Advantages of Characterising the Suprathermal Electrons Pitch-angle Distribution

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Introduction

Suprathermal electrons (~0.07 — 3 keV at 1 au) are released from the Sun and propagate through the interplanetary medium following the IMF with a small gyroradius (< 20 km). The shape of their PAD encloses valuable information about the large-scale structure of the IMF and about the presence, evolution and interaction of transient structures such as the ICMEs, stream interaction regions, and interplanetary shocks.

Using spherical harmonic series, we have characterised the suprathermal electron PAD measured by SWEA onboard STEREO-A, STEREO-B, and SWEPAM onboard ACE.

This characterisation allows the automatic identification of different types of distributions (pancake, counterstreaming, loss-cone, strahl, butterfly, isotropic...), identified both large and small structures in the interplanetary medium, analyse the strahl population and its variation with radial distance, orbital position, energy dependence, and even turbulent conditions of the plasma, among others.

F. Carcaboso. et al, A&A (2020)

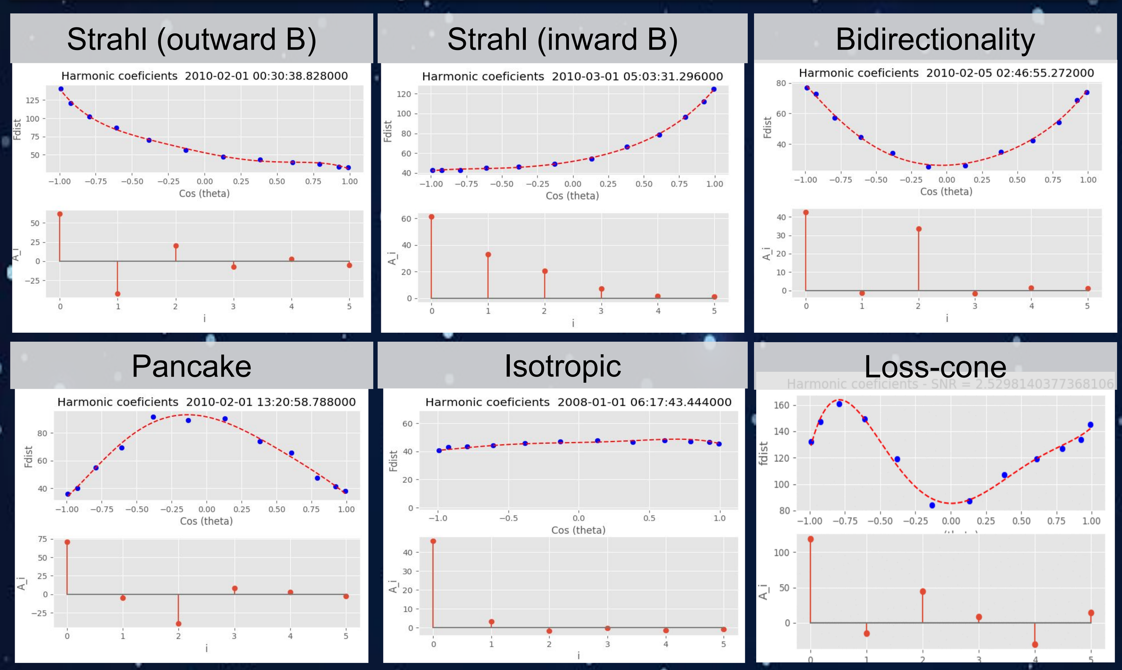
Identification of PAD type

PADs can be fitted to Legendre polynomials. Their coefficients have valuable information:

- ★ A_0 → Mean value
- ★ A_{odd} → Related to antisymmetry
- ★ A_{even} → Related to symmetry

Analogously to signal processing methods, we can for example look at the predominance of each harmonic to PADs by their power comparison.

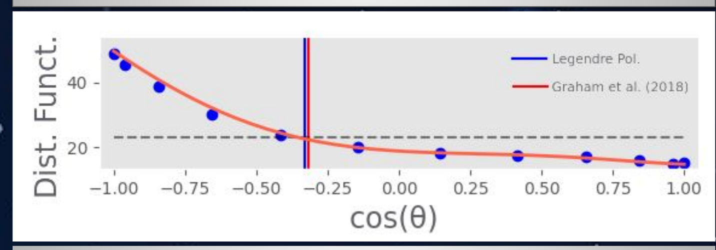
E.g, BDEs are characterised by symmetric PADs (fit dominated by contribution of even terms). Anisotropy can be represented by the comparison between the contribution of the harmonics and A_0.



