Acceleration of Solar Flare Particles to Relativistic Energies

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Abstract

We present previously unpublished measurements of high-energy proton spectra for several large particle events observed by the University of Kiel cosmic ray instrument onboard Helios 1 in 1977 to 1982, at distances from the Sun between 0.35 and 1 AU. The spectra which in some events extend to energies well above 1 GeV are compared with the predictions of a stochastic acceleration model. Most of the spectra were found to exhibit rounded, Bessel function like shapes, but in several cases they can also be modeled by a power law in energy. The spectra seem not to be so well correlated with the type of the associated flare, impulsive or gradual, as are energetic electrons which exhibit single power law spectra in gradual and double power law spectra in impulsive flares. This might indicate that for protons the processes of acceleration and escape into the interplanetary medium are more complicated than for electrons.

1 Introduction:

Energetic processes on the Sun are known to occasionally accelerate protons to GeV and electrons to tens of MeV energies. Particle spectra obtained from spacecraft observations, together with observations of the electromagnetic emissions produced by the particles in their interactions with the solar atmosphere can be used to study the environment in which the energetic processes take place as well as the nature of the acceleration mechanisms themselves. It seems that the above questions are still far from being resolved. Whereas it was thought for a long time that all solar energetic particles (SEPs) were accelerated in flares, it has been argued over the past few years (e.g., Reames 1995) that only particles observed in impulsive events originate from the associated flare, and particles in gradual events are instead accelerated at a shockwave in front of a CME. In a recent refinement of the above two-class picture (Cliver, 1996) it was suggested that gradual events possess an impulsive "core" in which similar acceleration processes as in impulsive flares operate, and from which particles can escape into the interplanetary medium where they can be observed together with particles accelerated by a CME-driven shock. This latter view is supported by the fact that in many SEPs two components can be identified, a prompt one with a hard spectrum and a delayed, shock associated one with a steeper spectrum, as well as by the observation of electron spectra from both types of events (Dröge, 1996) over a large azimuthal separation.

2 Data Analysis:

The cosmic ray instrument onboard Helios 1 (Kunow et al., 1977) consisted of five semiconductor and a Cherenkov detector surrounded by a plastic scintillator anticoincidence, and was designed to measure MeV electrons and ions from 2 to $\geq$ 400 MeV/n in various coincidence rate channels. For a statistical sample pulse heights of the last three penetrated detectors were also available. Investigating the reponse of the Cherenkov detector to protons above 100 MeV with the help of a Monte Carlo Simulation performed with the CERN Library program GEANT 3 (Brun et al. 1987) it was possible to extend the useful energy range for protons up to $\sim$ 2 GeV (Bialk & Dröge, 1996; Hamann 1997) and construct reliable proton spectra for events where a sufficiently high number of pulse-height analyzed particle data were transmitted. Proton spectra were constructed taking the maximum differential flux $J(E)$ in each energy interval (c.f., Lin, Mewaldt, & van Hollebeke 1982). The spectra derived with this method should be representative of the source spectra provided that the source is located close to the Sun, that particles escape within a time period which is short compared to the time to maximum flux (TOM) at the spacecraft, and that particle propagation through the interplanetary medium can be described by standard diffusion models. To further minimize propagation effects only such

