EGU 2020

Determination of Solar Energetic Particle anisotropies based on four-sector measurements - Study based on STEREO/SEPT in preparation of SolO/EPT

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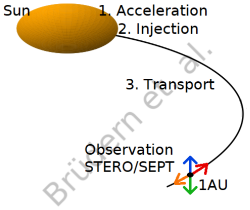
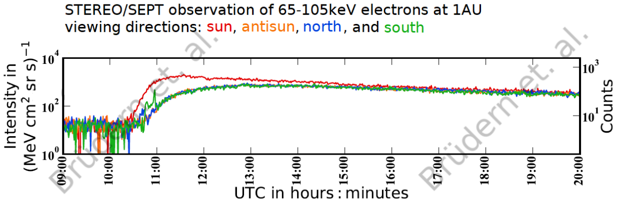
Solar Energetic Particle (SEP) observations are used to learn about their acceleration at the Sun, their injection into interplanetary space, and their transport through the Interplanetary Magnetic Field (IMF).



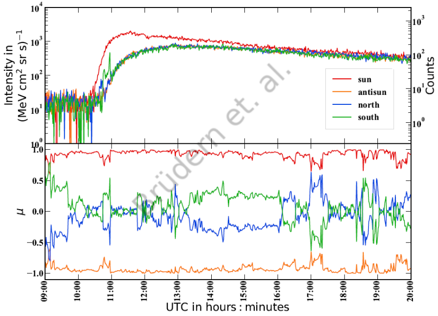


Def. Intensity:

Number of particles, per energy range, per detection area, per accumulation time, and steradian.

SEP event

- Sudden increase in particle intensity
- Particle intensity can depend on viewing direction



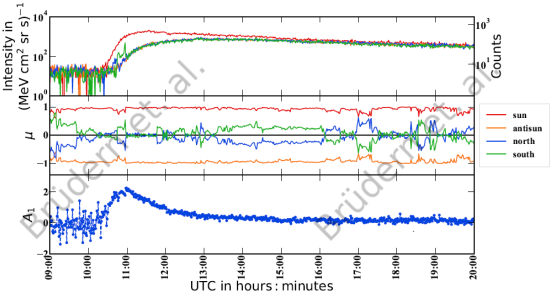
Transport

- Systematic changes of the pitch angle (e.g. focussing) lead to particles predominantly propagating parallel to the magnetic field ($\mu = 1$) explaining the directional dependency of intensity observations.
- Stochastic changes of the pitch angle (e.g. resonant pitch-angle scattering) lead to a progressive decrease in the intensity differences that were observed in the early stages of the event.

Def. Pitch angle:

Separation angle of the local magnetic field and the direction of motion (inverse of nominal viewing direction)

$$\mu = \cos(\text{pitch angle})$$



Def. Anisotropy:

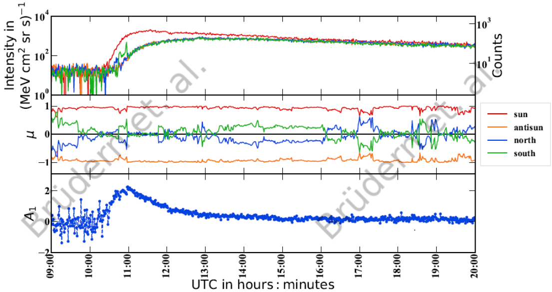
Preferential direction of a particle ensemble in respect to the magnetic field $\vec{B}$

$$A_1 = 3\frac{\int_{-1}^{+1} \mu \cdot I(\mu) d\mu}{\int_{-1}^{+1} I(\mu) d\mu}$$

Disentangle imprints of source and transport

- Strong anisotropies indicate periods of weak pitch angle scattering.
- Long lasting anisotropies imply a long lasting injection at the Sun.
- Careful, an anisotropy of zero doesn't mean isotropic!

Further details can be found in Appendix 1 or ask me directly.



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Question

What is the uncertainty of the anisotropy and how could we determine it?

Further details can be found in Appendix 1 or ask me directly.

Which parameters influence the anisotropy determination?

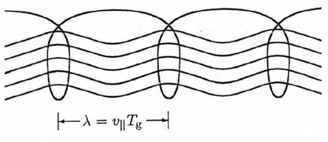
Considering

1. Variance of the magnetic field
2. Opening angle of the telescope
3. Angular detector response
4. *Poisson* statistics for measured counts

Impacts

The calculation of the pitch angle depends on the direction of the magnetic field.

