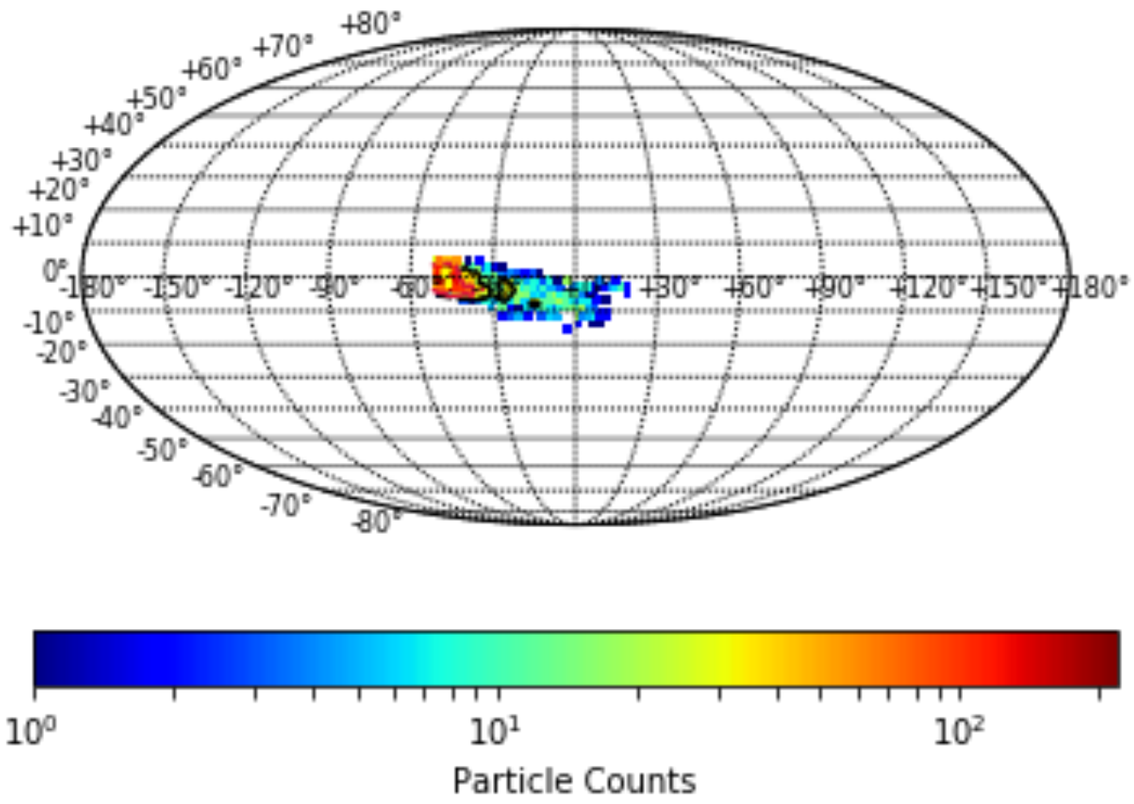
Mapping SEPs at 1 AU

- We also map the latitude and longitude of the particles when they cross 1 AU.

