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Proton energy spectra of Energetic Storm Particle events and relation with shock parameters and turbulence

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For more details see Chiappetta et al. (2021)

Introduction

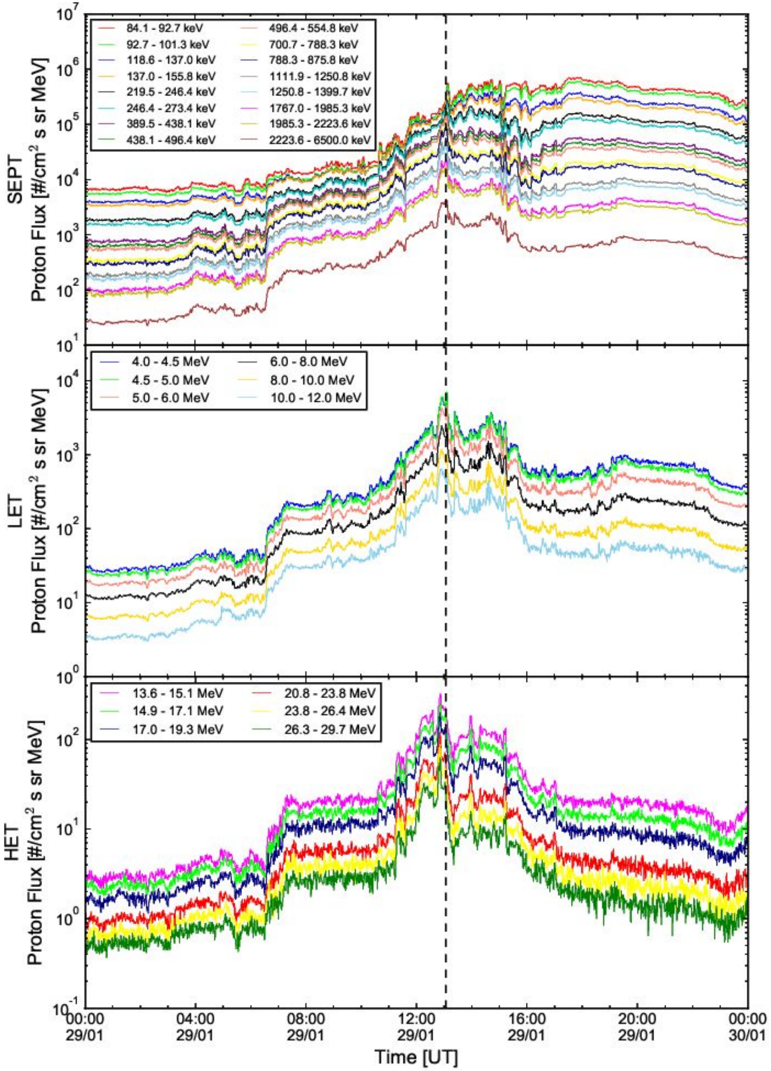
- ➔ Energetic Storm Particle events are increases of energetic charged particle intensities observed upstream and downstream of IP shocks.
- ➔ The DSA mechanism seems to describe particle acceleration at shocks and predicts a power-law energy spectrum in the range from a few tens up to a few hundreds of keV.
- ➔ The majority of the ESP events do not follow the prediction at high energies.
- ➔ The stochastic acceleration mechanism, through which charged particles gain energy by interacting with randomly moving magnetized clouds or turbulent fluctuations, can affect the particle energization processes occurring at shocks and modify the power-law spectral form produced by the DSA.

ESP selection

We took into account a pre-increase (background) value j_b where the solar wind is almost undisturbed and 4–6 MeV maximum proton flux value j_p within 3 hours around the shock. If the relative enhancement in proton flux, given by $j_n = j_p / j_b$, is higher than 1.5, the event is considered as an ESP event.

23 ESP events selected, occurring either in association with (16 events) or in absence of (7 events) Solar Energetic Particles.

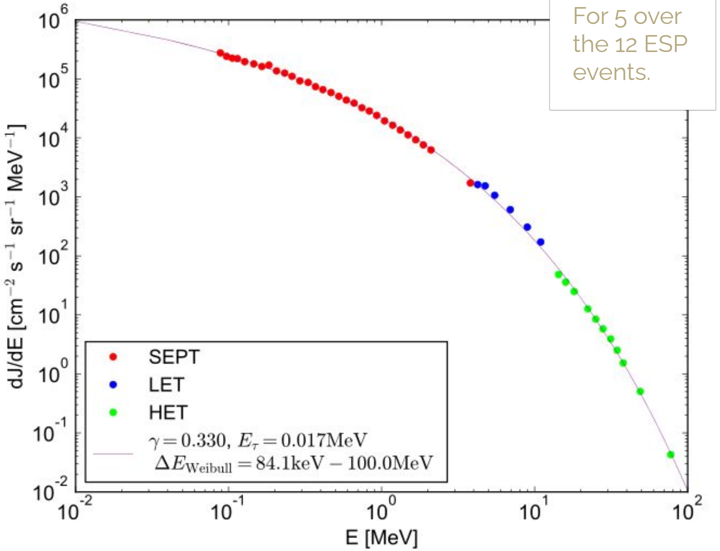
1-minute averaged proton fluxes data measured by SEPT, LET and HET instruments aboard STEREO A in 39 energy channels (84.1 keV – 100 MeV) from 2009 to 2016.



