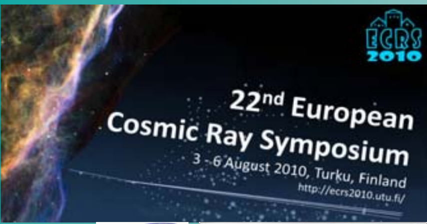

Shannon's entropy approach to the temporal evolution of SEP energy spectra

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The kinetic energy spectra of solar energetic particle (SEP) events contain information on the particle acceleration mechanisms. Several spectral laws have been proposed in the past, such as power law [1], soft exponentials, power law modulated by an exponential [2], broken power law [3]. The spectral shape is related to the characteristics of the CME-driven shock, which is believed to be responsible for particle acceleration in gradual SEP events [4]. Moreover, the particle spectra can be highly dynamic during each event due also to propagation effects [5-6]. On the other hand, impulsive SEP events are thought to be accelerated in solar flares and to propagate almost scatter-free from the Sun, and hence their spectrum should be that of accelerated particles. Here, we examine and compare spectral characteristics and timing of two SEP events of solar cycle 23: 1) the 26 December 2001 gradual SEP event; 2) 20 February 2002 impulsive SEP event. Proton differential flux recorded from SOHO/ERNE[1] have been used on 5 min basis at differential energies of 61 channels from 1.6 to 112 MeV. Association with the solar sources is also studied, by considering solar and interplanetary conditions during the event period. In order to understand the nature of the considered events, the energy spectra evolution is studied by evaluating the time evolution of Shannon's entropy derived from the SEP fluxes (see [7] and references therein). Preliminary results are presented.

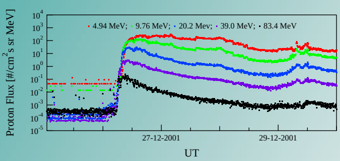

Figure 1 – Proton differential flux recorded from SOHO/ERNE for the 26 December 2001 SEP event

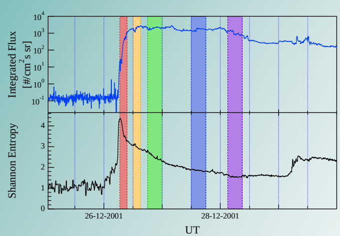

Figure 3 – Energy integrated flux (upper panel) and Shannon's entropy computed for the 26 December 2001 SEP event (lower panel). Coloured bands indicate time intervals during which the different spectra of Figure 5 have been derived.

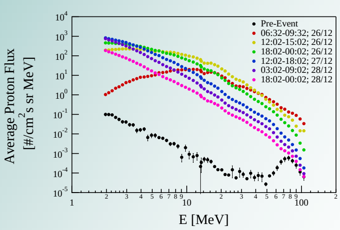

Figure 5 – Spectrum evolution for the 26 December 2001 SEP event.

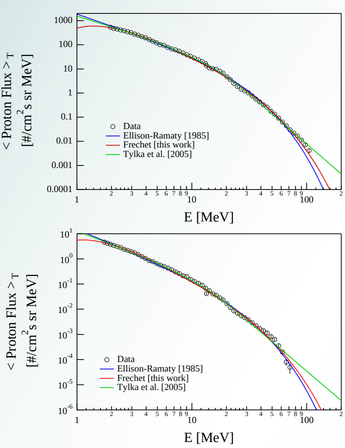

Figure 8 – Time averaged spectrum for the 26 December 2001 SEP event (upper panel) and for the 20 February 2002 SEP event (lower panel).

SEP event associated solar sources and interplanetary conditions

26 December 2001 SEP event

- ✓ Active Region: 9742.
- ✓ Location: N08W54.
- ✓ Flare: M7.6; maximum time at 05:36 UT, on December 26th; e-folding time: 01:19 hr.
- ✓ CME: at 05:30; partial halo; v =1446 km/s.
- ✓ Type II and Type IV radio emissions.
- ✓ ACE shock passage: at 4:47 UT on December 29th.

20 February 2002 SEP event

- ✓ Active Region: 9825.
- ✓ Location: N12W72.
- ✓ Flare: M5.7; maximum time at 06:12 UT, on February 20th; e-folding time:00:04 hr.
- ✓ CME: at 06:30; halo, v = 952 km/s.
- ✓ Type II and Type IV radio emissions.
- ✓ No shock passage or interplanetary disturbances.
- ✓ drop-outs

Shannon's Entropy

Given the differential flux $f(E,t)$, we can define the probability density function $p(E,t)$ (for particles having energy E at time t) and the Shannon entropy $S(t)$, which is sensitive to changes in the particle spectrum.

$$f(E,t) \equiv \frac{dJ(E,t)}{dE}$$

$$p(E,t) = \frac{f(E,t)}{\int_{E_{min}}^{E_{max}} f(E,t)dE}$$

$$S(t) = -\int_{E_{min}}^{E_{max}} p(E,t)\ln p(E,t)dE$$

Spectrum evolution

The spectral shape (Figure 5) changes throughout all the event, as clearly shown by the change of the Shannon entropy (lower panel of Figure 3). In particular, during the event prompt phase (corresponding to the fast rise of the Shannon entropy) the lack of low energy particles is due to the velocity dispersion effect (compare red and yellow curves of Figure 5). Later, the spectrum shows a more gradual evolution, during which the relative contribution of low and high energies continuously changes. The same features are observed (see Figure 6) in the spectrum evolution for event 2).

