Solar energetic particle events (SEPs) and the properties of coronal shock waves

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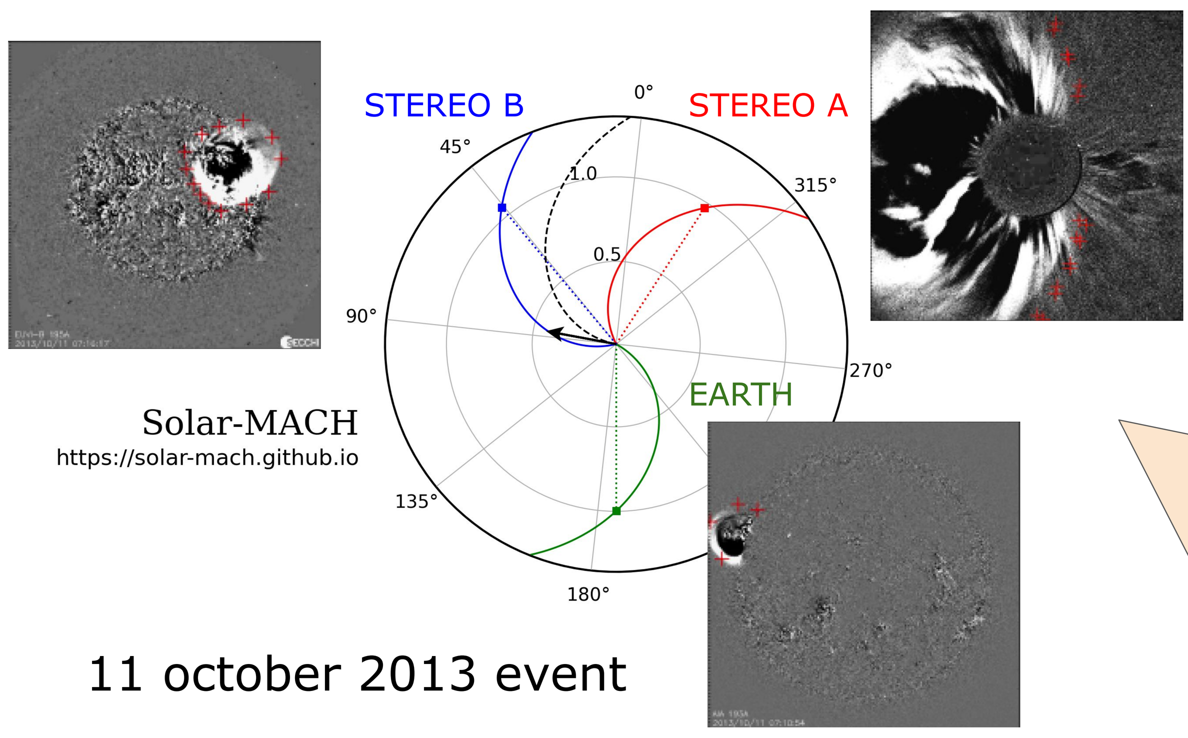
Introduction and motivation