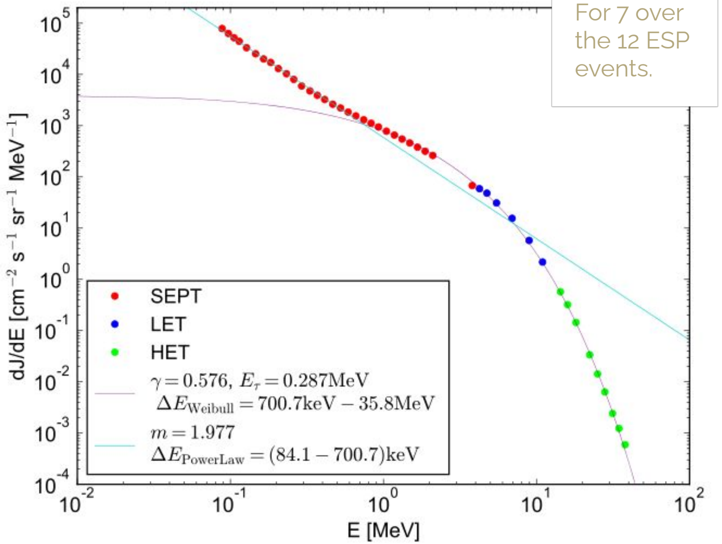
SEP spectra at quasi-perpendicular shocks

➔ Fit of the spectra by using a Weibull distribution (Frisch & Sornette 1997)

$$\frac{dJ}{dE} = C\left(\frac{E}{E_\tau}\right)^{\gamma-1} E^{1/2} e^{-\left(\frac{E}{E_\tau}\right)^{\gamma}}$$



For 5 over the 12 ESP events.



For 7 over the 12 ESP events.

➔ Good fit to the spectrum derived over 3 hr around the shock arrival (Laurenza et al. 2015) over the all energy range.

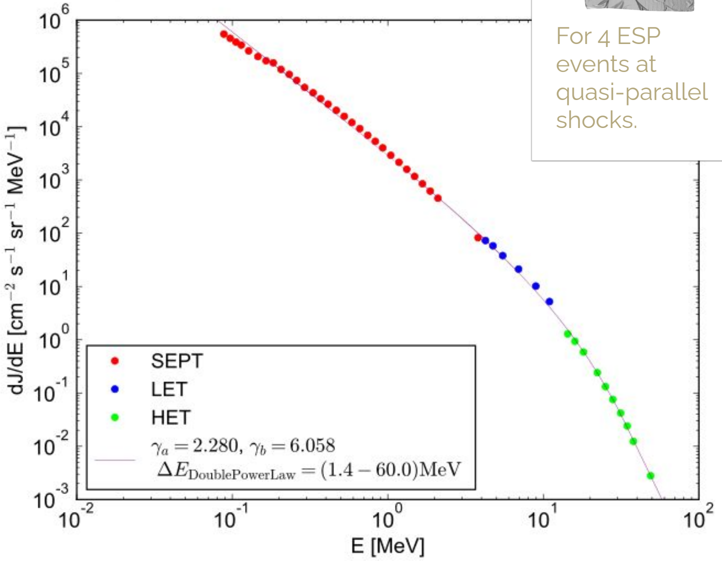
➔ Weibull-like shape fits at least the high energy tail, whereas the power law fits at lower energies. This suggests that two acceleration mechanisms can be at work (Kallenrode, 1996).

SEP spectra at quasi-parallel shocks

- ➔ Fit of the spectra by using a double power law (Band, 1993)

$$\frac{dJ}{dE} = C\ E^{-\gamma_a} e^{-\left(\frac{E}{E_0}\right)} \quad \text{for } E \leqslant (\gamma_b - \gamma_a) E_0$$

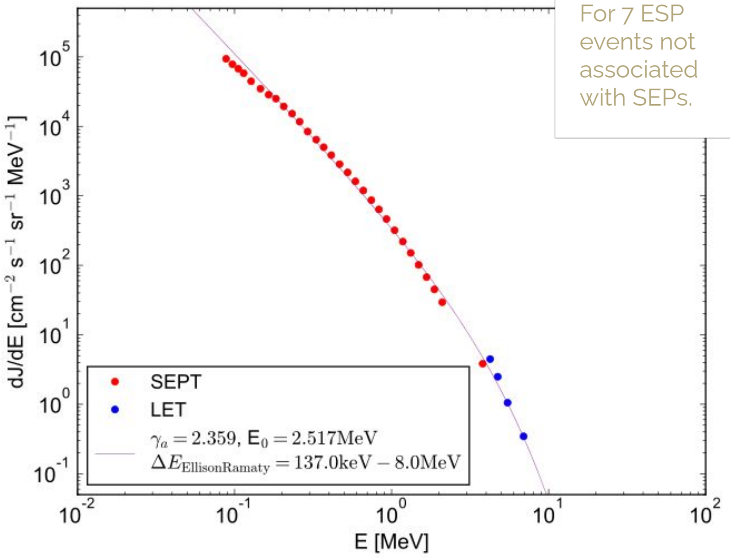
$$\frac{dJ}{dE} = C\ E^{-\gamma_b} \{[(\gamma_b - \gamma_a) E_0]^{(\gamma_b - \gamma_a)}\ e^{(\gamma_a - \gamma_b)}\} \text{ for } E \geqslant (\gamma_b - \gamma_a) E_0$$



For 4 ESP events at quasi-parallel shocks.

