Flat Particle Fluxes Upstream of Interplanetary Shock

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Abstract / Objectives

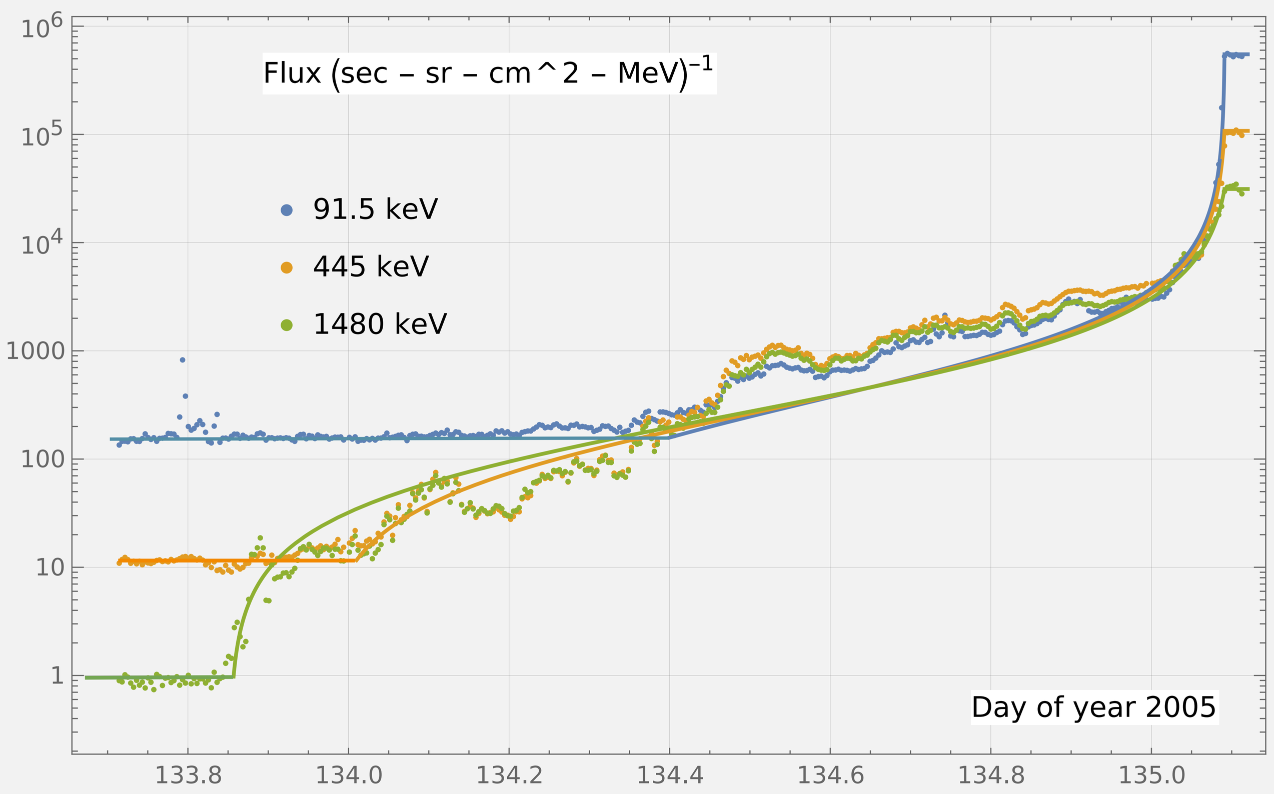
Abstract The observed energy spectra of accelerated particles at interplanetary shocks often do not match the diffusive shock acceleration (DSA) theory predictions. In some cases, the particle flux forms a plateau over a wide range of energies, extending upstream of the shock for up to seven e-folds before submerging into the background spectrum. Remarkably, at and behind the shock, the flux falls off in energy as ϵ^{-1}, consistent with the DSA. The upstream plateau suggests a different than in the DSA particle transport mechanism. A standard (linear) DSA solution based on a widely-accepted diffusive particle transport with an underlying resonant wave-particle interaction cannot explain the plateau in the particle flux. To explain it, we modify the DSA theory in two ways. First, we include a dependence of the particle diffusivity κ on the particle flux F (nonlinear particle transport). Second, we invoke short-scale magnetic perturbations that are self-consistently generated by, but not resonant with, accelerated particles. In this solution, the particle diffusivity increases with energy as $\propto \epsilon^{3/2}$, simultaneously decaying with the particle flux as $1/F$ almost everywhere in the shock precursor.