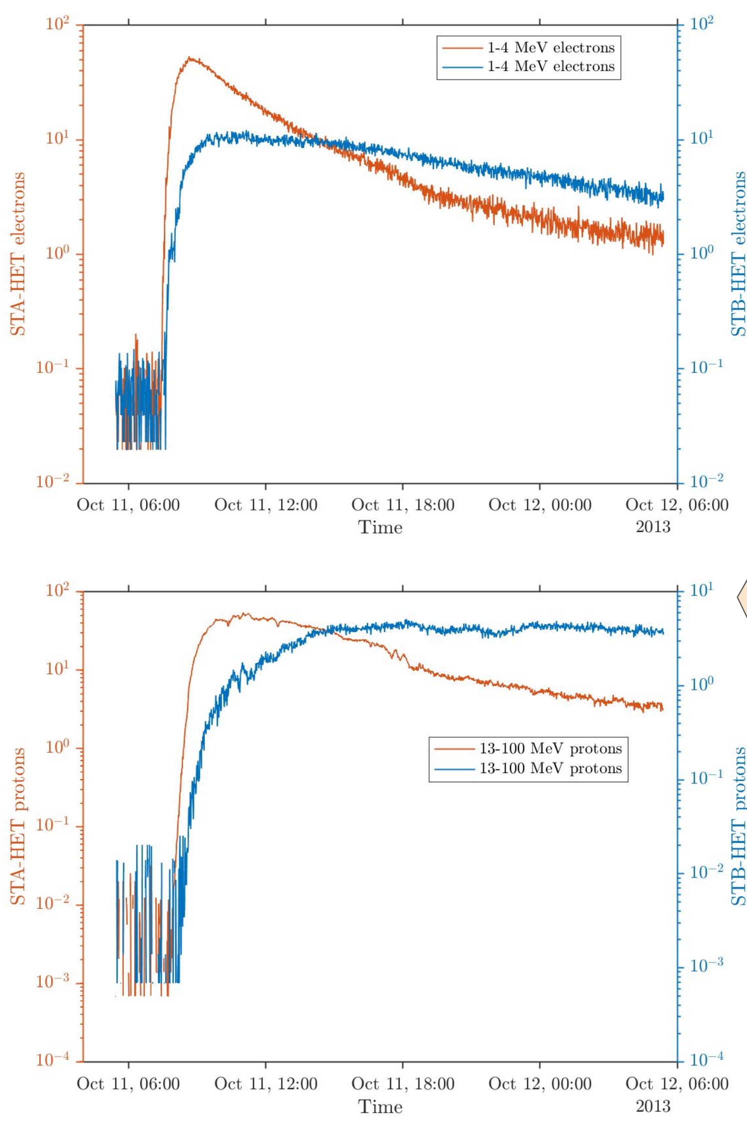
Coronal shock waves and solar flares have been proposed as the main acceleration sites of SEPs. The most intense SEPs are commonly associated with fast and wide coronal mass ejections (CMEs). These CMEs generate and drive shock waves in the solar atmosphere that have been proposed as key particle accelerators. During the first hour of a fast CME event, shock waves propagate through a highly structured corona inducing rapid changes in their properties (e.g. shock geometry and Mach). These changes are reflected in the SEP event, which contains the entire history of the evolution of shock parameters. Since spacecraft measuring SEPs connect magnetically to specific regions of the shock, it is essential to model shock waves in detail in order to evaluate which properties of the shock control SEP properties.