Different SWEA pitch-angle snapshots and the corresponding fits. The value of each coefficient and the SNR allows a characterisation of different classes of PADs.

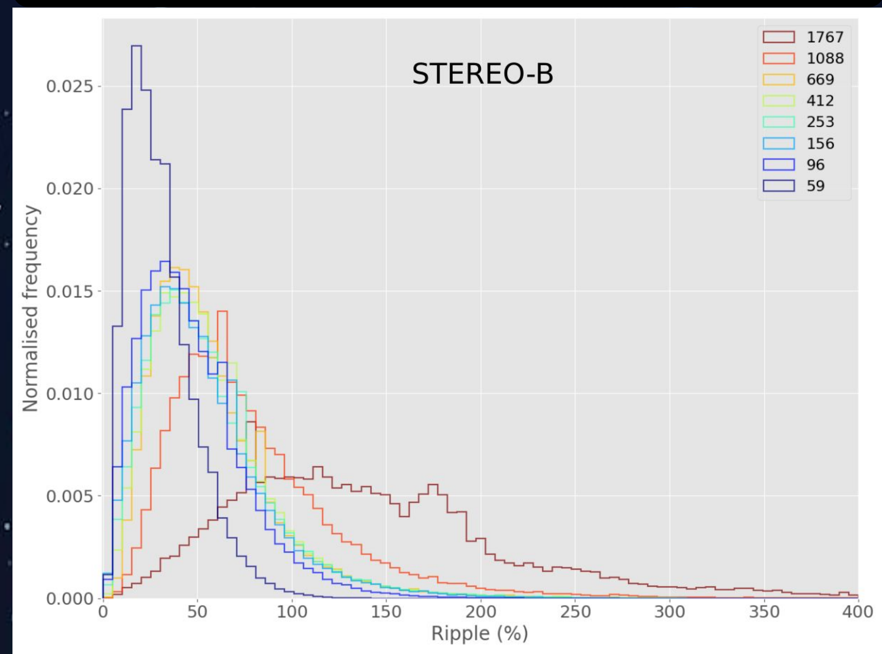
Strahl Width

The power of the Legendre polynomials also allows having a robust method of quantifying the width of the *strahl*. This term can be calculated as the roots of the the fit when subtracting the mean value.



Comparison to previous method of double-Gaussian-fitting explained in Graham et al. (2018) of an arbitrary observation of STEREO-A.

Anisotropy -Energy Dependency



The quantification of the anisotropy allows to see the dependency with the energy. On top: Normalised cumulative histograms of the anisotropy coefficient γ for the different available energy channels (in eV) of STEREO-B from 2007 to 2014.