Overview Diffusive shock acceleration (DSA) is the most universal and robust mechanism whereby particles are accelerated to high energies in various shocks across the universe. Its physical and intuitive grounds are accessible. In particular, the shape of the particle spectrum behind a passing shock comes from a "back-of-the-envelope" calculation. It is a power-law in momentum $\propto p^{-q}$, with an index $q = 3r/(r-1)$, that merely depends on the shock compression, r.

This paper considers a DSA disagreement with the observed spectra. Namely, at interplanetary shocks observed *in situ*, e.g., [1], the particle flux often *flattens upstream*, whereas the downstream part agrees with the DSA. Since the disagreement is partial, it helps identify the DSA elements responsible. In addition, it might shed light on how the DSA is sped up by waves excited by the accelerated particles themselves.

Resonant waves typically saturate at a level not significantly higher than $\delta B/B_0 \sim 1$. Other, macroscopically-driven instabilities may continue to grow, such as an acoustic instability driven by the pressure gradient of accelerated particles. We argue that this *nonresonant* instability may result in the spectrum flattening observed ahead of interplanetary shocks. At the same time, it does not affect the DSA-predicted spectral slope downstream, as also observed.

Observational Hints and Model Fits



- The left panel demonstrates disagreements with the "standard" DSA model on the upstream side of the shock ($t < 135.1$)
- At the same time, on the downstream side $t > 135.1$, the particle flux decreases approximately as ϵ^{-1} with energy, which is consistent with the DSA
- Immediately on the upstream side, the low-energy part of the spectrum decays more steeply with distance from the shock, which is also qualitatively consistent with the DSA, if the particle diffusivity grows with energy.
- Further ahead, the disagreements with the DSA become obvious since the particle intensity does not depend on energy (flat spectrum)
- In the "standard" DSA high-energy particles diffuse farther upstream, which is in stark disagreement with the present observations
- Right panel shows fits in three energy channels produced using eq.(3)
- The fits correctly reproduce the observations over the entire shock precursor and many orders of magnitude in particle intensity
- Deviations of the theoretical curves from the data points may be caused by
  - time dependent effects, which are not included in the model described below
  - magnetic traps that are seen in the bottom plot at the left panel

Acceleration Model

Assumptions

- macroscopic wave generation by the pressure gradient or current of accelerated particles upstream
- nonresonant interaction of accelerated particles with self-generated waves
- nonlinear particle diffusivity (diffusion coefficient depends on the particles intensity through the wave energy)

Particle diffusion

$$\kappa_{\parallel} \simeq \frac{v^3}{l\omega_c^2}\frac{1}{E_{\mathrm{w}}} = \frac{\kappa_0}{E_{\mathrm{w}}}$$

E_{w}- normalized wave energy, related to the particles flux $F(\epsilon) = p^2 f(p)$, f -conventional momentum distribution of accelerated particles, ϵ - particle energy. Since l is a fixed turbulence correlation length, not associated with the resonant wave number $k = r_g^{-1} \propto 1/\sqrt{\epsilon}$, the energy scaling of $\kappa_{\parallel} \sim \epsilon^{3/2}\omega_c^2$, where ω_c is the particle Larmor frequency. Wave energy is related to the particle flux as follows:

$$E_{\mathrm{w}} = \frac{16\pi\sqrt{2m}\epsilon^{3/2}}{3(M_A - 1)\rho V_A^2}(F + \psi). \qquad (1)$$

$\psi(\epsilon)$ parameter associated with the background particle and wave spectra far upstream, M_A is the Alfvenic number of the shock, V_A -Alfven velocity, ρ is the plasma density

Particle transport and acceleration

$$u\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\kappa_{\parallel}\cos^2\vartheta_{Bn}\frac{\partial f}{\partial z} - \frac{p}{3}\Delta u\frac{\partial f}{\partial p}\delta(z) + Q(p)\delta(z) \qquad (2)$$

Solution in terms of $F(\epsilon)$

$$F = (\Psi - \psi)\left[\left(1 + \frac{\Psi - \psi}{F_0 + \psi}\right)e^{(\psi - \Psi)\zeta} - 1\right]^{-1} - \psi. \qquad (3)$$

