Energetic Storm Particle events: proton energy spectra and relation with magnetic turbulence nearby IP shocks

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Introduction

Most of the energetic particles observed in the heliosphere are accelerated by shock waves propagating in the interplanetary space. In order to have information on the acceleration processes of particles at the shocks associated with energetic storm particle events (ESP), we analyzed kinetic energy spectra of proton flux enhancements. We considered ESP events by using data from particle instruments aboard STEREO A and B satellites in the energy range from 84.1 keV to 100 MeV. We also investigated the correlation of the downstream magnetic field intensity fluctuations with the proton flux enhancements in the intermediate energy range $4 - 6$ MeV for all the ESP events associated with solar energetic particles (SEPs), and with the Weibull parameters for quasi-perpendicular shocks. Our results suggest that 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.

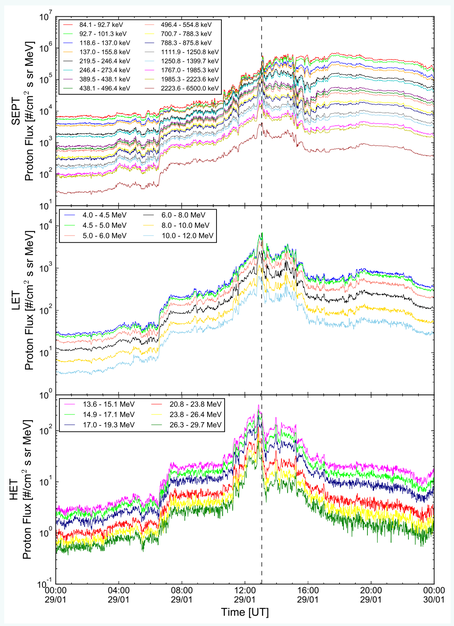
Selection of events

- ESP events are local increases of energetic charged particle intensities observed upstream and downstream of interplanetary shocks.
- ESPs can occur at the shock arrival when a SEP event is in progress or on a quiet background, in the absence of SEPs.

We selected only shocks for which an effective enhancement in proton flux is observed at energies $4 - 6$ MeV. In order to evaluate the real increase in proton flux, we took a pre-increase (background) value j_b where the solar wind is almost undisturbed and a maximum proton flux value within 3 hours around the shock j_p. If the relative enhancement in proton flux

$$j_n = j_p / j_b$$

is higher than 1.5, the event is considered as an ESP event.



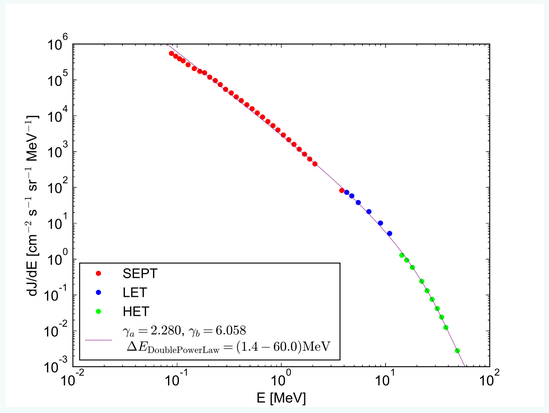
SEP spectra at quasi-parallel shocks

For the 5 ESP events occurring in association with SEPs (4 from STEREO A and 1 from B), at quasi-parallel shocks, the double power law function, proposed by Band (1993),

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

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

fits the spectra better than the Weibull function.

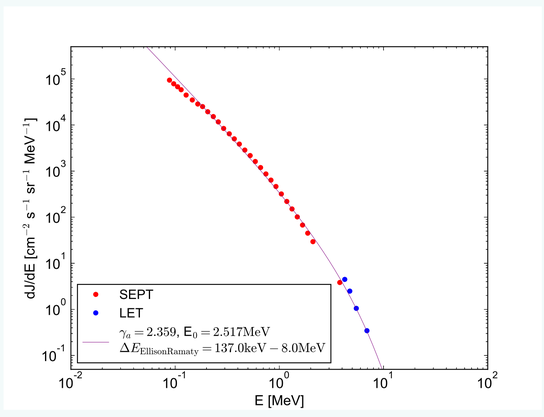


DSA is modified by some process, such as SA.