Moreover, the Shannon entropy (lower panel of Figure 4) shows an additional peak following the prompt phase of event 2). The spectra computed before, during and after the peak (time periods are those indicated by blue, cyan and green color in Figure 4, respectively) are displayed in Figure 7. A noticeable change in the spectral shape is observed: during the peak period the spectrum flattens at low energies (E < 10 MeV; see dashed line in Figure 7); it becomes sharper again soon after the peak. This behavior can be related to drop-outs [see 8].

Model fit

We computed the time averaged spectrum of both events and fit them with three spectral forms (Figure 8):

$$\frac{dJ}{dE} = K_0 E^{-\gamma}\exp\left(-\frac{E}{E_0}\right)$$ Ellison-Ramaty (1985)

$$\frac{dJ}{dE} = \begin{cases} CE^{-\gamma_a}\exp\left(-\frac{E}{E_0}\right) & \leftrightarrow \quad E \le (\gamma_b-\gamma_a)E_0 \\ CE^{-\gamma_b}\{[(\gamma_b-\gamma_a)E_0]^{(\gamma_b-\gamma_a)}\exp(\gamma_a-\gamma_b)\} & \leftrightarrow \quad E \ge (\gamma_b-\gamma_a)E_0 \end{cases}$$ Tylka et al., (2005)

$$\frac{dJ}{dE} = N_0\left(\frac{\sigma^\alpha}{E}\right)^{\frac{1}{1-\alpha}}\sqrt{E}\exp\left[-\frac{1-\alpha}{\alpha}\left(\frac{\sigma}{E}\right)^{\frac{\alpha}{1-\alpha}}\right]\exp\left(-\frac{E}{E_0}\right)$$ Frechet

Table 1 – Fitting parameters

SEP event	Ellison - Ramaty				Tylka et al., 2005					Frechet				
	k_0	γ	E_0 (MeV)	χ^2_ν	c	γ_a	γ_b	E_0 (MeV)	χ^2_ν	N	α	σ	E_0 (MeV)	χ^2_ν
1)	2000±30	1.57±0.01	15.5±0.2	12.00	1690 ±30	1.35±0.02	4.13±0.04	11.1±0.2	4.65	1430±50	0.604±0.003	2.27±0.07	21.2±0.04	5.19
2)	15.9±0.5	1.84±0.3	15.7±0.6	2.62	13.7±0.5	1.60±0.05	3.88±0.08	10.6±0.6	2.47	11±1	0.626±0.007	1.9±0.2	20±1	1.86

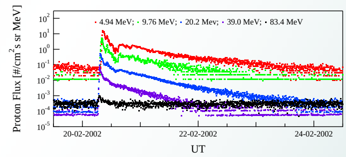

Figure 2 – Proton differential flux recorded from SOHO/ERNE for the 20 February 2002 SEP event.

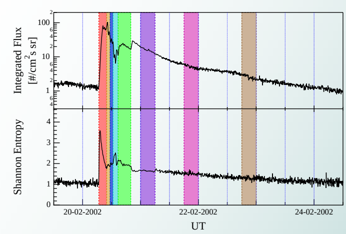

Figure 4 – Energy integrated flux (upper panel) and Shannon's entropy computed for the 20 February 2002 SEP event (lower panel). Coloured bands indicate time intervals during which the different spectra of Figure 6 have been derived.

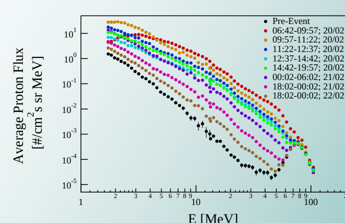

Figure 6 – Spectrum evolution for the 20 February 2002 SEP event.

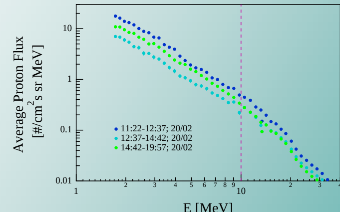

Figure 7 – Spectrum evolution for the 20 February 2002 SEP event.

Parameters obtained for the Frechet form (slope and rollover energy) are basically the same for both events. They are also consistent with those obtained for Ellison-Ramaty form in the high energy limit.

Acknowledgments

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[1]SOHO/ERNE data from http://www.srl.utu.fi/erne_data/main_english.html

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Conclusions

- The Shannon entropy for the 20 February 2002 event shows two main peaks, indicating an abrupt change in the particle distribution after the initial prompt phase of the event. An examination of energy spectrum evolution shows the existence of drop-outs in the particle flux recorded by SOHO\ERNE up to energies of ~ 10 MeV.

- The Shannon entropy exhibits a gradual change in the decay phase of both the considered events, indicating a slowly evolution of the event spectrum (i.e a non stationary shape).

- The Shannon entropy behavior for the two events seems to indicate that a common mechanism is involved in both events, although event 2) is classified as impulsive (see [8]) and event 1) as gradual.

- Results from fit of the time averaged event spectra are consistent with a shock acceleration mechanism. However, the best fit is a Frechet distribution, which is characterized by the existence of a threshold at low energies. More work is needed to relate this spectral shape to phenomena involved in particle acceleration.