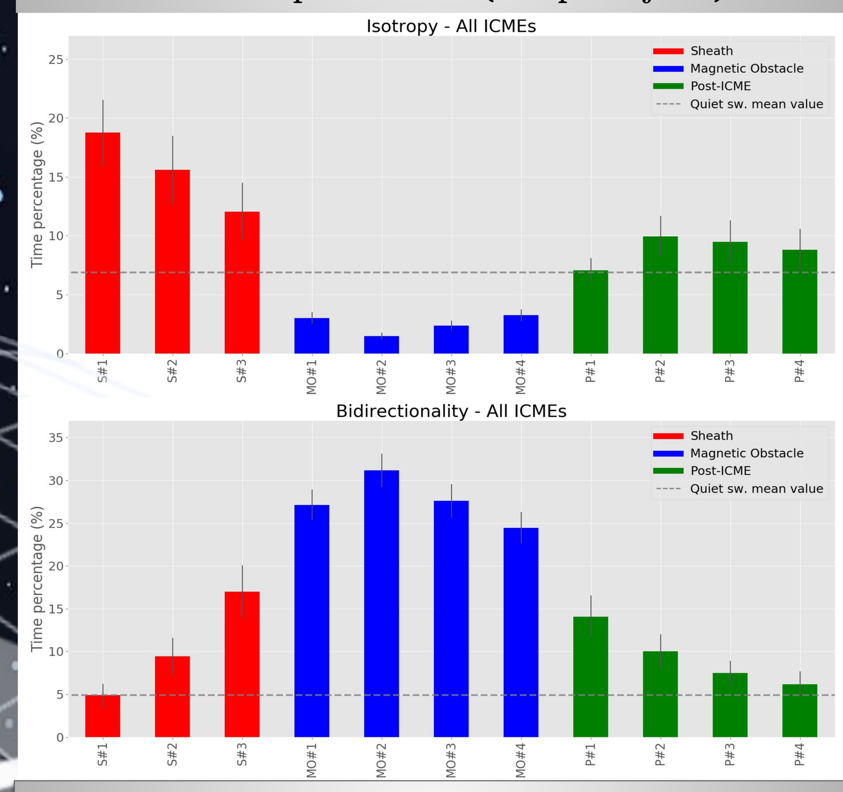
Percentage of BDE and Isotropy

Shape of PADs can tell information of IMF topology (e.g. broad *strahl* width could indicate turbulent IMF). It is also possible to analyse the properties of different structures. For example, BDE is present inside ICMEs due to:

- ★ Mirroring (Closed loops)
- ★ Streaming from both legs (Link to Sun)

And not present due to:

- ★ Erosion of IMF lines
- ★ Non-flux-rope structure (complex ejecta)

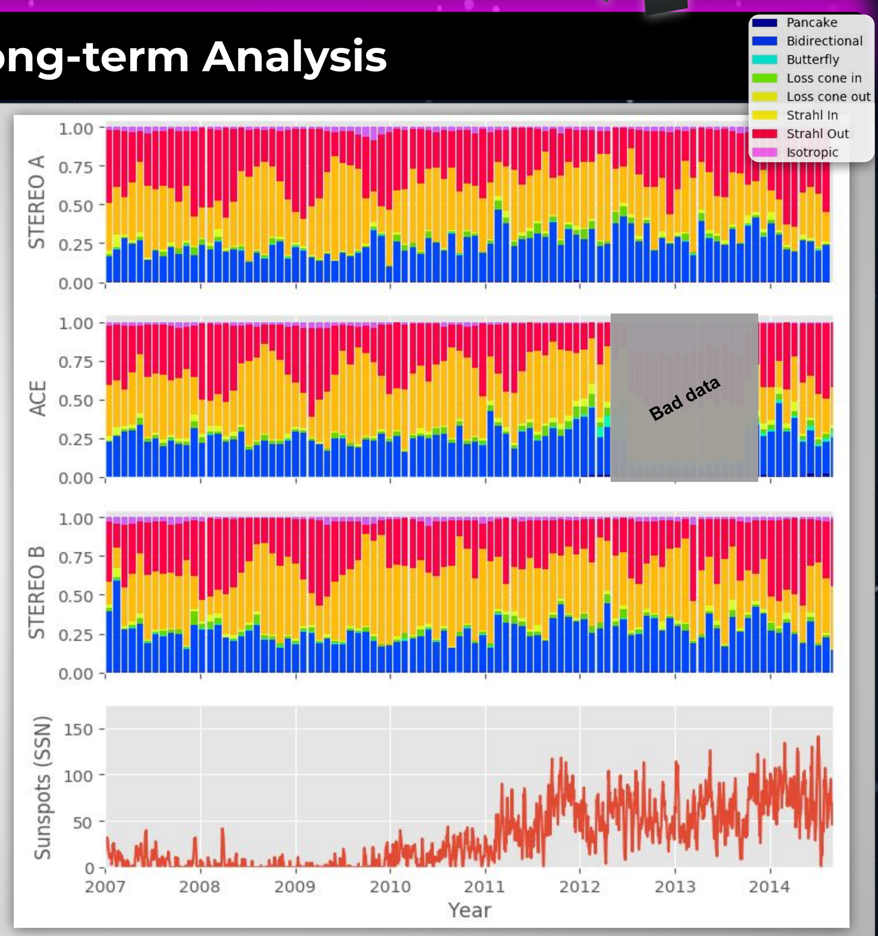


Superposed epoch analysis of the ICMEs observed by STEREO show these profiles. BDE is more common inside MOs and while isotropy is found in sheath with higher probability.

