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# Superdiffusive transport of energetic particles through the heliosphere

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## Abstract

Anomalous transport regimes have been observed both in laboratory plasma experiments and in numerical simulations. Here we study the propagation of energetic particles, accelerated by interplanetary shock waves, upstream of the shock. By using the appropriate propagator, we show that in the case of superdiffusive transport, the time profile of particles accelerated at a traveling planar shock is a power law with slope $0 < \gamma < 1$. By analyzing a dataset of interplanetary shocks in the solar wind, we find that the time profiles of energetic electrons correspond to power laws, with slopes $\gamma \simeq 0.30$–$0.98$, implying a mean square displacement $\langle \Delta x^2 \rangle \propto t^\alpha$, with $\alpha = 2 - \gamma > 1$, i.e., superdiffusion. In some cases, the propagation of protons is also superdiffusive, with $\alpha = 1.07$–$1.13$.

Energetic particles are frequently detected by spacecraft in space plasmas. They come from violent solar events as solar flares and coronal mass ejections (CMEs), and from interplanetary shock waves. Energetic particles, while propagating, can interact with magnetic turbulence, undergoing a pitch angle scattering [1]. Previous works underlined how the diffusive propagation of ions is required by the diffusive shock acceleration (DSA) theory [2, 3], that is a first-order Fermi acceleration mechanism, during which particles can reach very high energies being diffused back to the shock, owing to the presence of magnetic irregularities [4]. However, a large variety of observations highlight a transport of solar energetic particles (SEPs) varying from diffusive to ballistic. In addition, anomalous transport regimes, characterized by a mean square displacement which grows as $\langle \Delta x^2(t) \rangle \propto t^\alpha$, both slower ($\alpha < 1$, subdiffusion) and faster ($\alpha > 1$, superdiffusion) with respect to normal diffusion ($\alpha = 1$), have been observed in various systems [5, 6, 7]. An important question, relevant both for shock acceleration and for space weather forecasts, is whether energetic particles, propagating through the heliosphere, can exhibit an anomalous transport.

In this work we analyze fluxes of energetic particles (both electrons and ions) accelerated at interplanetary shocks and we compare them with theoretical fluxes expected in the case of a normal transport and a superdiffusive transport.

Assuming a planar shock and a one-dimensional geometry, the energetic particle fluxes, measured by a spacecraft at $(x,t)$ can be computed by using a propagator $P(x,x',t,t')$ [8], which is the probability of finding a particle at position $x$ at time $t$, if injected at $x'$ and $t'$.

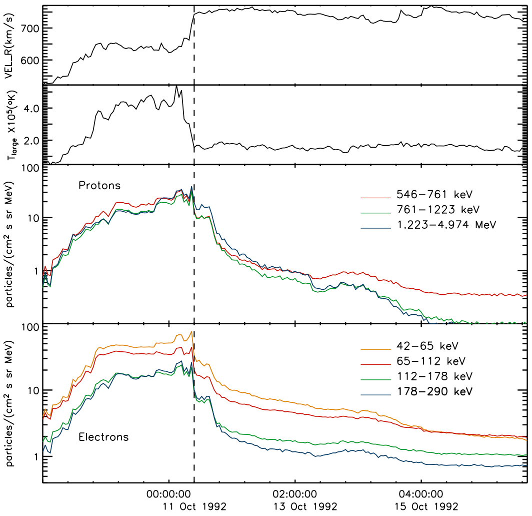

Figure 1: Plasma and energetic particle profiles for the Ulysses shock crossing on 1992 October 11. From top to bottom, panels show 1 hr averages of plasma radial velocity, plasma temperature (from SWOOPS, PI D. McComas), proton fluxes and electron fluxes (from HI-SCALE LEFS 60, PI L. Lanzerotti). Vertical dashed line indicates the shock crossing time.

In the case of normal diffusion the propagator is Gaussian and the particle flux corresponds to an exponential decay, $J = K\exp[V_{sh}|x|/D]$, where $V_{sh}$ is the shock velocity, $|x|$ is the distance upstream from the shock and $D$ is the parallel diffusion coefficient [3]. In the case of superdiffusive transport the propagator has power-law tails [8] and the particle flux is a power-law in time, i.e., $J \simeq 1/(-t)^{\gamma}$ [9, 10]. The exponent $\gamma$ is related to the exponent of the power-law propagator, namely $\mu$, via the equation $\gamma = \mu - 2$. For $2 < \mu < 3$ superdiffusion is obtained for large $t$, $\langle \Delta x^2(t) \rangle \propto t^{\alpha}$ with $\alpha = 4 - \mu$ [8, 9, 10].

We analyze two datasets of energetic particles accelerated at corotating interaction region (CIR) shocks [11], detected by the Ulysses spacecraft on 1992 October 11 and by the Voyager 2 S/C on 1980 June 20. CIR shocks form when the fast solar wind ($V_{SW} \simeq$ 750 km/s) encounters the slow wind ($V_{SW} \simeq$ 400 km/s) giving rise to two collisionless shocks moving in opposite directions — the reverse one sunward, and the forward one anti-sunward. Because at those times the two spacecraft were at large heliocentric distance, $> 5$ AU, then the assumption of planar shock can be considered a reasonable first approximation.

