# PARTICLE ACCELERATION BY WAVES AND FIELDS

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## 1. Introduction

The acceleration of electrons and charged nuclei to high energies is a phenomenon occuring at many sites throughout the universe, including the galaxy, pulsars, quasars, and around black holes. In the heliosphere, large solar flares and the often associated coronal mass ejections (CMEs) are the most energetic natural particle accelerators, occasionally accelerating protons to GeV and electrons to tens of MeV energies. The observation of these particles offers the unique opportunity to study fundamental processes in astrophysics. Particles that escape into interplanetary space can be observed in situ with particle detectors on spacecraft. In particular, particle spectra can be diagnostic of flare acceleration processes. On the other hand, energetic processes on the sun can be studied indirectly, via observations of the electromagnetic emissions (radio, X-ray, gamma-ray) produced by the particles in their interactions with the solar atmosphere. The purpose of this article is to give a brief overview on current models on particle acceleration and the present status of observations of solar energetic particles.

## 2. Theory

A complete theory of particle acceleration in solar flares must explain how electrons and ions are energized out of the thermal plasma as well as provide time scales, energy spectra, fluxes and abundance ratios of the various particle species, and the characteristics of the induced emission of neutral radiation which are consistent with observations. However, the interpretation of spacecraft and ground-based data is often difficult because of the chain of assumptions required regarding the convolution of properties of energetic particles with properties of the photospheric and coronal plasma and the interaction between them. Although a complete model is not yet available, considerable progress in the understanding of the physical mechanisms producing energetic particles has been made recently.

Current theories of acceleration mechanisms in solar flares focus on direct acceleration by DC electric fields, acceleration at shock waves, and stochastic acceleration in turbulent magnetic fields (for a recent review, see Miller *et al.*, 1997). Direct acceleration by large-scale electric fields, probably induced by magnetic reconnection, seems to be the least well understood of the above processes. Although these models can account for the acceleration of electrons up to a few hundred keV within the observed time scales, they still fail to produce electrons and protons of high energies and also make no particular predictions for the energy spectra which can be compared with observations.

The idea that particles are accelerated in the vicinity of a magnetohydrodynamic shock wave is not a new one. Among several proposed models, the concept of diffusive shock acceleration, a process whereby particles gain energy by reflecting off converging magnetic fluctuations on both sides of the shock, is probably the most promising candidate to accelerate particles to relativistic energies. In the simplest version of this theory, namely steady acceleration of test particles at a one-dimensional parallel shock, the phase space density $f(x,p)$ of the accelerated particles with momentum $p$ in the shock's rest frame is given by (cf., Drury, 1983)

$$f(x,p) \;=\; p^{-3r/(r-1)} \times \begin{cases} \exp\left(\frac{Ux}{K}\right) & x < 0 \quad \text{upstream} \\ \text{const.} & x > 0 \quad \text{downstream} \end{cases} \tag{1}$$

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where $x$ is the spatial coordinate, $U$ the fluid velocity and $K$ the spatial diffusion coefficient along the field lines. What makes this theory so attractive is the fact that the particle spectrum depends only on the parameter $r$, the shock's compression ratio. Observations of travelling interplanetary shocks in the inner heliosphere, where the theory can be tested with in-situ measurements, have shown that predictions of the simple model are in reasonable agreement with $\leq 0.5$ MeV protons. At higher energies, and for electrons, the model fails to explain the observed interplanetary particle events, due to the typically large values of $K$ in the inner heliosphere (corresponding to scattering mean free paths of 0.1 to 1 AU) and the inferred large acceleration times (days to weeks). However, one cannot exclude the possibility that $K$ is much smaller in the solar corona to provide acceleration time scales of minutes to one hour, neccessary to be consistent with observations. On the other hand, a simple model can then probably not be applied, and effects such as a finite shock size and spatially and temporally varying values of the shock parameters $U, r$ and $K$ have to be taken into account.

