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Resolving multiple sources of solar relativistic particles

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We consider the time-profile morphology of solar high-energy particle emissions, including relativistic electrons in three energy channels of *SOHO*/EPHIN, relativistic protons as registered by the worldwide network of neutron monitors, and $\sim$ 100 MeV/n protons and helium in several energy channels of *SOHO*/ERNE. Based on numerical modeling of the interplanetary transport, we formulate a simple method for investigation of the high-energy particle sources operating at / near the Sun during the first hour of particle event. The method is applied to Ground Level Enhancement (GLE) and Solar Energetic Particle (SEP) events of the solar cycle 23. We conclude that depending on the GLE-SEP event scenario and detector vantage point, the observed particles originate from at least three sources. Possible nature of the sources is discussed in the framework of previous and new models of the high-energy particle production associated with global coronal (EIT) waves and CME shocks within about five solar radii from the Sun.

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1. Method and results

We start with modeling of the SEP transport from a source near the Sun to a detector at 1 AU. Interplanetary propagation of high-energy particles is modeled in the framework of focused transport [1] for the Kolmogorov turbulence spectrum in the standard solar wind. The energy dependence of the proton mean free path is according to the standard quasi-linear theory, while the mean free path of ≈ 1 MeV electrons is equal to that of the 1 MeV protons [2]. For analysis of real events, we simulate particle transport and registration with actual energy spectra, energy channels, aperture and viewing direction of a particular instrument. At large values of the mean free path, $\lambda \gtrsim 3$ AU, the particle source profile may be estimated by a proper shifting of the instrument's counting rate profile back in time. The mean free path value is estimated using the flux anisotropy measurements.

Based on the results of particle transport and registration modeling, we shift the observed time-intensity profiles in time back to the Sun but add eight minutes to facilitate a comparison with electromagnetic emissions observed at 1 AU: $t_S = t - \Delta t + 8\,\mathrm{min}$. The time-shifted and renormalised profiles of the 13 December 2006 event (GLE 70) are shown in Figure 1. Plotted only the neutron monitor profile revealing the earliest and steepest onset in this GLE. For a convenience of comparison of different particle species and energy channels, the background levels are reduced to one and the same level that is 1% of the real neutron monitor background.

2. Discussion and conclusions

Inspection of $\sim$(0.1–1) GeV/n protons and helium and $\sim$(0.3–3) MeV electrons of GLEs associated with flares at $\sim$(10°–25°)W has revealed at least three particle sources: Source 1 is a short source associated with flare and CME launch (Period 1 in Figure 1); Source 2 is a prolonged source operating from Period 1 through Period 3, naturally identified with the CME bow shock on open magnetic field lines extending to the solar wind; and Source 3 releases particles in Period 2, could be a compact structure left behind the shock. Source 3 is responsible in particular for the prompt component of GLE. Delayed component of the GLE may contain helium recycled from Source 3.

Different sources, however, do not necessarily suggest different acceleration mechanisms. For instance, a shock can produce different energy spectra and time profiles depending on the environment met, which may include different magnetic structures, plasma turbulence and seed particle populations [3, 4]. Possible scenario is illustrated with Figure 2.

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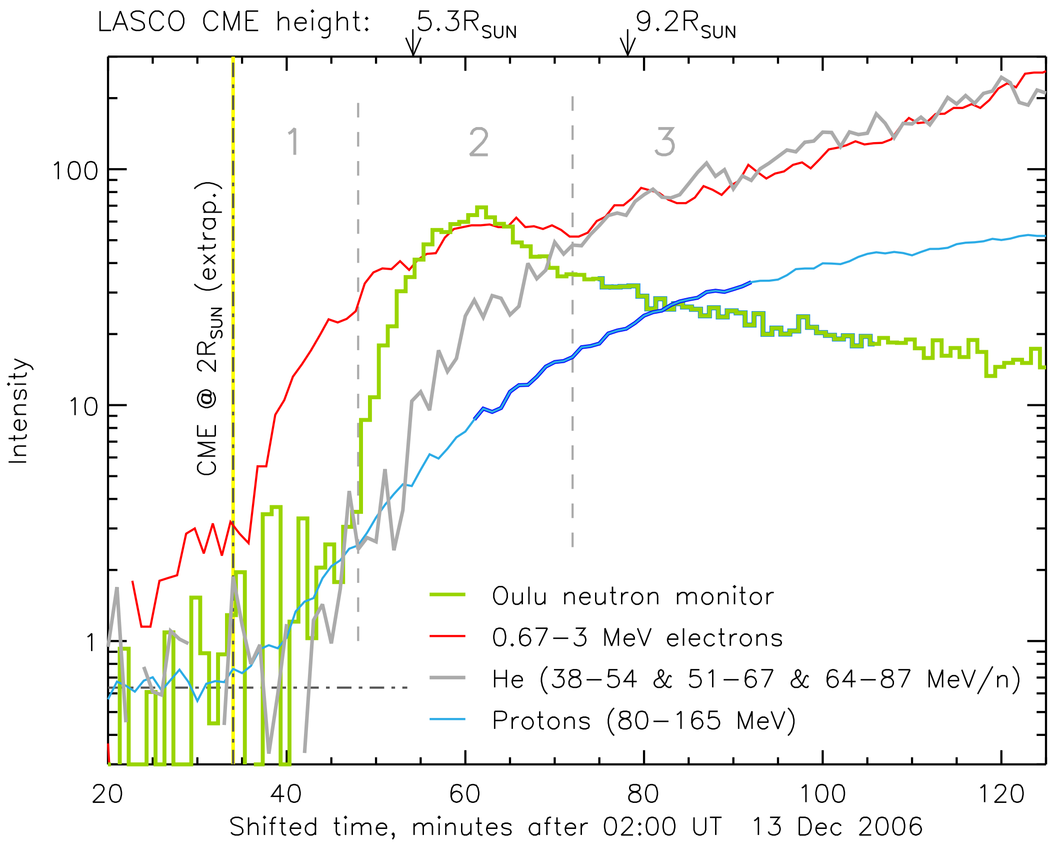
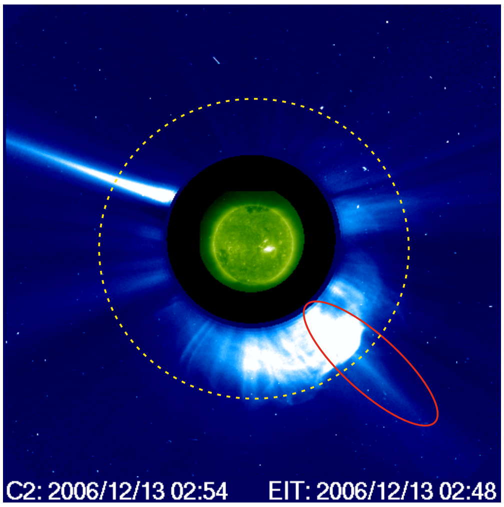