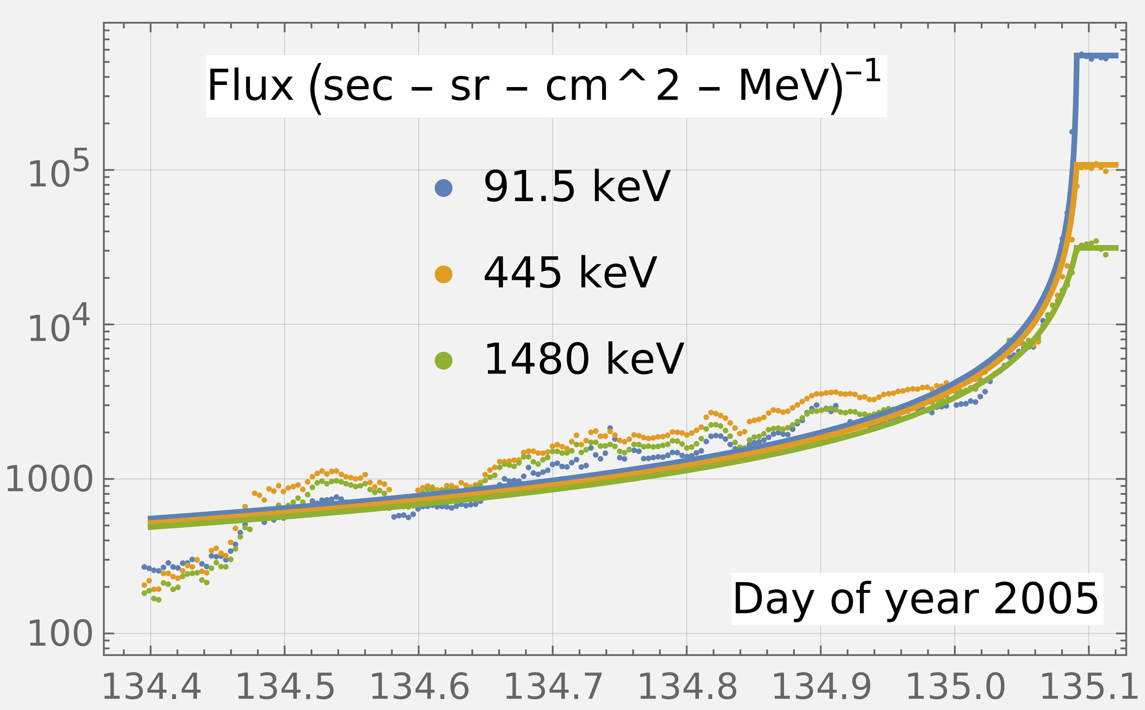
Here $F_0 \propto \epsilon^{-1}$ is the downstream flux, $\Psi(\epsilon)$ is associated with the particle injection at the shock front and shock parameters (Mach number)

$$\zeta = \frac{\epsilon^{3/2}}{\kappa_0(\epsilon)}\int_0^z \frac{dz'}{K(z')} \qquad K \equiv \frac{3\rho V_A\left(1 - M_A^{-1}\right)}{16\pi\sqrt{2m}}\cos^2\vartheta_{Bn}(z)$$

Since for nonresonant wave-particle interactions $\kappa_0 \propto \epsilon^{3/2}$ the normalized distance ζ upstream does not depend on energy series expansion for $|(\psi - \Psi)\zeta| \ll 1$ and $\psi \ll F_0$

$$F \simeq \frac{F_0}{1 - F_0\zeta}. \qquad (4)$$

For $-F_0\zeta > 1$ ($\zeta < 0$ upstream), $F \approx -1/\zeta$, which is a completely flat spectrum, as observed



As seen from this plot, eq.(4) fits the data reasonably well not far from the shock. To fit the data in the whole upstream region, somewhat uncertain functions Ψ and ψ need to be included. We approximate them using a power-law dependence of particle energy. The result is shown in the previous section.

Conclusions The following two modifications to the DSA theory are required to explain the flat spectra observed ahead of several interplanetary shocks

- Dependence of particle diffusivity κ on the particle flux F (nonlinear particle transport)
- Short-scale magnetic perturbations that are self-consistently generated by, but not resonant with, accelerated particles
- In the resulting DSA solution, the particle diffusivity increases with energy as $\propto \epsilon^{3/2}$, simultaneously decaying with the particle flux as $1/F$ almost everywhere in the shock precursor

References

[1] D. Lario, L. Berger, L. B. I. Wilson, R. B. Decker, D. K. Haggerty, E. C. Roelof, R. F. Wimmer-Schweingruber, and J. Giacalone. Flat proton spectra in large solar energetic particle events. *Journal of Physics: Conference Series*, 1100(1):012014, oct 2018.