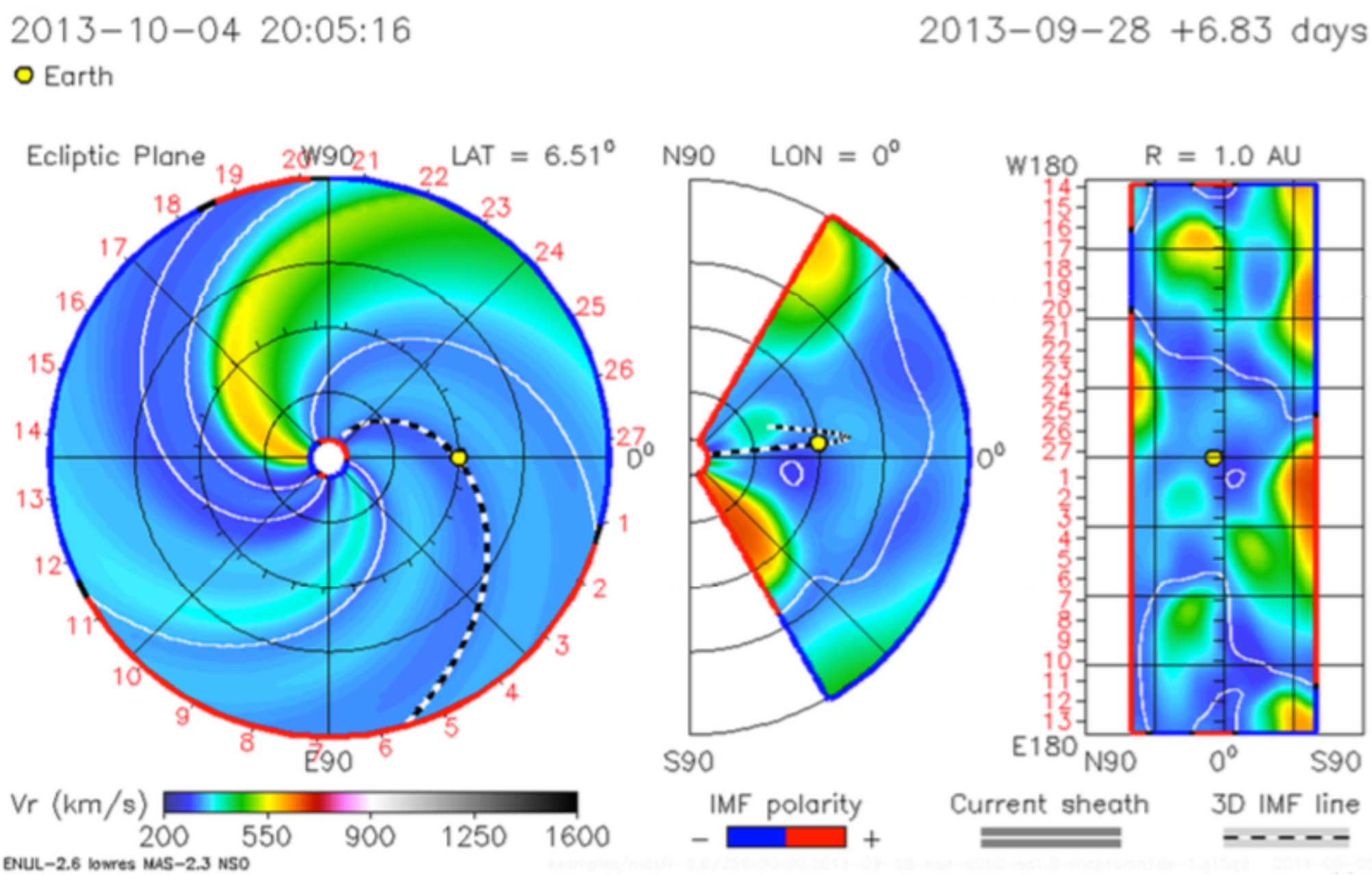
- The figure on the right shows the test-case.

- This can be used to deduce the flux of particles incident on Earth.

- Adaptable for other planets / locations.