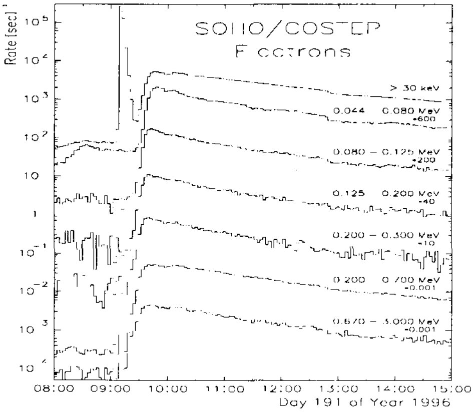

*Figure 1. Time profiles of solar electrons in selected energy intervals observed on the SOHO spacecraft on 9 July 1996. The spike occuring at ~ 9:10 is due to solar X-ray emission (from Sierks et al., 1997).*

There are several physical processes that lead to stochastic acceleration of particles by magnetohydrodynamic turbulence. In the original stochastic Fermi mechanism (Fermi, 1949), the process was reflection from randomly moving clouds, but stochastic acceleration can also result from interaction of the particles with waves of the various modes which can exist in a magnetized plasma. In general, these mechanisms can be regarded as a systematic acceleration of particles plus a diffusion in momentum space. The effects of stochastic acceleration, additional energy gain and loss processes and particle escape can be incorporated in a transport equation in momentum space for the phase space density $f$

$$\frac{\partial f}{\partial t} - \frac{1}{p^2}\frac{\partial}{\partial p}\left( p^2\, D(p)\, \frac{\partial f}{\partial p} \right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left( p^2\, (\, \dot{p}_G + \dot{p}_L)\, f \,\right) + \frac{f}{T(p)} = Q(p) \qquad (2)$$

where $D(p)$ is the momentum diffusion coefficient which is determined by the microphysics of the particle interaction with the respective wave mode, $\dot{p}_G$ and $\dot{p}_L$ represent additional energy gain and loss processes, Q(p,t) describes sources and sinks of the particles, and $T(p)$ the escape of particles from the acceleration region. Analytical solutions of the transport equation which can be expressed in terms of power laws, Bessel functions, hypergeometric functions or combinations thereof, are known for certain forms of the coefficients in equation (2) (cf., Park and Petrosian, 1995). Numerical solutions, which allow the investigation of more general assumptions about the coefficients and boundary conditions of equation (2) have also been obtained (cf., Miller *et al.*, 1997).

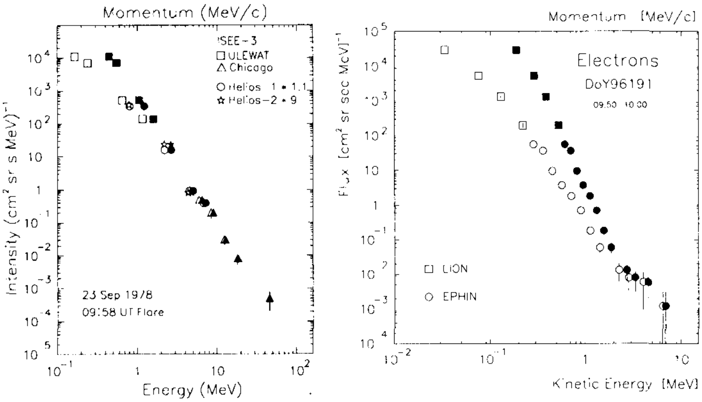

*Figure2. Electron spectra of the solar particle events of 23 Sep 1978 (LDE, left panel) and 9 Jul 1996 (SDE, right panel, measured by LION and EPHIN instruments onboard SOHO ). Spectra are plotted both as a function of energy (open symbols) and momentum (closed symbols).*

## 3. Observations

Observations of solar particles and radiation and their implication for theoretical models of energetic processes in solar flares have been treated extensively in the literature (for recent reviews and compilation of new results see Ramaty, Mandshavidze, and Hua, 1996). As an example we show in Figure 1 the time profile of the electron component of the July 9, 1996 solar particle event observed in different energy windows by the LION and EPHIN particle telescopes onboard SOHO. To relate spacecraft observations to proposed models for acceleration close to the Sun, assumptions about the escape of particles into and propagation in the interplanetary medium have to be made. A recent study (Dröge, 1996) has shown that spectral shapes of electron events in the energy range 0.1 - 20 MeV observed simultaneously with instruments on the *ISEE-3* and *Helios* spacecraft were in very good agreement inspite of the sometimes considerable difference in azimuthal and radial distances of the s/c with respect to the flare. This indicates that transport processes at the Sun and in the interplanetary medium depend only weakly on the electron energy and that the observed spectra could be considered as representative of the accelerated electron spectra at the Sun.

