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Global Spectral Curvature of Energetic Protons in GLEs of Solar Cycle 23

The power-law momentum distribution of charged energetic particles is a unique prediction for infinitely planar stationary one-dimensional shock waves, for example solar energetic particles (SEPs), accelerated to tens of MeV/nuc. The acceleration at higher energies (0.1 GeV/nuc or more) is likely to be affected by the corrugation of the shock surface, and by the finite spatial extent or limited lifetime of the shock, due to the increase of the typical length-scales of particle motion at those energies. Thus, spectra at 1 AU are commonly fit with double, or multiple, power laws over 3-4 decades in particle kinetic energy.

Mewaldt et al. (Sp. Sci. Rev. 171,97,2012) reported proton spectra for the 16 Ground Level Enhancements (GLEs) in solar cycle 23, i.e., events with a proton flux exceeding the galactic cosmic-ray background in neutron monitors. Li and Lee (ApJ. 810,82,2015), neglecting transport perpendicular to the magnetic field, have shown that SEPs injected with a power-law spectrum near the Sun can produce double power-laws at 1 AU, as a result of propagation effects only.

Another model for SEP spectra assumes a probability of remaining close to the shock decreasing with energy (E) as E^{-q}, with no need of a free escape boundary. This model leads to a log-parabola spectrum (i.e., a parabola in a log-log plot) where the power law is a straight line (Massaro et al., A&A, 413, 489, 2004). The interest of this approach is that the global spectral curvature, β, is unequivocally related to q. Recently, Fraschetti & Pohl (MNRAS, 471, 4856, 2017) modeled the Crab Nebula photon spectrum and showed that a single log-parabola spectrum of electrons, accelerated at the Nebula termination shock, can reproduce observations over 21 decades in photon energy. This spectrum was previously reproduced only with multiple power-laws. We suggest interplanetary shocks provide a valuable test of this model.

In Zhou et al. (RNAAS, 2, 145, 2018) the solar-cycle 23 GLE spectra allow establishment of a relation between β and the E_o break in the double power-law fit. The spectra are assumed not to change during propagation after injection (likely for late-escape particles in shocks driven by gradual coronal mass ejections). In particular, several-day event-integrated GLE proton spectra from ACE/ULEIS, ACE/EPAM, GOES-8/11, and SAMPEX/PET (available at the ACE Science Center) have been used. Figure 1 (left panel) compares the best-fit log-parabola for the August 24, 2002 GLE with the two asymptotic power-laws from Mewaldt et al. (2012; see Figure 2). Figure 1 (right panel) shows the best-fit β vs. the best-fit E_0 (Mewaldt et al. 2012; see Figure 5 therein). Despite the limited sample, we find an anti-correlation of the form $\beta \sim E_0^{-0.36}$.

The anti-correlation found here results from the fact that a shock confining particles with energy above (E_o) enables diffusive shock acceleration up to higher energies with a spectrum closer to a power-law (smaller β). This anti-correlation suggests that the widely-used phenomenological parameter E_0 can be replaced with β, i.e., a global description of the progressive escape as the energy increases. We encourage further analysis in adopting a log-parabola fit for comparison, while theoretical developments proceed.

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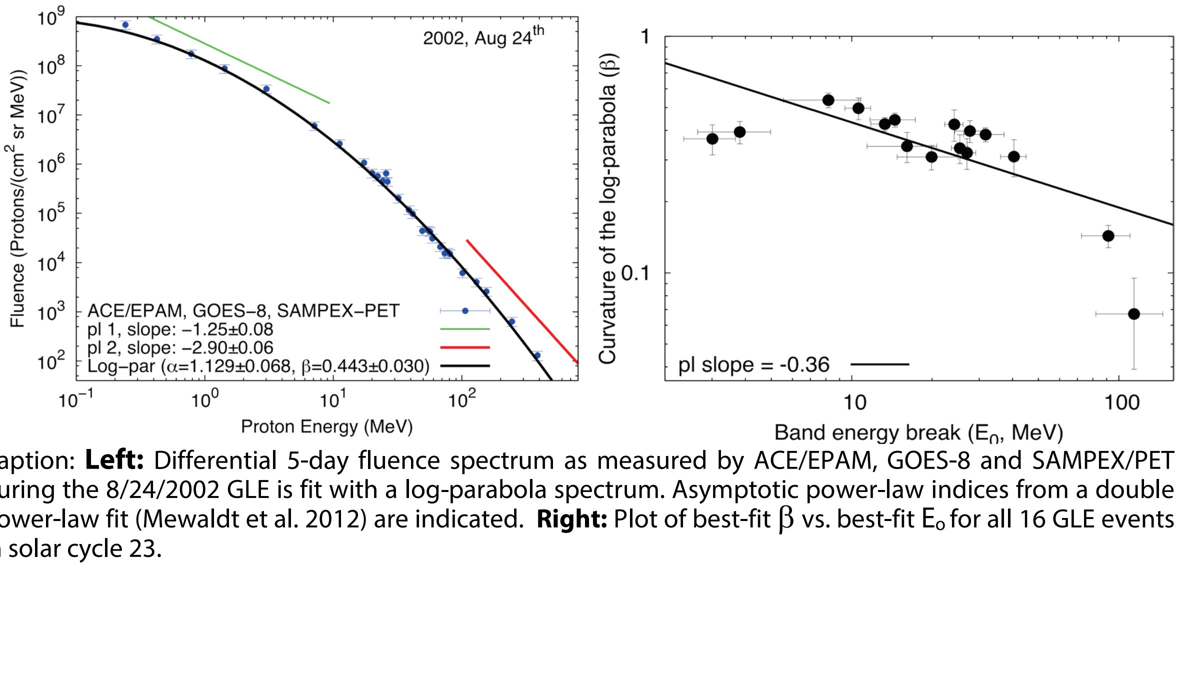

Caption: **Left:** Differential 5-day fluence spectrum as measured by ACE/EPAM, GOES-8 and SAMPEX/PET during the 8/24/2002 GLE is fit with a log-parabola spectrum. Asymptotic power-law indices from a double power-law fit (Mewaldt et al. 2012) are indicated. **Right:** Plot of best-fit β vs. best-fit E_o for all 16 GLE events in solar cycle 23.