An introduction to diffusive shock acceleration in space sciences

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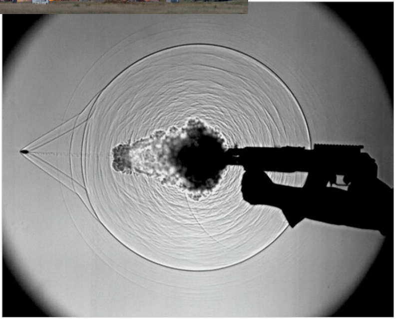
Outlook...

- What is a shock?
- What shocks exist in space?
- How do these shocks accelerate particles?
- How do we model this acceleration?
- How is this relevant to space sciences?

What is a shock?

"A shock is a disturbance, extending over a narrow spatial interval, across which physical properties of a medium change abruptly, and travels faster than disturbances that may forewarn of its arrival."



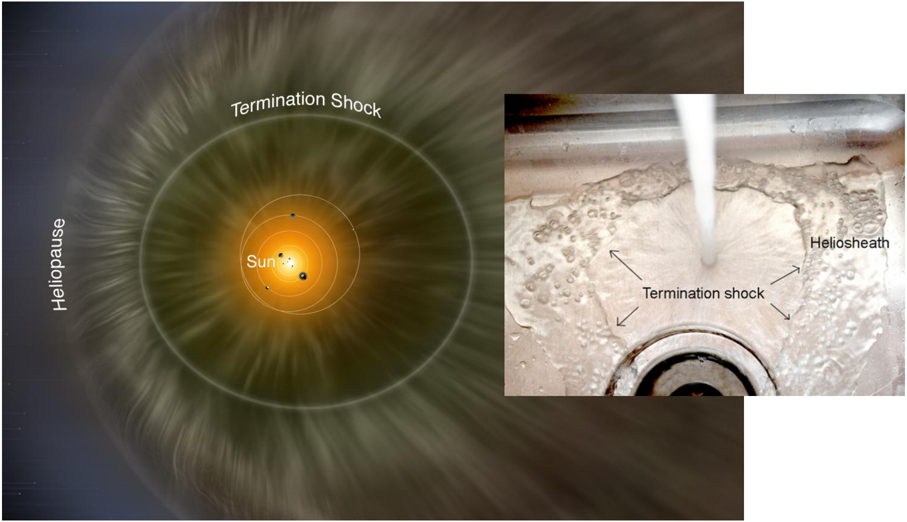
A hydraulic analogy:

- Water moves outward from the point of impact at some (super-)critical speed.
- The flow of water slows with an accompanying rise in water depth - a 'hydraulic jump'.

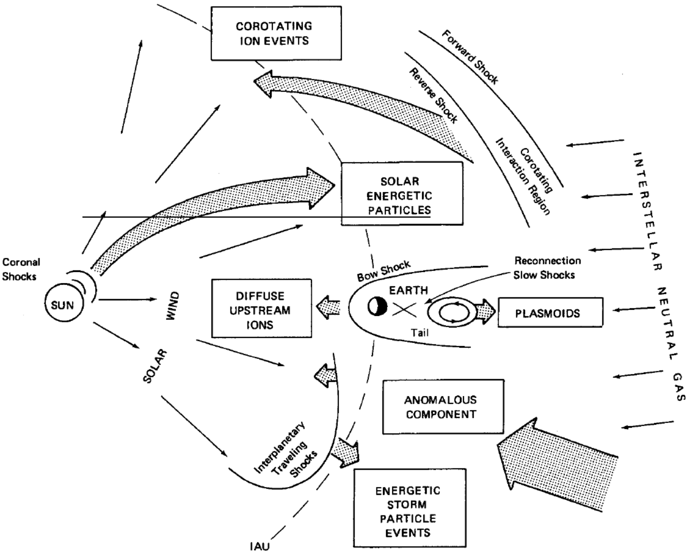
Similarities with shocks include:

- Abrupt change in physical properties
- $V_{\text{jump/sh}} > V_{\text{waves}}$

tidal bores and other hydraulic jumps...



See also Jokipii, J. R., Solar System: A shock for Voyager 2, Nature, 454, 38-39, 2008



Scholer, M., Adv. Space Res. 4, 419, 1984

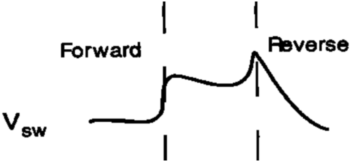
Shock terminology:

Collisionless shocks:

- Particle-particle collisions replaced by magnetic field-charged particle interactions.