ESP not associated with SEPs

The best fit for the 22 ESP events not associated with SEPs, 7 from STEREO A and 15 from STEREO B, is obtained with the Ellison-Ramaty function (Ellison & Ramaty, 1985)

$$\frac{dJ}{dE} = C\,E^{-\gamma} e^{-\left(\frac{E}{E_0}\right)}$$

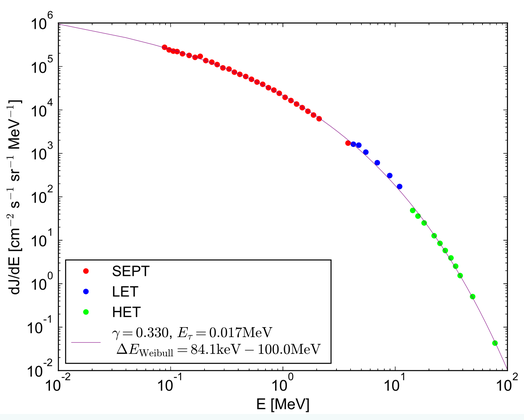


DSA is the only acceleration mechanism at work, although with a reduced efficiency and in order to have an efficient second mechanism at work strong shocks are needed,

SEP spectra at quasi-perpendicular shocks

We selected 12 ESP events occurring in association with SEPs at quasi-perpendicular shocks from STEREO A and 5 from STEREO B. We performed a fit of the time-averaged energetic particle differential fluxes, calculated over 3 hours around the shock arrival, by using the Weibull distribution

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



For some of these events, the best fits are obtained with the Weibull spectrum (Laurenza et al. 2015) over almost the whole energy range.

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This distribution can be related to Stochastic Acceleration (SA) or to Shock Surfing Acceleration (SSA), Pallocchia et al., 2017.

For the others, Weibull-like shape fits at least the high energy tail, whereas the power law fits at lower energies.

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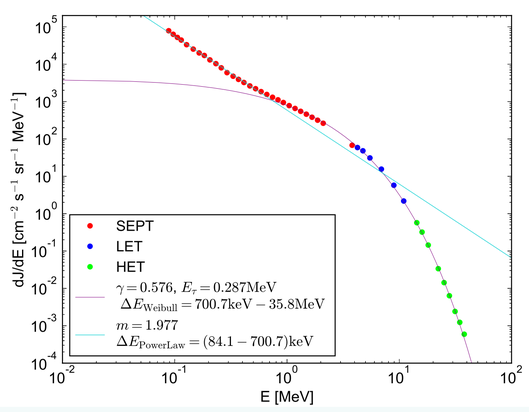
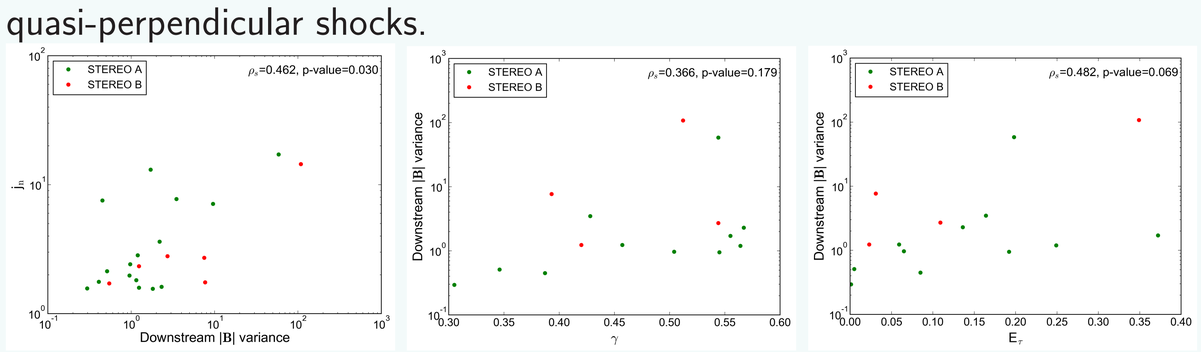
This suggests that two acceleration mechanisms can be at work in different energy ranges, as proposed by Kallenrode, 1996.



Relations with magnetic field fluctuations

We used the Spearman's nonparametric rank correlation analysis to investigate the relation of the level of magnetic field fluctuations downstream of the shocks with the relative proton flux enhancements for all the ESP events associated with SEPs, and with the Weibull parameters for quasi-perpendicular shocks.



Conclusions

- SEP spectra at quasi-perpendicular shocks are best fitted with the Weibull distribution. The high correlation between the Weibull parameters and the magnetic field fluctuations downstream of the shocks suggest the idea that SA plays an important role at high energies.
- Double power law form fits the SEP spectra at quasi-parallel shocks.
- ESP spectra not associated with SEPs are best fitted with the Ellison-Ramaty function, as expected from the modification of the DSA.

References

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Acknowledgements

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