Shock wave parameters



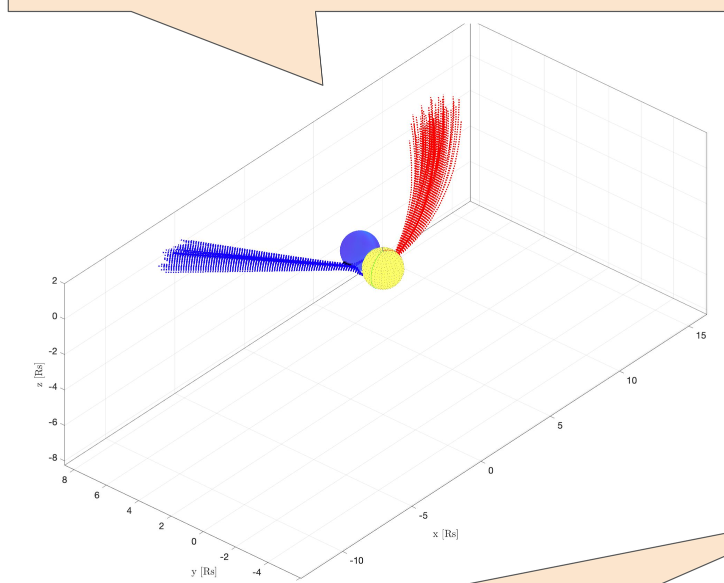
11 october 2013 event

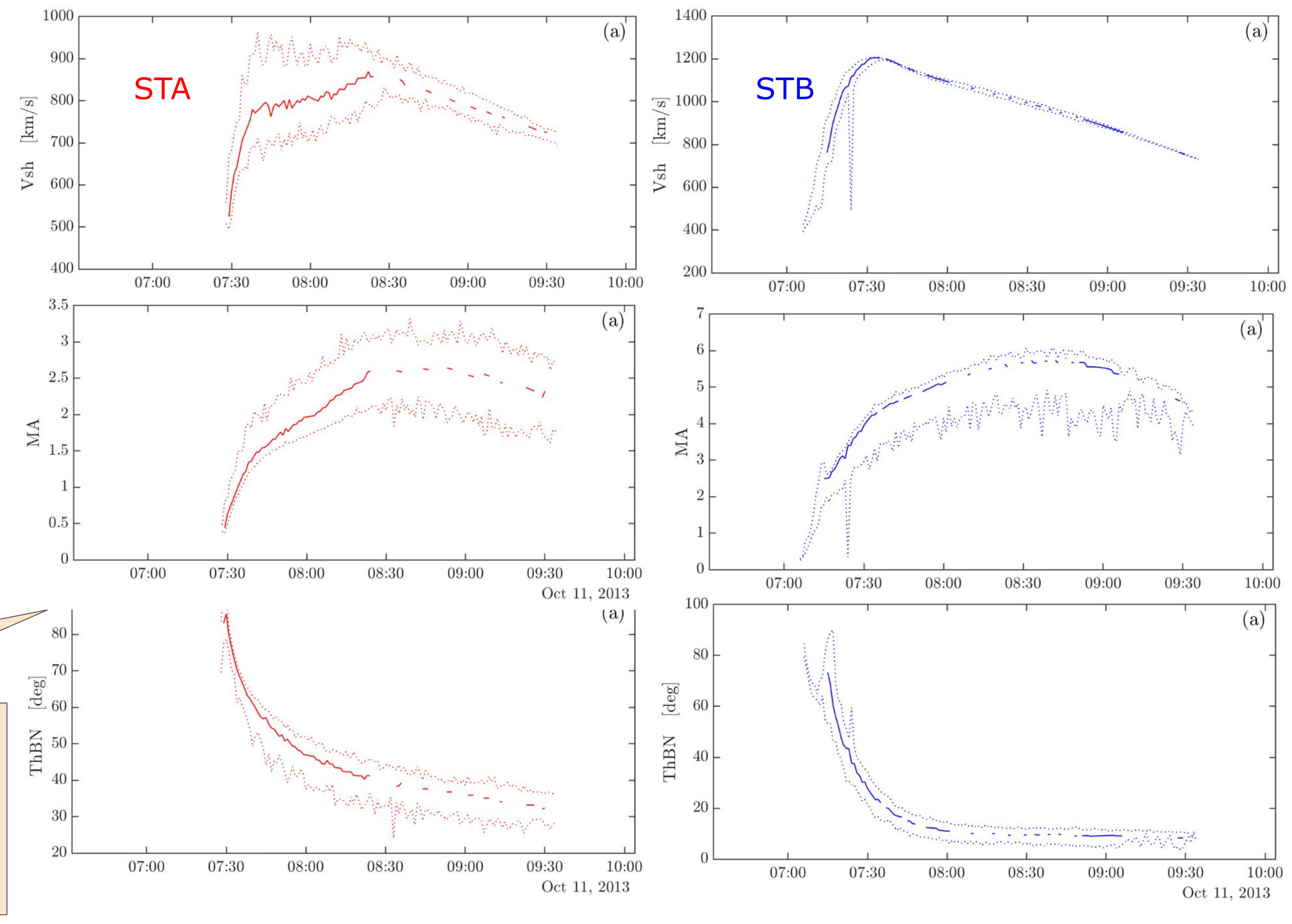
Figure representing the three differents points of view of the expanding shock wave for the same time. Thanks to this good triangulation of the event, we can reconstruct the 3D ellipsoidal shape of the expanding shock wave enabling the extraction of its geometry and kinematic properties. Using magneto-hydrodynamics (MHD) cubes, we then reconstruct the magnetic connectivity of spacecrafts and retrieve the MHD properties of the shock wave at the intersections with these magnetic field lines.



Figures representing electrons (top) and protons (bottom) intensity for STEREO-A (STA, in red) and STEREO-B (STB, in blue) as a function of time. They presents a very low background before a clear onset. STA intensities reach higher levels but decrease more rapidly than STB intensities.

Figure representing the 100 magnetic field lines connecting spacecrafts to the surface of the Sun (STA field lines in red, STB in blue) calculated using MHD cubes.





Figures representing the evolution of different shock parameters for STA (in red, on the left) and STB (in blue, on the right). Panels (a) : Shock speed, panels (b) : Mach Aflvénic number (MA), panels (c) : Theta_BN, the angle between the normal of the shock surface and the magnetic field line.

Take away message

We employ a methodology to analyse a **solar energetic particles (SEPs)** event involving a **coronal shock wave**. In this way, direct temporal correlations between the shock parameters (such as speed, Alfvénic Mach Number, or theta_BN) and SEPs time-series can be determined. We found **high correlations coefficients** between them for both electrons and protons, with little or no dependence on particle energy. This seems to suggest a common energisation at the shock through respectively shock drift acceleration and diffusive shock acceleration.