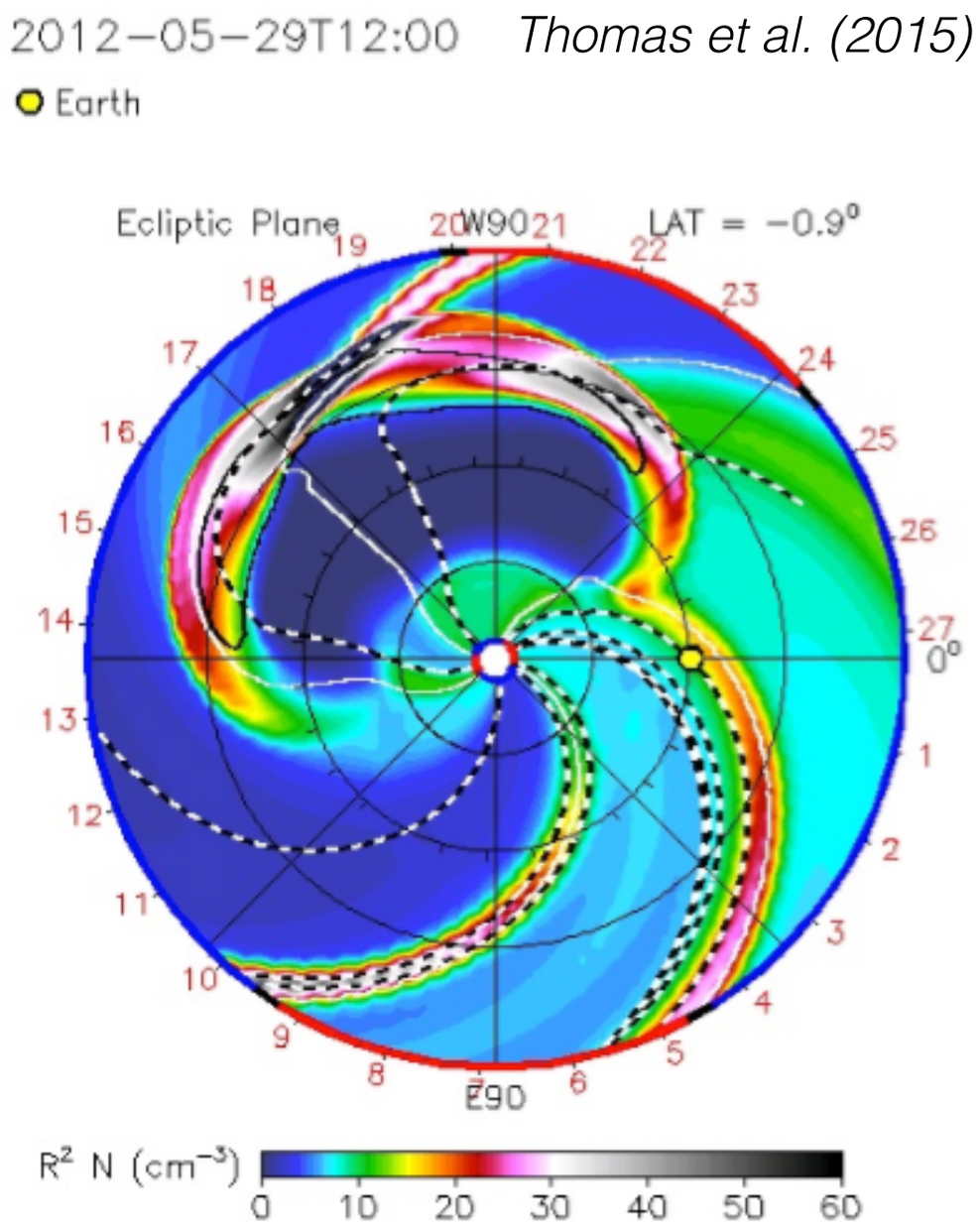


The ENLIL Solar Wind Model



The ENLIL Solar Wind Model

- ENLIL is a 3-D MHD model of the solar wind (note CMEs not MHD).
- Initiated from the sonic point between 21 and 30 solar radii where boundary conditions are from WSA or MAS.
- Output is grid of HMF, solar wind speed and solar wind density at grid expanding up to 10 AU in 360 degrees longitude and out to plus or minus 60 degrees latitude.

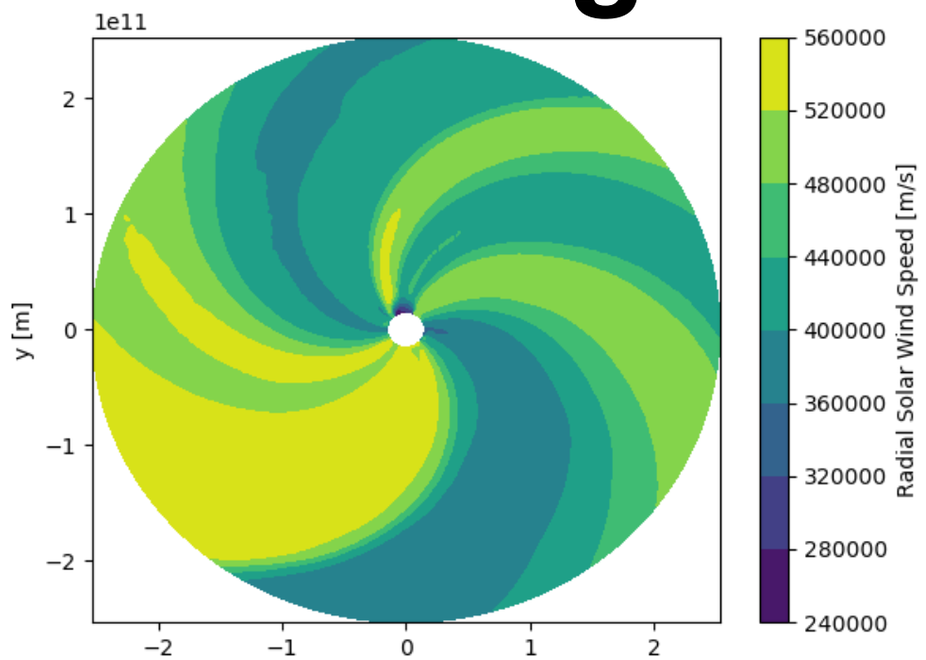


Thomas et al. (2015)