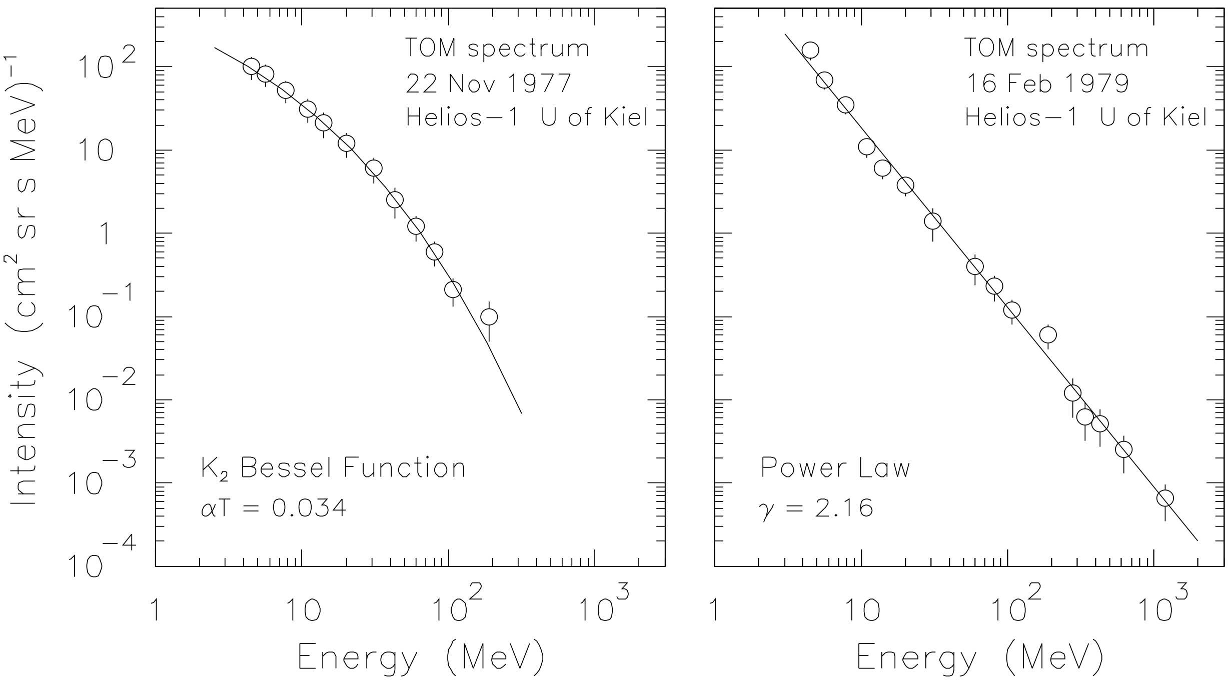

Figure 1: *Proton spectra of the 22 Nov 1977 (left panel) and the 16 Feb 1979 (right panel) solar particle events measured by the University of Kiel particle telescope onboard Helios-1.*

events were selected were the nominal azimuthal distance to the associated flare was less than 50°, and the TOM was short compared to the travel time of the solar wind and of associated CMEs and interplanetary shocks.

3 Theory:

Current theories of acceleration mechanisms in solar flares focus on direct acceleration by DC electric fields, acceleration at shock waves, and stochastic acceleration which results from interaction of the particles with waves of the various modes which can exist in a magnetized plasma. In this work we will test the hypothesis that energetic protons observed in the interplanetary medium after solar flares come from a stochastic acceleration process. The effects of stochastic acceleration and particle escape from the acceleration site, which in our case could be a single closed magnetic loop, post flare loop systems high in the corona (cf., Cliver 1996) or the turbulent region behind a developing CME, can be incorporated in a transport equation in momentum space for the spatially averaged phase space density $f(p,t)$

$$\frac{\partial f}{\partial t} - \frac{1}{p^2}\frac{\partial}{\partial p}\Big(p^2\, D(p)\,\frac{\partial f}{\partial p}\Big) + \frac{f}{T(p)} = Q(p,t) \tag{1}$$

where $D(p)$ is the momentum diffusion coefficient which is determined by the microphysics of the particle interaction with the respective wave mode, Q(p,t) describes sources and sinks of the particles, and $T(p)$ the escape of particles from the acceleration region. A steady-state solution at non-relativistic energies for $D(p) = a_2\, p^{2-\eta}$, $T(p) = T_0\, p^{-b}$ and impulsive monoenergetic injection at low energies is

$$J(E) \quad \sim \quad p^{(\eta+1)/2}\ \mathrm{K}_\nu(\mathrm{x}) \tag{2}$$

where $J(E) \sim p^2 f(p)$ is the particle flux, $\mathrm{K}_\nu(x)$ is a modified Bessel function or order 2, $\nu = |(3-\eta)/(\eta+b)|$ and $x = (4/((\eta+b)^2 a_2 T_0)p^{\eta+b})^{1/2}$. The variable η allows to relate the momentum dependence of $D(p)$ to the spectral index of the turbulence spectrum of certain wave modes (for details of the physics of stochstic