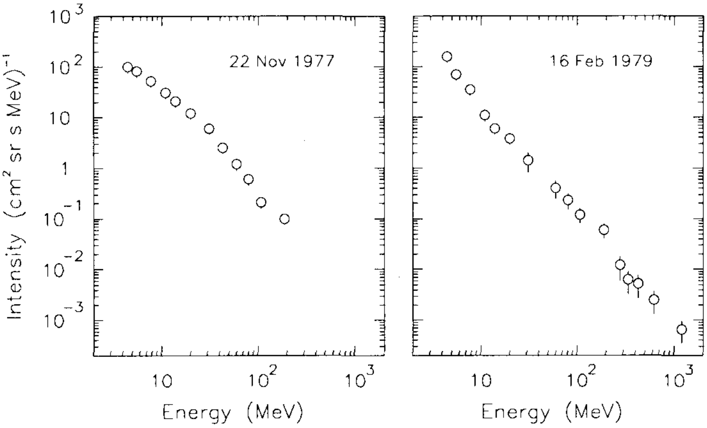

*Figure3. Proton spectra of the 22 Nov 1977 (left panel) and the 16 Feb 1979 (right panel) solar particle events measured by the University of Kiel particle telescope onboard Helios-1.*

It was recognized some time ago (Moses *et al.*, 1989) that electron spectra can be divided into two distinct classes. The spectra of the first class can be modeled by single power laws in momentum over the entire energy range (cf., Fig.2 left panel). Spectra of the second class are steeper at low momenta and flatter at high momenta and hence cannot be fitted by a single power law in momentum. Spectra of the first class are associated with gradual flares (LDEs) while spectra of the second class are associated with impulsive flares (SDEs), in agreement with the well known classification of flare properties with respect to the duration of their soft X-ray emission (Pallavicini, Serio, and Vaiana, 1977). The spectrum of the July 9, 1996 flare (Fig. 2, right panel, from Sierks *et al.*, 1997), for the first time measured continuously over a large range in energy on a single s/c, confirms the above results. These findings may indicate that in LDEs electron acceleration above 200 keV occurs in or is dominated by a single stage mechanism which produces a power law in momentum whereas in SDEs electrons are accelerated by two different mechanisms or in two (or more) different locations.

Spectra of energetic protons and ions often have rounded, Bessel function like shapes, but in several cases they can also be modeled by a single power law in energy (cf., Tylka, Dietrich, and Boberg, 1997). The shapes of proton spectra seem not to be so well correlated with the type of the parent flare as is the case for electrons. Reames *et al.* (1997) have reported WIND observations which show that the spectra of H, He, C, O, and Fe from a gradual event are well represented as power laws in energy in the range 20 keV/amu to 100 MeV/amu, wheras spectra from gradual flares have more rounded spaectra. Preliminary results from a reanalysis of Helios proton spectra (Dröge, 1998, in preparation) from which two examples are shown in Figure 3 have shown that all power law spectra are correlated with gradual events and all impulsive events can be fit by a $K_2$ Bessel function. A few cases do not fall in either of the two categories. However, the above studies used somewhat different methods to construct spectra from the observed interplanetary proton events. Contrary to electrons spectra of protons observed simultaneously on different s/c exhibit in general not such a similar shape, probably proton spectra are much more influenced by the escape process into the interplanetary medium or by a coronal or CME driven shock wave close to the Sun.

## 4. Summary

Recent research regarding solar energetic particles has been very active and has brought us much new information about the processes associated with particle acceleration. Approaching the next solar maximum we can expect exciting new measurements from upcoming, unprecedented spaceflight missions and corresponding progress in the theoretical interpretation.

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