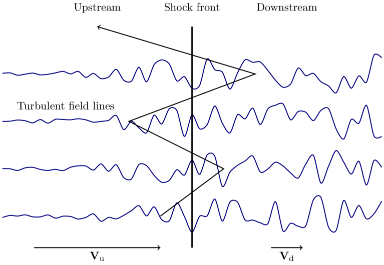
Shock propagation:

- *Forward* shocks propagate away from the Sun, and
- *Reverse* shocks propagate toward the Sun, w.r.t. the solar wind frame.

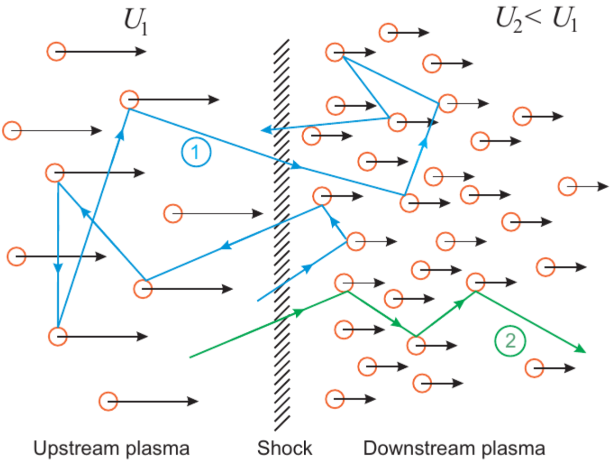


Shock orientation:

- For *perpendicular* shocks, $\mathbf{n} \perp \mathbf{B}$, and
- For *parallel* shocks, $\mathbf{n} \parallel \mathbf{B}$, where **n** is the shock normal and **B** is the magnetic field.



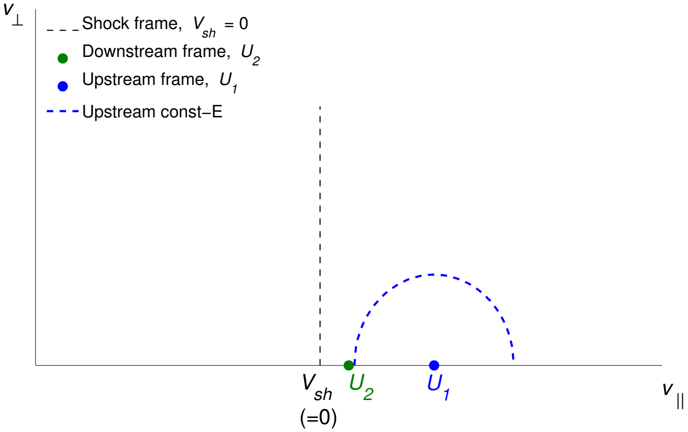
How do shocks accelerate particles?



from Achterberg, B., Cosmic Accelerators, IAC, 2008

Energy gain i.t.o. difference in reference frame:

$$v = \sqrt{v_{||}^2 + v_\perp^2}$$



see also Sugiyama, T., *et al.*, JGR, 106, A10, 2001

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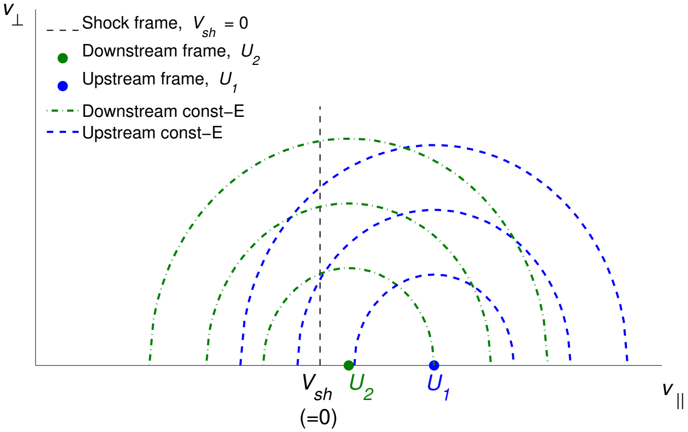

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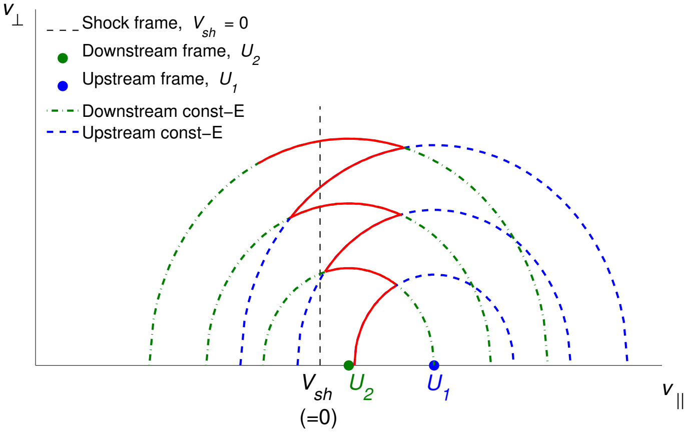