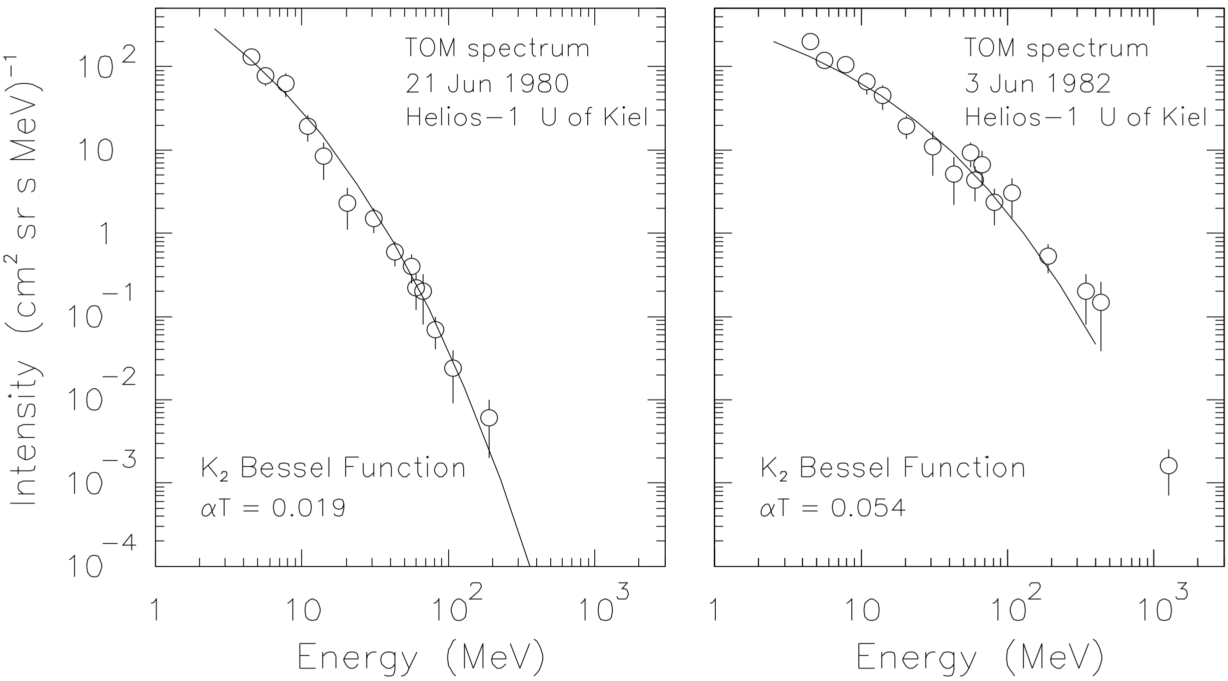

Figure 2: *Proton spectra of the 21 Jun 1980 (left panel) and the 3 Jun 1982 (right panel) solar particle events measured by the University of Kiel particle telescope onboard Helios-1.*

acceleration, and more general solutions and appropriate boundary conditions of eq. (1) see recent reviews by Park & Petrosian 1995, and Miller et al. 1997). A special model of stochastic acceleration, the scattering of particles by hard spheres moving with speed V, has been compared with observations to some extent. Here $D(p) = p^2\alpha/3\beta$, $\alpha = V^2/lc$, $c\beta$ the particle's speed, and l the scattering mean free path, assumed to be constant as well as the escape time T. One then finds $\eta = 1$ and hence $J(E) \sim p\,\mathrm{K}_2(x)$, with $x = (12/(\alpha T)p/(Mc))^{1/2}$, and the shape of the spectrum is solely determined by the constant parameter αT. In the following, we will apply fits with this function or with power laws in energy to the observed proton spectra.