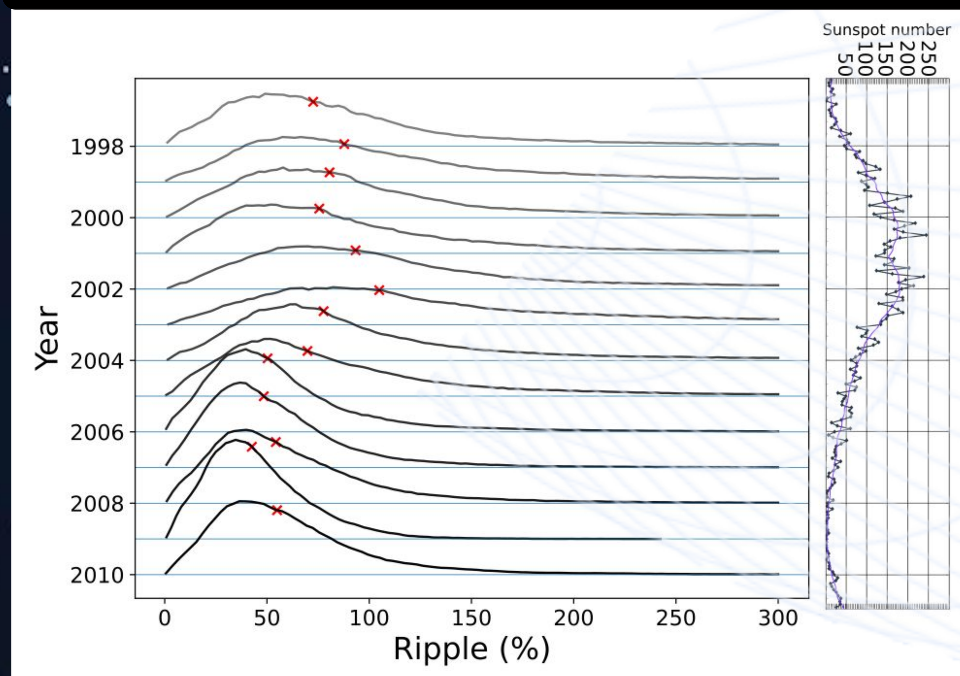
Long-term Analysis

Using Machine Learning classifiers, the different distributions above shown could be identified. The possibilities of this identification are infinite. For instance, we can see the percentage variation of the different PADs with this monthly-averaged occurrence observed by ACE, STEREO-A and STEREO-B in the solar wind.

All the spacecraft present similar results. Small correlation of BDE to the solar cycle can be appreciated. A clear distinction at solar minimum of both types of strahl (with inward B or outward B) can be found, while in solar maximum this distinction is not very defined. ACE observations became increasing sparse as the primary channel electron multiplier detectors had aged.



Anisotropy - Solar Cycle Dependency



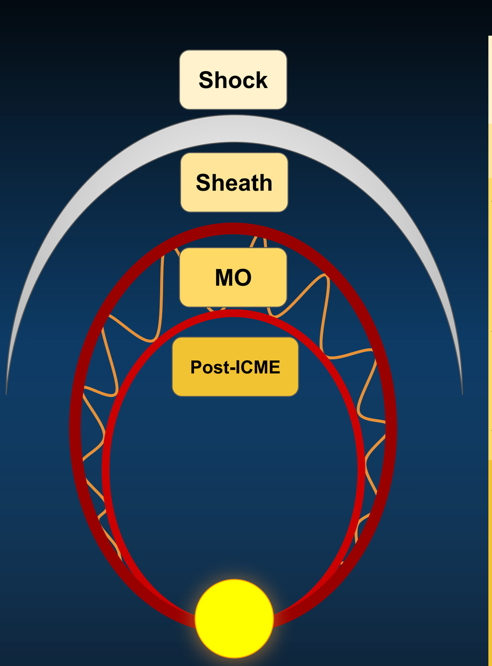
Once the anisotropy is quantified, it can analysed and compared to see its dependencies.