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A monoenergetic population of test particles are accelerated into a power law given by $j \propto P^{(s+2)/(1-s)} \propto E^{\gamma(s)}$ with

$$\gamma(s) = \begin{cases} \frac{1}{2}(s+2)/(1-s) & E \ll E_0 \\ (s+2)/(1-s) & E \gg E_0 \end{cases}$$

where s is the compression ratio and E_0 is the rest-mass energy.

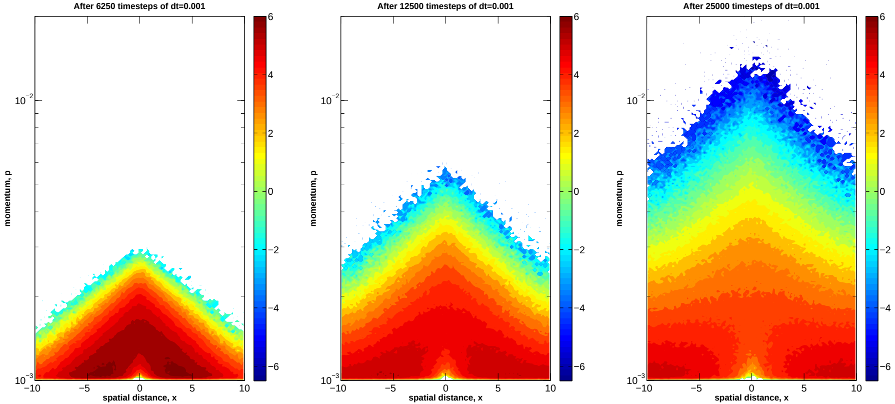
For a non-relativistic shock in a monatomic medium (ratio of specific heats $= 5/3$), the power-law index depends only on the compression ratio, s, which in the case of large Mach numbers, $M \to \infty$, has a maximum value of

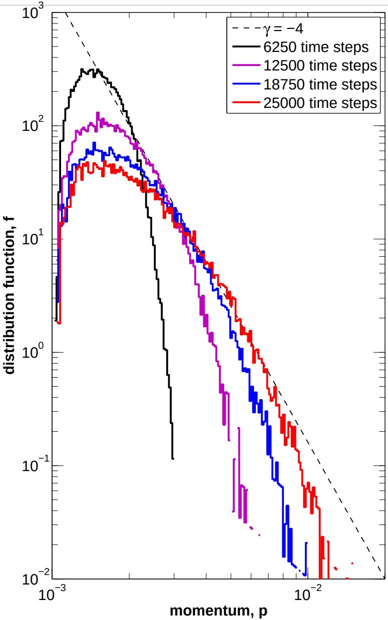
$$s \sim \frac{5/3+1}{5/3-1} = 4$$

Parker (1965) transport equation:

$$\frac{\delta f}{\delta t} = -(\boldsymbol{V}_{sw} + \langle \boldsymbol{v}_d \rangle) \cdot \nabla f + \nabla \cdot (\mathbf{K}_s \cdot \nabla f) + \frac{1}{3} (\nabla \cdot \boldsymbol{V}_{sw}) \frac{\delta f}{\delta \ln p} + Q,$$

- Energy gains attained through the convergence of scattering centres.
- Scattering centres characterised in terms of diffusion coefficients.




γ = −4
6250 time steps
12500 time steps
18750 time steps
25000 time steps
distribution function, f
momentum, p
10^3
10^2
10^1
10^0
10^−1
10^−2
10^−3
10^−2

Summary:

- Charged particles in space environments are accelerated at magnetised collisionless shocks.
- Diffusive shock acceleration occurs when particles are repeatedly scattering across shock fronts.
- Energy gains can be understood in terms of differences in up- and downstream reference frames.
- The resultant energy spectrum is a power law, of which the spectral index is a function of the compression ratio.

Current and future applications:

- Re-acceleration of galactic electrons at the termination shock (Prinsloo *et al.*, ApJ, 836:100, 2017).
- Acceleration in the inner heliosphere at travelling interplanetary shocks, CIRs, etc. - relevant to space weather.