4 Results:

In the present study a total of ten proton events have been analyzed. Figure 1 (left panel) shows the spectrum of 22 Nov 1977 observed on Helios 1 (r = 0.63 AU, magnetic footpoint at W08), associated with a gradual flare (N24 W40). The spectrum can be well fitted up to the highest useful energy point at 200 MeV with a K_2 Bessel function and αT = 0.034. It is interesting to note that a spectrum of a very similar shape was observed on IMP 8 (r = 1 AU, magnetic footpoint at W08; cf., McGuire & von Rosenvinge, 1984). The right panel of the figure shows data for the 16 Feb 1979 event and gives an example for a spectrum which can be modeled by a single power law in energy up to above 1 GeV. The spectra derived for the well-studied impulsive flares of 21 June 1980 and 3 June 1982 are shown in Figure 2. Both spectra can be reasonably well fitted with the K_2 function and αT = 0.019 and αT = 0.054, respectively in the non-relativistic regime although fits with a lesser degree of curvature, corresponding to a Bessel function with a larger index might model the spectrum better. Finally, Figure 3 shows examples for spectra where neither the K_2 function nor power laws give good fits. We find that out of the total sample four spectra can be modeled by the K_2 function with αT between 0.019 and 0.054, four by power laws in energy with spectral indices between 1.9 and 2.3, and two by neither of the above functions. All impulsive flares are associated with K_2 type spectra, all power law spectra are associated with gradual flares, however, from the small number of spectra analyzed so far we do not claim a statistical significance.

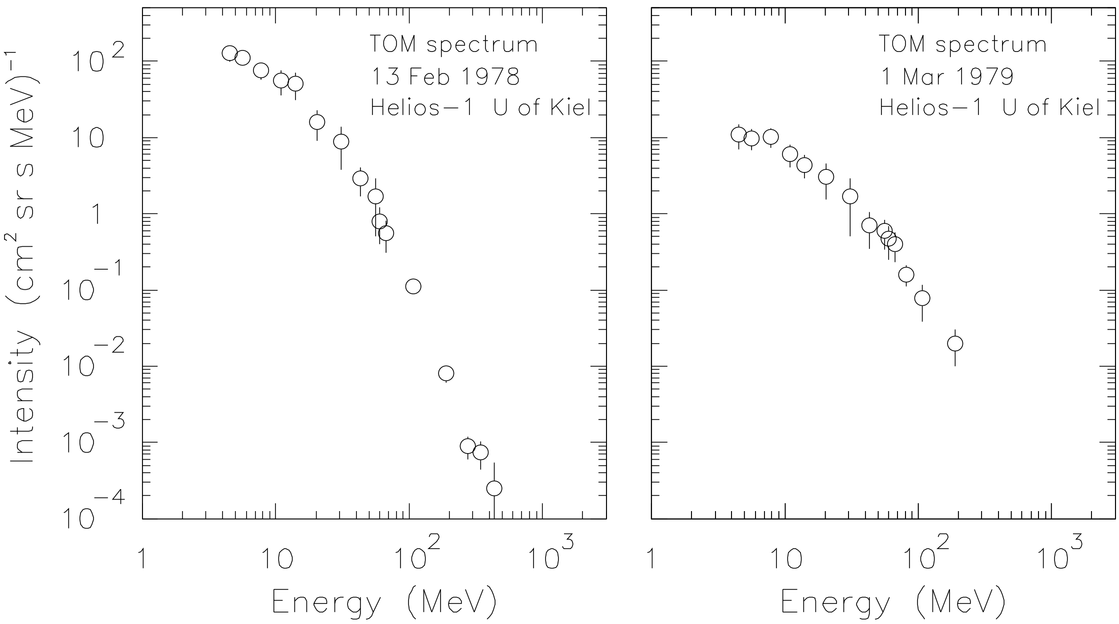

Figure 3: *Proton spectra of the 13 Feb 1978 (left panel) and the 1 March 1979 (right panel) solar particle events measured by the University of Kiel particle telescope onboard Helios-1.*

5 Conclusions:

The proton spectra analyzed in this study are in accordance with the picture of originating from a stochastic acceleration process and can thus serve as diagnostics of processes which take place in a flare or close to the flare site and not at a CME driven shock. The ordering of spectral shapes with respect to associated gradual/impulsive flares is not as strong as is the case for electron spectra, but proton spectra from gradual events tend to have a weaker curvature than spectra from impulsive events. Recent WIND observations of H, He, C, O, and Fe spectra in the range of 20 keV/amu to 100 MeV/amu (Reames et al. 1997), and observations of heavy ion spectra at higher energies (Tylka, Dietrich, & Boberg 1997) seem to reveal a similar ordering although those studies used somewhat different methods to construct particle spectra and draw different conclusions on the acceleration mechanisms. Future work will focus on applying fits with the more general solution (eq. 2) to a larger sample of high energy proton and He spectra from Helios 1 and 2, in order to investigate a possible energy dependence of the acceleration efficiency and the escape time within the stochastic acceleration model.

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