In the first dataset analyzed, we used hourly averages data both for electron and for proton fluxes obtained from the CDAWeb service of the National Space Science Data Center (`cdaweb.gsfc.nasa.gov`). In Fig. 1, plasma radial velocity component, plasma temperature and proton and electron fluxes in log-lin scale are reported. From plasma data it is possible to localize the shock pairs corresponding to jumps in velocity and temperature. Particle fluxes upstream of the reverse shock exhibit a long tail with upward concavity in semi-log scale, corresponding to a power-law. The presence of bumps and irregularities in particle time profiles are probably due to local effect in the magnetic field structure and to variation in the spacecraft-shock connection; these structures last on time scales of $10-30$ hr [12].

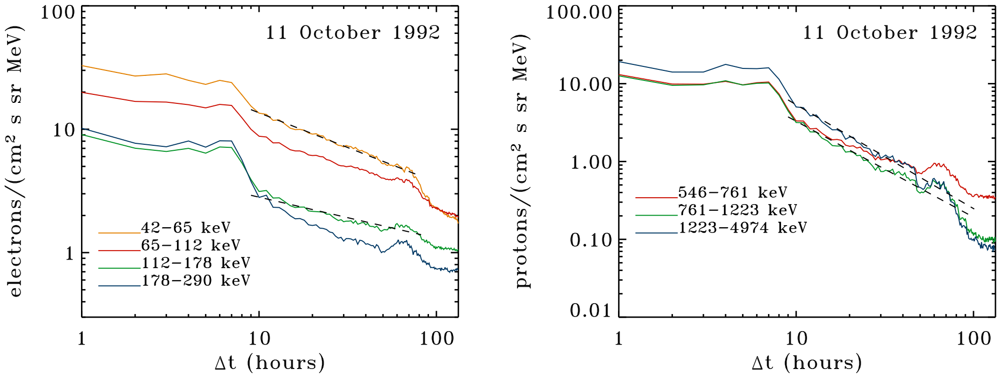

Figure 2: Electron fluxes (on the left) and proton fluxes (on the right) upstream of the reverse shock of 1992 October 11 in log-log scale. Dashed lines represent power-law fits. Energies as indicated.

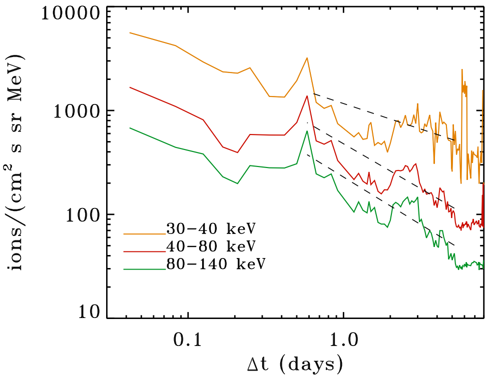

Figure 3: Ion fluxes upstream of the forward shock of 1980 June 20, detected by Voyager 2 (from LECP, PI S. Krimigis). Dashed lines indicate power-law fits.

In Fig. 2 the energetic particle fluxes in log–log axes are displayed as a function of the difference $\Delta t = |t - t_{sh}|$ between the observation time upstream of the shock and the shock crossing time $t_{sh}$. The panel on the left reports the electron fluxes at different energy channels, with dashed lines representing the power-law fits (not all shown for clarity). Fits have been made in the tails of the electron distributions and give values of $\gamma = 0.30$–$0.56$, implying $\mu = \gamma + 2 = 2.30$–$2.56$, that is superdiffusion with $\langle \Delta x^2(t) \rangle \simeq t^{4-\mu} = t^{1.44}$–$t^{1.70}$. A reduced chi square computation show that for the power-law fit values of $\chi^2_{pl}$ are much lower than those of $\chi^2_e$ for the exponential decay. Note that a power-law profile is obtained over almost 100 hours in time, so that the variations due to the turbulence do not influence the fit. On the right of Fig. 2 proton time distributions are displayed: tails are well fitted by a power-law profile for a period of roughly 100 hours, however the exponent assumes values in the range $\gamma = 1.0$–$1.3$, i.e., in this case proton transport is 'at the borderline' between normal diffusion and superdiffusion.

The second dataset consists of hourly averages of energetic ion fluxes from LECP on board of the Voyager 2 spacecraft (`sd-www.jhuapl.edu/VOYAGER/vgr_data_files.html`). Fig. 3 shows three ion fluxes, extending for some days upstream of the forward shock on 1980 June

20, in log-log scale. The 30–40 keV energy channel is characterized by several bumps and fluctuations superimposed that do not permit to perform a good fit. On the contrary, power-law fits of the higher energy channels, 40–80 keV and 80–140 keV, give $\gamma = 0.87, 0.92$ with much lower chi square values than those coming from exponential fits. This corresponds to a mean square displacement $\langle \Delta x^2(t) \rangle \simeq t^{1.08}$–$t^{1.13}$, growing faster than linearly in time.

The two datasets analyzed have highlighted a superdiffusive transport for electron and ions accelerated at CIR shocks. While in previous works [10, 9] proton transport appeared to be normal, in these two events ions are close to be superdiffusive (Fig. 2), or just superdiffusive (Fig. 3). Perri and Zimbardo [10, 9] argued that different transport properties of electrons and protons can be understood in terms of different interaction with magnetic turbulence. Due to the small Larmor radius, electrons can interact weakly with waves, causing a decrease in pitch angle diffusion and a faster parallel transport. However the superdiffusive transport of ions, here found, can be due to a lower level of magnetic turbulence upstream of the shock, owing to the higher heliocentric distance. Indeed, further analysis, made on fluxes of energetic ions accelerated at the termination shock, show a superdiffusive transport of ions in several energy channels.

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