Figure 1: Time-shifted profiles of the 13 December 2006 SEP and GLE event (GLE 70). Shown are the time-shifted and re-normalized profiles of the Oulu neutron monitor count rate (shifted by −3 min), the proton channel P6 (80–165 MeV) of *GOES 11* (−17 min), the 0.67–3 MeV electrons from *SOHO*/EPHIN (−4 min), and the sum of three time-shifted profiles of helium (*SOHO*/ERNE). The helium channels (and time shifts) are 38–54 MeV/n (−28 min), 51–67 MeV/n (−24 min), and 64–87 MeV/n (−20 min). Most of the neutron monitor background is subtracted (99%). All other background levels are reduced to the remnant background of the neutron monitor. The He/p abundance ratio in the 64–87 MeV/n channel of ERNE in early phase of the event, t_{S1} = 46–53 min, is $(\mathrm{He/p})_1 = 0.95 \pm 0.25\%$. Simultaneously with the rise of the GLE's prompt component (in Period 2), the helium abundance increases by a factor of 2.8 ± 0.5 (between the t_{S1} and t_{S2} = 57–74 min). For a comparison with PAMELA data [5], we indicate the shifted time interval that corresponds to the first period of PAMELA observations, 03:18–03:49 UT (thicken segments of the neutron monitor and *GOES* profiles). At the high-energy end, PAMELA observed only the delayed component of GLE 70 (Period 3), while on the whole, the observed spectra are the weighted sum of ions from at least two different sources.



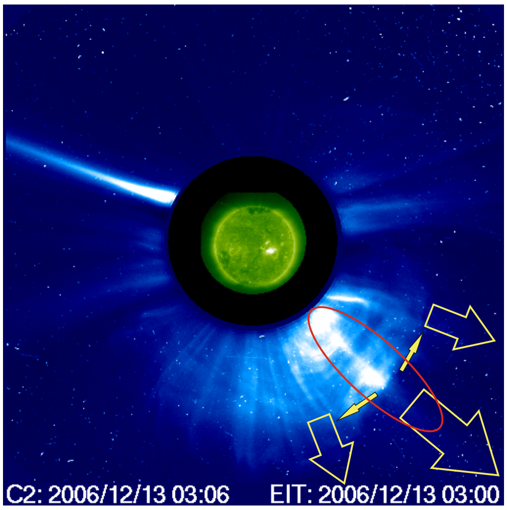


Figure 2: Hypothetical source region of GLE 70. *Left*: *SOHO* LASCO and EIT images of solar corona at the main rise of the GLE's prompt component (the rise started at t_S = 02:48 UT, Figure 1). Yellow circle shows the height of the LASCO CME at 02:48 UT (quadratic extrapolation). Red oval shows location of a previous brightening at intersection of the streamer with preceding ejection, which was observed within half an hour prior to the GLE. *Right*: Red oval is possible acceleration and/or release region of the GLE's prompt (core) component. A pair of tangential arrows illustrates the cross-field transport of accelerated particles, which may populate the CME's loops and contribute to the delayed (halo) component of GLE. Alternatively, the delayed component may be produced far aside of the core at the lateral expansion associated with CME liftoff and visualised close to the Sun by the EUV wave. Radial arrows illustrate the particle escape to interplanetary medium.

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