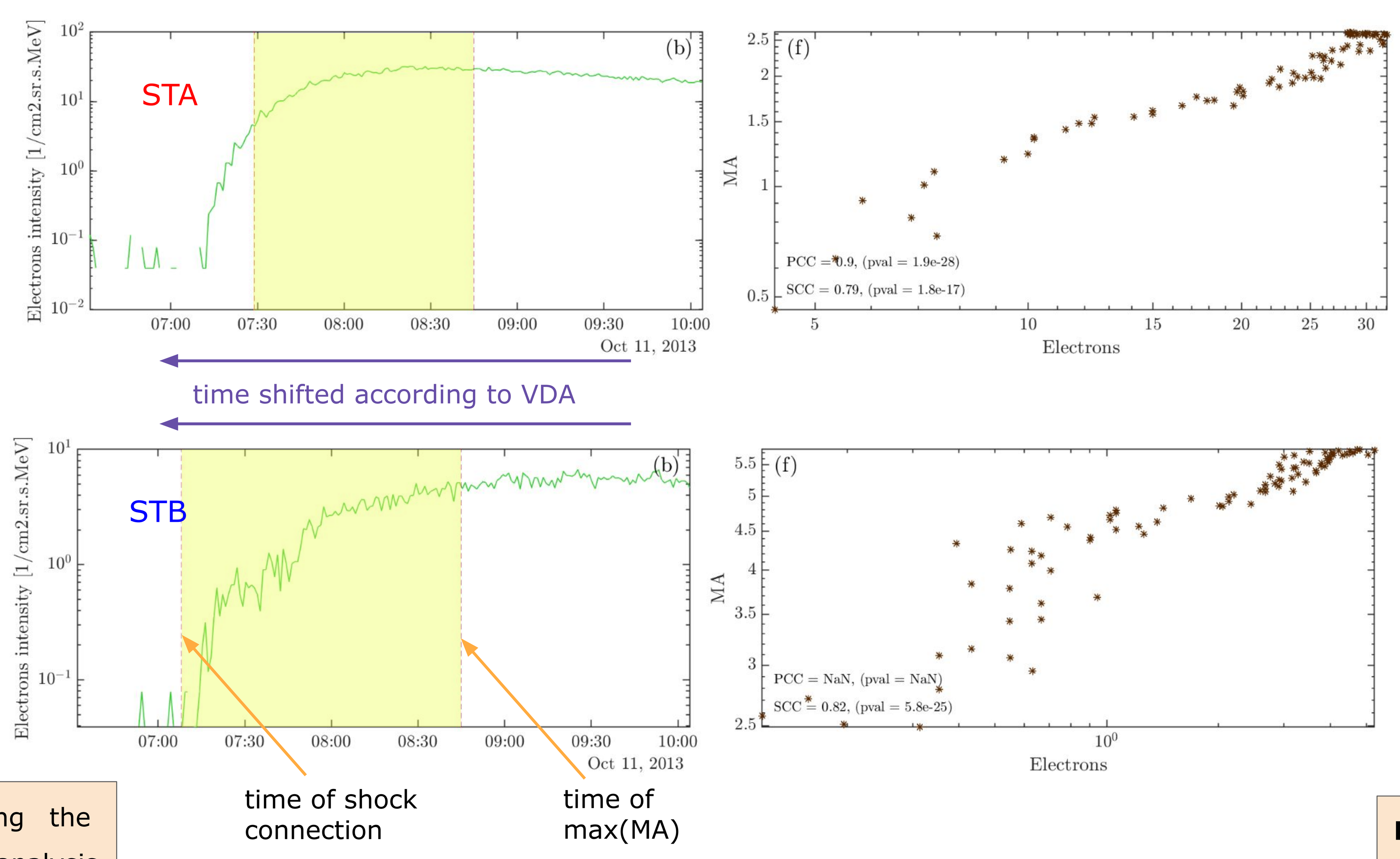
Application

With a velocity dispersion analysis (VDA), we obtain an estimated path length for particles from the solar release site to the point of in situ measurement. The VDA also provides the solar release time of SEPs at each energy band.

→ Time-shifted SEP flux time-series can then be compared directly with shock parameters. We calculate Pearson's and Spearman's Correlation Coefficients (PCC and SCC) for each SEPs energy and shock parameter.