Using ENLIL for SEP Modelling

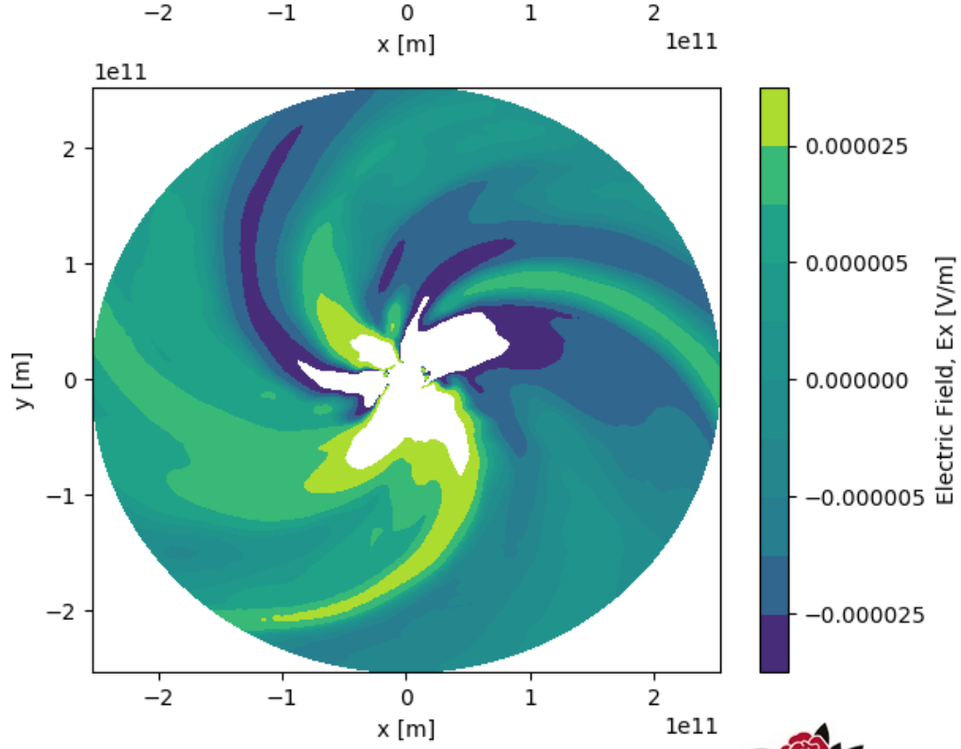
- We aim to use the magnetic and electric fields from the ENLIL model to run the test particles through.

- The ENLIL field will be more realistic and has more structure compared to the Parker Spiral field currently used.



- We need to interpolate the fields to obtain B and E for the location of test particle in the simulation.

- Important to choose correct interpolation method to conserve the particle's magnetic moment.



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Interpolation of ENLIL Fields

- To interpolate the ENLIL magnetic and electric fields at the required locations, I am using two approaches:

- Firstly, a simple linear interpolation (e.g. Gerald & Wheatley, 1989):

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0} = \frac{y_0(x_1 - x) + y_1(x - x_0)}{x_1 - x_0}$$

- Secondly, a cubic-spline method (e.g. Mackay et al., 2005).

- The latter is likely to remove any unrealistic, sharp changes in the magnetic field's direction.

- Any other recommendations welcome…

Future Work

- Find the best interpolation method.
- Compare particle transport in the ENLIL model to that in a Parker Spiral field.
- Examine interesting cases where there has been a ground level enhancement due to SEP event.
- Model radiation doses.
- Include time-dependent injection from a coronal mass ejection.

Summary

- Our test particle simulations have been introduced for use in forecasting solar energetic particles.

- Examples of our simulation outputs from using a Parker Spiral magnetic field have been given.

- Our ongoing work in using ENLIL fields to run the test particles through has been discussed.

- Any questions or thoughts on this are, of course, appreciated.

Thank you for listening. Any questions?