Here, we show yearly histograms of the anisotropy coefficient γ calculated for the 272 eV energy channel measured by ACE together with the monthly sunspot number in black and smoothed values in purple.

Red crosses indicate the median value of the histograms.

BASIC CONCEPTS

ICMEs



Discontinuity of the solar wind, produced by supersonic ICMEs (<1h)

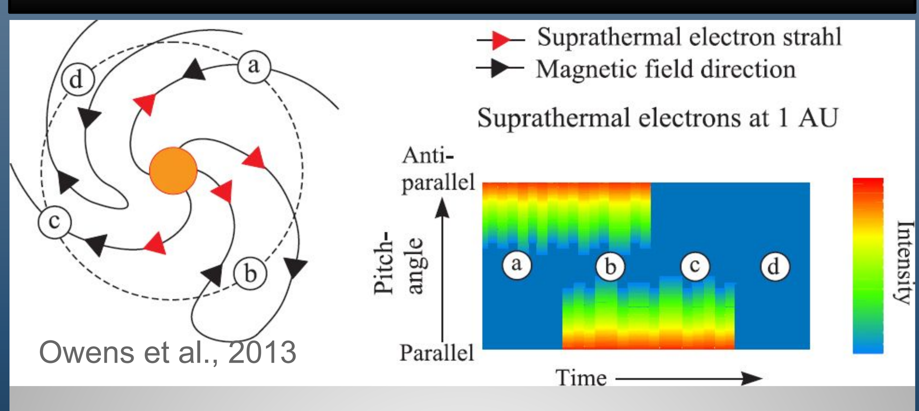
Turbulent region of ICMEs (10h)

- ★ Solar wind signatures:
  - Relative low proton temperature
  - Often a gradual decrease in solar wind speed
- ★ Magnetic field signatures
  - Enhanced IMF
  - Smooth IMF vector rotation
- ★ BDE

(24h)

Rear part of the ICMEs where BDE and other properties recover the solar wind normal conditions (35h)

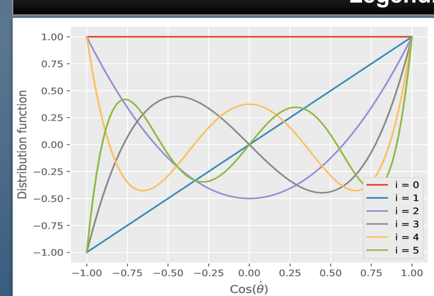
Suprathermal electron PADs



Suprathermal electrons are streaming continuously from the Sun. Depending on the IMF topology, they will show different PADs. Most common ones are *strahl*, BDE and isotropic.

- ★ ***Strahl*** is the population of suprathermal electrons that emerges from the Sun following the IMF lines and provides information of the directionality by comparing the pitch-angle with the in-situ polarity. *Strahl* width is an indicator of IMF turbulent conditions.
- ★ **BDE** can be the addition of two *strahls* in closed structures.
- ★ **Isotropy** can be found in detached IMF lines

Legendre Polynomials



$F_0 = A_0$

$F_1(\theta) = A_1 \cdot cos(\theta)$

$F_2(\theta) = A_2 \cdot \frac{1}{2} \cdot (3cos^2(\theta) - 1)$

$F_3(\theta) = A_3 \cdot \frac{1}{2} \cdot (5cos^3(\theta) - 3cos(\theta))$

$F_4(\theta) = A_4 \cdot \frac{1}{8} \cdot (35cos^4(\theta) - 30cos^2(\theta) + 3)$

$F_5(\theta) = A_5 \cdot \frac{1}{8} \cdot (63cos^5(\theta) - 70cos^3(\theta) + 15cos(\theta))$

$$F(\theta) = \sum_{x=0}^{5} F_x$$

A_0 → Mean value of the DF

$A_{1,3,5}$ → Characterise the asymmetry of the DF

$A_{2,4}$ → Characterise the symmetry of the DF

Signal processing analysis

Analogously to signal processing methods, we can characterise the predominance of each harmonic to the final distribution defining a SNR considering as "signal" the harmonic under study and the rest of the harmonics as the "noise".