What is the average $\vec{B}$ over one gyration? (very simplified)



Gyration time: $T_g = \frac{2\pi m_{\mathrm{rel}}}{|\vec{B}||q|}$

Timescale for averaging $\vec{B}$:

$$\Rightarrow t_{\mathrm{av}} = \frac{T_g \cdot v_{\parallel}}{v_{\mathrm{sw}}}$$

Figure: Kallenrode (2003)

Which parameters influence the anisotropy determination?

Considering

1. Variance of the magnetic field
2. Opening angle of the telescope
3. Angular detector response
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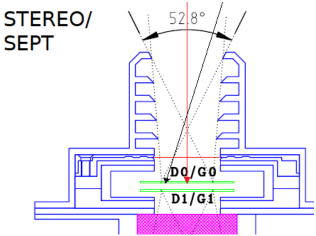
Impacts

The determination of the pitch angle depends on the direction of motion.

Not just one possible trajectory



Opening angle of the telescope allows multiple trajectories. Usually only the inverse of the nominal viewing direction (red arrow) is considered to determine the pitch angle.

Figure: Müller-Mellin (2007)

Which parameters influence the anisotropy determination?

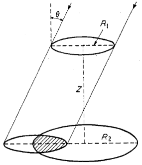
Considering

1. Variance of the magnetic field
2. Opening angle of the telescope
3. Angular detector response
4. *Poisson* statistics for measured counts

Impacts

Not all possible particle trajectories (pitch angles) have the same likelihood.

Angular detector response

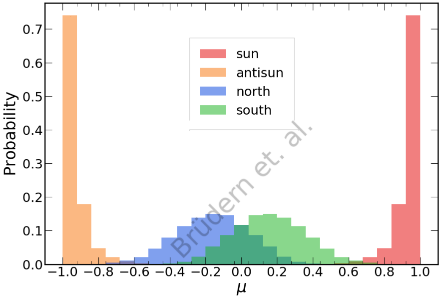


- Particle detection depends on the zenith angle
- Also dependent on initial energy of the particles (e.g. scattering at instrument housing)

Figure: G. R. Thomas (1972)

Def. μ-response:

Probabilistic mapping of possible μ values for a single detected particle considering all possible trajectories weighted by the angular detector response.



Accumulated μ-response

1. Compute all possible $\mu_i = \frac{\vec{B}(t_{\mathrm{av}})\cdot\vec{r_i}}{|\vec{B}(t_{\mathrm{av}})||\vec{r_i}|}$ for each viewing direction. Where $\vec{B}(t_{\mathrm{av}})$ labels the averaged magnetic field and $\vec{r_i}$ the trajectories.
2. Accumulate the μ-response until matching the measurement time interval of STEREO/SEPT.

Further details can be found in Appendix 2 or ask me directly.

Which parameters influence the anisotropy determination?

Considering

1. Variance of the magnetic field
2. Opening angle of the telescope
3. Angular detector response
4. *Poisson* statistics for measured counts

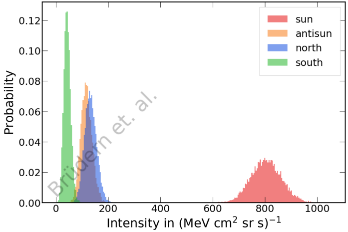
Impacts

The outcome of the anisotropy depends on the intensity weighting.

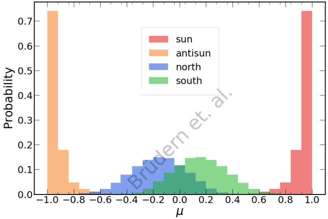
Observing k hits within a time interval

$$P(k) = \frac{N^k \exp(-N)}{k!}$$

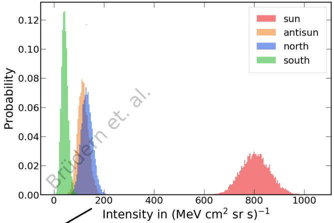
Where N is the mean of the distribution.