→ The temporal correlations between the shock properties and the SEPs recorded by individual spacecraft can be compared.

for one energy



for all energies

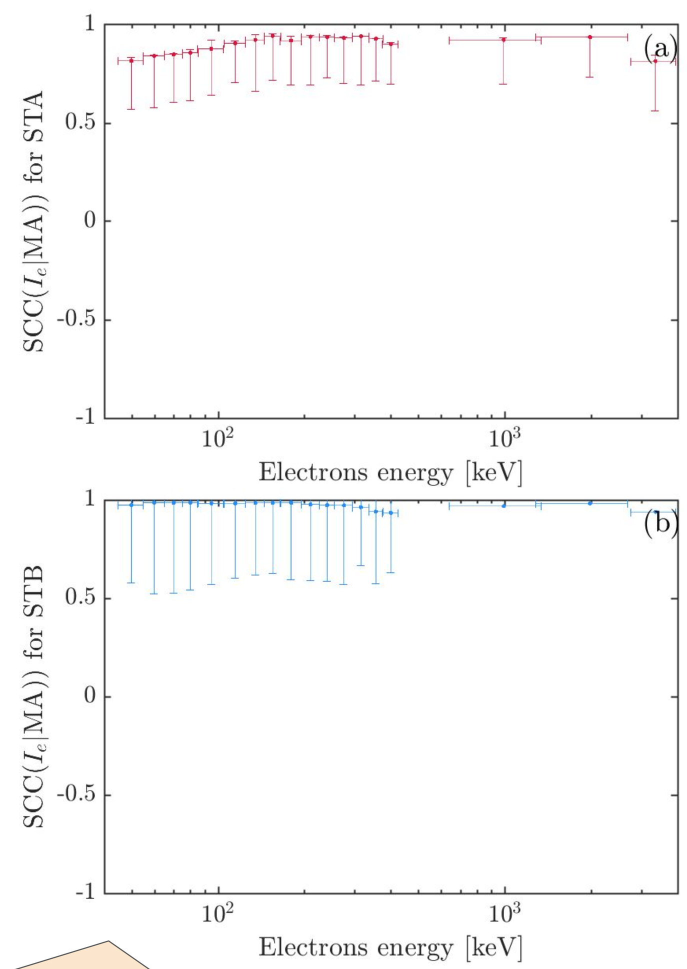


Figure representing correlations coefficients obtain for electrons time-series and MA as a function of electrons energy

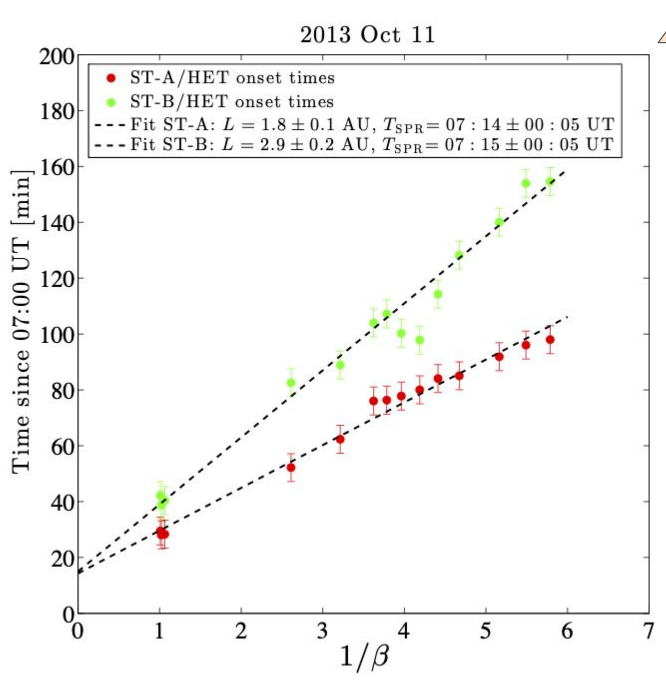


Figure representing the velocity dispersion analysis (VDA) of the event for electrons and protons

Results

Spearman's Correlation Coefficients (SCC) between MA and electrons time-series of differents energies are comprise between 0.75 and 0.97 for STA, and 0.77 and 0.97 for STB.

Conclusion and moving forward

Results suggests that particles, whatever their energy, are energised in the same way at the shock, through shock drift acceleration for electrons and diffusive shock acceleration for protons.

To improve our method, we can take into account the uncertainty on VDA. In the future we will try to fit to the real SEP profile a modeled one, from transport particles codes, with an injection fonction including real shock parameters. This injection function will take into account the diffusion of particles.

Bibliography

Dresing et al. (2022), Gieseler et al. (2023), Jarry et al. (2023), Jarry et al. (2024 in prep), Kouloumvakos et al. (2019), Plotnikov et al. (2017), Rouillard et al. (2012, 2017)

my first article →