$$SNR_{dB} = 10log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

$$P_x = \frac{1}{2\pi}\int_{-\pi}^{\pi} |F_x(\theta)|^2 \partial\theta$$

$P_1 = 0.5 \cdot A_1^2$

$P_3 = 0.266 \cdot A_3^2$

$P_5 = 0.186 \cdot A_5^2$

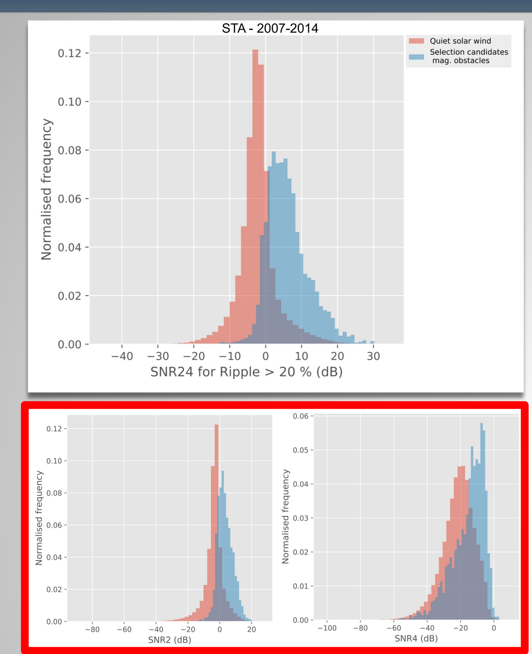
$P_2 = 0.344 \cdot A_2^2$

$P_4 = 0.218 \cdot A_4^2$

$$\gamma = f_{rms}/A_0$$

$$f_{rms} = \sqrt{\frac{1}{2\pi}\int_{-\pi}^{\pi} |F(\theta)|^2 \partial\theta}$$

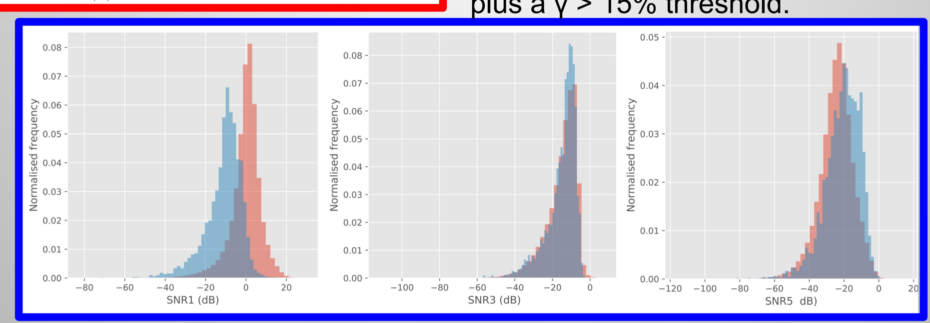
When the PAD is nearly isotropic, the possible contributions of the harmonics are negligible compared to the value of A_0. We use a "ripple" coefficient (γ) to identify how significant the angle-dependent deviations are. Apart from the SNR, we fix a threshold γ > 15% for considering a non-isotropic DF.



BDEs are characterised by symmetric PADs, where the fit is dominated by the contribution of the even terms (A_2, A_4).

A selection of magnetic obstacles from the ICME list showing a particularly clear suprathermal electron bidirectionality has been performed.

In order find suitable criteria for automatic identification of bidirectional periods, we first excluded all periods with $A_2 < 0$. Then, the SNR corresponding to each coefficient has been calculated for the sample of ICME events (blue) as well as for the quiet solar wind (red). We have found that bidirectionality is best identified when using the combined SNR for A_2 and A_4 (SNR_{24}) plus a γ > 15% threshold.



Acknowledgements

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Owens, M.J. & Forsyth, R.J. Living Rev. Sol. Phys. (2013)

Legend

BDE	– Suprathermal electrons bidirectionality	MO	– Magnetic Obstacle
I/CME	– Interplanetary/Coronal Mass Ejection	PAD	– Pitch-Angle Distribution
IMF	– Interplanetary Magnetic Field	SNR	– Signal-to-Noise Ratio