Bootstrapping anisotropy distribution

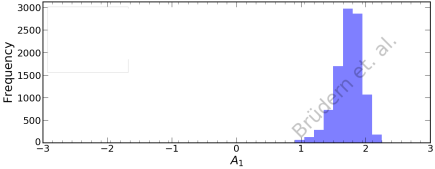


1. redraw pitch angle intensity pairs for each sector



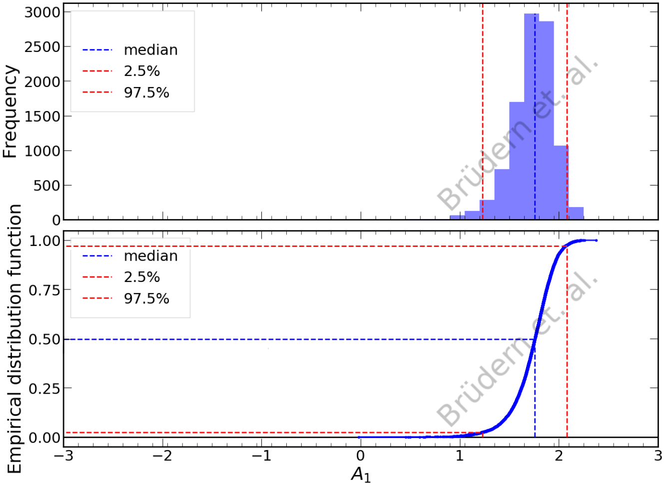
2. recompute $A_1 = 3\frac{\int_{-1}^{+1} \mu \cdot I(\mu) d\mu}{\int_{-1}^{+1} I(\mu) d\mu}$

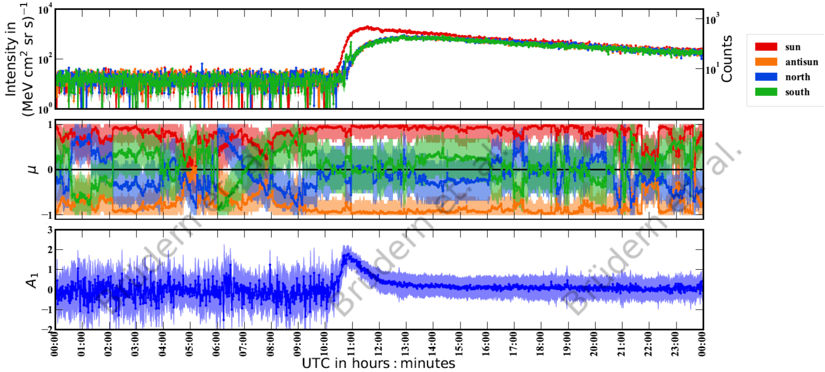
3. result



Uncertainty

We choose 95% confidence intervals of the bootstrapped anisotropy distribution as a representative value for the uncertainty.





Anisotropy time profile including its uncertainty (for the first time!) for STEREO B/SEPT observation taken on August 14 2010. The shaded areas in the μ panel show the extend of the $\mu-$response. Even tough, the uncertainty can range up to ± 1 before the event observation a significant anisotropy increase can clearly be seen.

Summary

We developed a procedure to determine uncertainties of SEP anisotropies for a four-sector instrument like SEPT under consideration of :

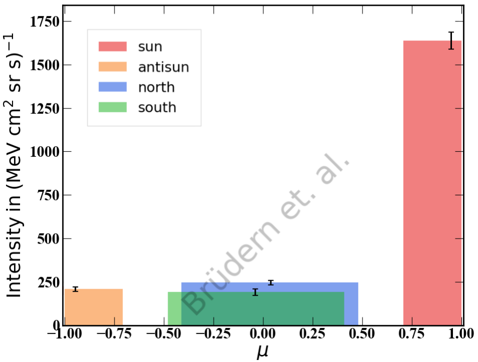
- A varying magnetic field
- The opening angle of the telescopes
- Estimated uncertainties of measured intensities
- The angular response of the detector

Work in progress & Outlook

- Perform validity check using model data.[1]
- Determine uncertainty data product for the whole STEREO/SEPT mission and in future for SolO/EPT as well.

[1] See Appendix 3 for an outlook

Computing anisotropies for observations



Measured intensities are given by the height of the bars. The width of the bars represent the opening angle.