ESP events not associated with SEP

- ➔ Below the transition energy the trend of the double power law is equal to the Ellison–Ramaty form (Ellison & Ramaty, 1985)



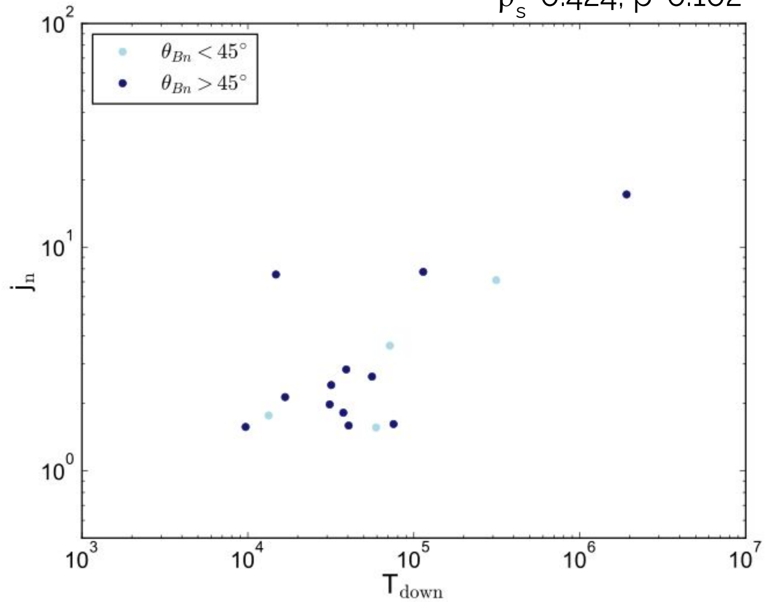
For 7 ESP events not associated with SEPs.

Relation with Turbulence Level

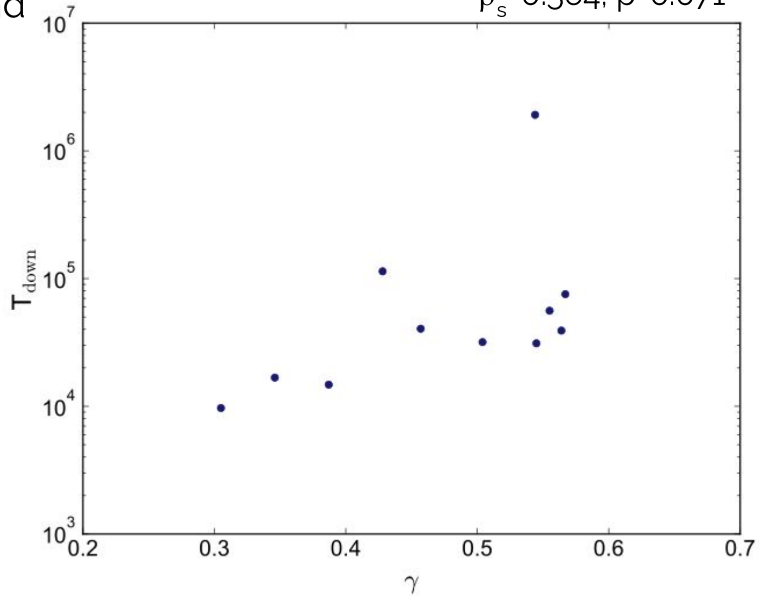
- We investigated the relation of the proton flux enhancements in the range 4-6 MeV with the level of magnetic field turbulence downstream of the shocks.
- Turbulence measure as proposed by Claßen et al. (1999) $T_{down} = \sum_{i=f_{min}}^{f_{max}} |F(i)|$

where $f_{max} = 1/2\, t_{min}$ (with t_{min} being the sampling time) and f_{min} is given by the inverse of the total sampling time t_{max}.

ρ_s=0.424, p=0.102



ρ_s=0.564, p=0.071



- Spearman's correlation between Weibull function parameters for quasi-perpendicular shocks and T_{down}.

Conclusions

- The Weibull functional form fits quasi-perpendicular shocks.
- A quite significant correlation is found between the turbulence level computed downstream of the shock and the Weibull parameters.
- The downstream turbulence is a relevant factor in particle acceleration and that stochastic acceleration can be a plausible mechanism for re-acceleration at interplanetary shocks.
- Further theoretical studies are needed to address the questions related to the types of turbulence at shocks and how they affect the trapping and the acceleration of energetic particles.