Method

- Discrete representation when computing I_{omni} and A_1 for observations
- Opening angle $\delta\mu_i$ (width of the bars) as additional weights improves the result (Brüdern et. al., 2019)

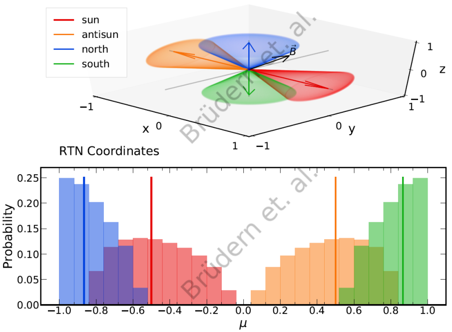
$$I_{\mathrm{omni}} = \frac{\sum_{i=1}^{4} w_i \cdot I(\mu_i)}{\sum_{i=1}^{4} w_i}$$

$$A_1 = 3\frac{\sum_{i=1}^{4} w_i \cdot \mu_i \cdot I(\mu_i)}{\sum_{i=1}^{4} w_i \cdot I(\mu_i)}$$

where $w_i \in \{1, \delta\mu_i\}$

Pitch-angle response

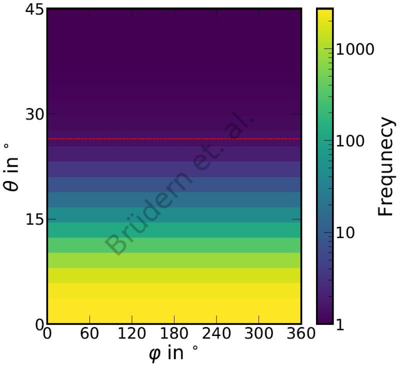
- All trajectories within the opening angle of STEREO/SEPT form a spherical cap (shaded areas in the top figure).
- Select a subsample of trajectories by dividing the surface of the spherical cap into many equally sized elements (This corresponds to an isotropic flux!)
- Compute $\mu_{i,j} = \frac{\vec{B}\cdot\vec{r}_{i,j}}{|\vec{B}||\vec{r}_{i,j}|}$



Pitch-angle response for $\theta_{\vec{B}} = 30^\circ$ and $\varphi_{\vec{B}} = 0^\circ$. The solid lines represent the nominal pitch angles that are a result of only considering the inverse of the viewing direction as trajectory.

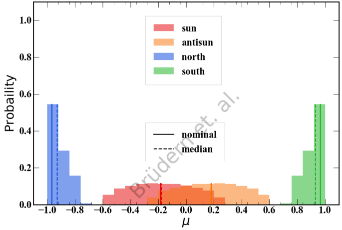
Angular response

Azimuth: φ, Zenith: θ

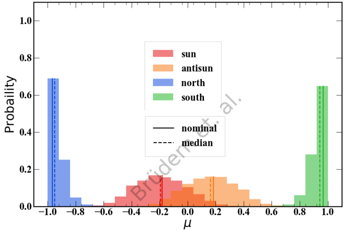


Simulation of the angular detector response for 85 to 105keV electrons.

None weighted response for an opening angle of 90°



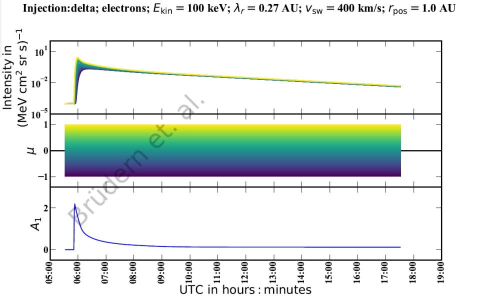
μ-response weighted by angular response

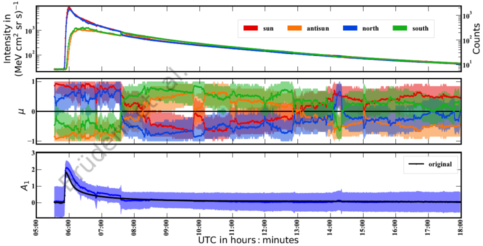


Validity check

Setup

1. Generate synthetic observations using a 1d transport model[1]
2. Reduce model output accordingly to match the pitch-angle coverage of STEREO/SEPT





[1] Strauss & Fichtner (2015)

Results

- The original (black solid line) is in good agreement with the bootstrapped anisotropy and its uncertainty (blue line and shaded area respectively).
- Changes in the pitch-angle coverage can lead to an increased uncertainty.
- Careful, the quality of STERO/SEPT A_1 strongly depends on the pitch-angle coverage.