Constraints on the Acceleration of Charged Particles in the Heliosphere

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The energy change of a charged particle in the absence of collisions comes from the electric force. In a collisionless MHD fluid this may be written:

$$\Delta T = \int_{t_0}^{t_0+\Delta t} \mathbf{w} \cdot \mathbf{E}(\mathbf{r},\mathbf{t})dt$$

$$= -\int_{t_0}^{t_0+\Delta t} \mathbf{w} \cdot \frac{\mathbf{U}(\mathbf{r},\mathbf{t}) \times \mathbf{B}(\mathbf{r},\mathbf{t})}{c}dt$$

One may use the second relation above to express the energy change in terms of **B** and **U**. Since the position is needed we must include spatial transport as well.

Observational Constraints on the Time Taken to Accelerate

- SEP ions and electrons – acceleration time apparently less than minutes. Significant temporal changes occur in seconds, but these may not reflect acceleration times. These are not significant constraints now.

- Heliospheric Particles
  - The only real constraint is the time available for acceleration. At present these are not significant constraints.

- Anomalous Cosmic Rays
  - The observed ACR charge states limit the acceleration time of ACR to less than a few years (e.g., Adams, 1991; Jokipii, 1992; Mewaldt, etal, 1996).

Spatial Constraints

- Larger systems can accelerate to higher energies.
- In quasi-static flows such as shocks and reconnection events, the available electric potential is relevant.

Stochastic vs Deterministic Acceleration

- Stochastic acceleration
  - Example: 2nd-order Fermi
  - Involves a *random walk* or *diffusion* in energys.

- Deterministic acceleration
  - Examples: Diffusive shock acceleration; compression acceleration.
  - Usually is uni-directional in energy – involves a directed electric field.

Stochastic Acceleration

- Has appeared in various forms since Fermi's famous paper on 2nd-order Fermi acceleration by randomly moving magnetic clouds.
- The acceleration time may be written, quite generally, as , (see next slide)

  where τ_{scat} is the time for magnetic scattering.
- The lowest value of τ_{st} is clearly when $\tau_{scat} = \tau_{gyro}$, the particle cyclotron period.
- This is generally very slow. Applying these considerations to the heliosheath and ACR yields $\tau_{st} \approx 200$ yr, which is much too long.

Deterministic Acceleration: The Role of Electrostatic Potential Energy

- In an MHD fluid, the electric field $\mathbf{E} = -\mathbf{U} \times \mathbf{B}/c$ is specified by the flow velocity and magnetic field.

- In approximately steady flows such as in quasi-perpendicular shocks and reconnection, the maximum energy is just $T_{max} \approx q \int \mathbf{E} \cdot d\mathbf{l} \approx q \, \Delta \phi \approx qUBL/c$.

- Example: using this in the *latitudinal* direction in the heliosphere, integrating from 0 to $\pi/2$, at *any* fixed radius R in the solar wind in the$T_{max} \approx 300$ Z MeV.

- Applying this to the *heliospheric termination shock* then readily yields the ≈ 200 MeV/charge anomalous cosmic-ray (ACR) energy. *The termination shock can readily give us the ACR.*

A Note on Quasi-Parallel Shocks

- Acceleration at a quasi-parallel shock is not caused by a directed electric field.
- It is determined by the fluctuating electric fields associated with the advection of magnetic fluctuations.
- The acceleration is much slower than at quasi-perpendicular shocks. They cannot do the ACR because of the time constraints.
- I will not discuss quasi-parallel shocks further, here.

Lazarian and Opher (2009) proposed turbulent reconnection in the heliosheath, with multiple Sweet-Parker reconnection regions.

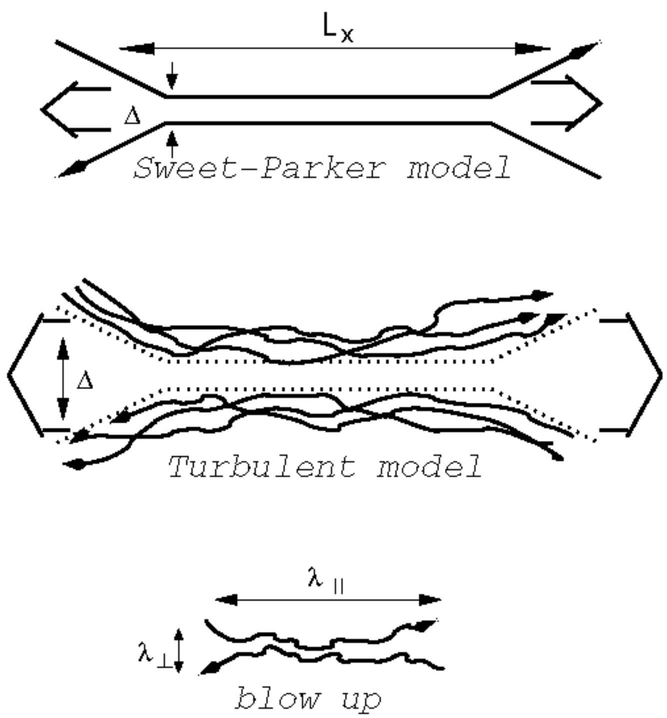


Figure 4. Upper plot: Sweet–Parker model of reconnection. The outflow is limited by a thin slot Δ, which is determined by Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \Delta$. Middle plot: reconnection of a weakly stochastic magnetic field according to LV99. The model that accounts for the stochasticity of magnetic field lines. The outflow is limited by the diffusion of magnetic field lines, which depends on field line stochasticity. Low plot: an individual small-scale reconnection region. The reconnection over small patches of the magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches come together (from Lazarian et al. 2004).

Drake, et al, 2009 had a different proposal which also involved reconnection:

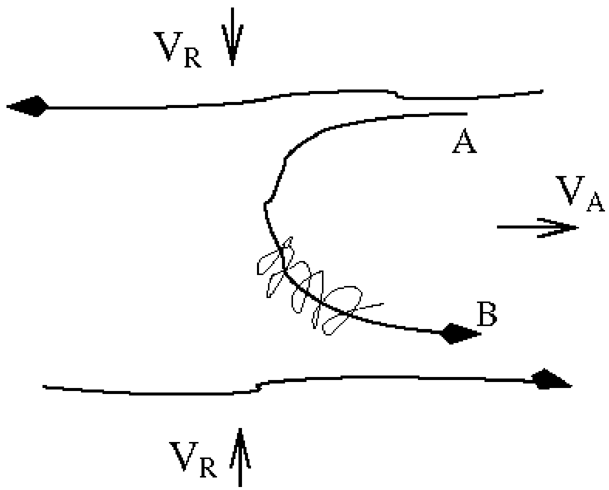


Figure 6. Cosmic rays spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move toward each other with the reconnection velocity V_R. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of V_A. Bouncing at points A and B happens because of either streaming instability induced by energetic particles or magnetic turbulence in the reconnection region. In reality, the outflow region gets filled in by the oppositely moving tubes of reconnected flux (see Figure 5) that collide only to repeat on a smaller scale the pattern of the larger scale reconnection. Thus, our figure also illustrates the particle acceleration taking place at smaller scales (from Lazarian 2005).

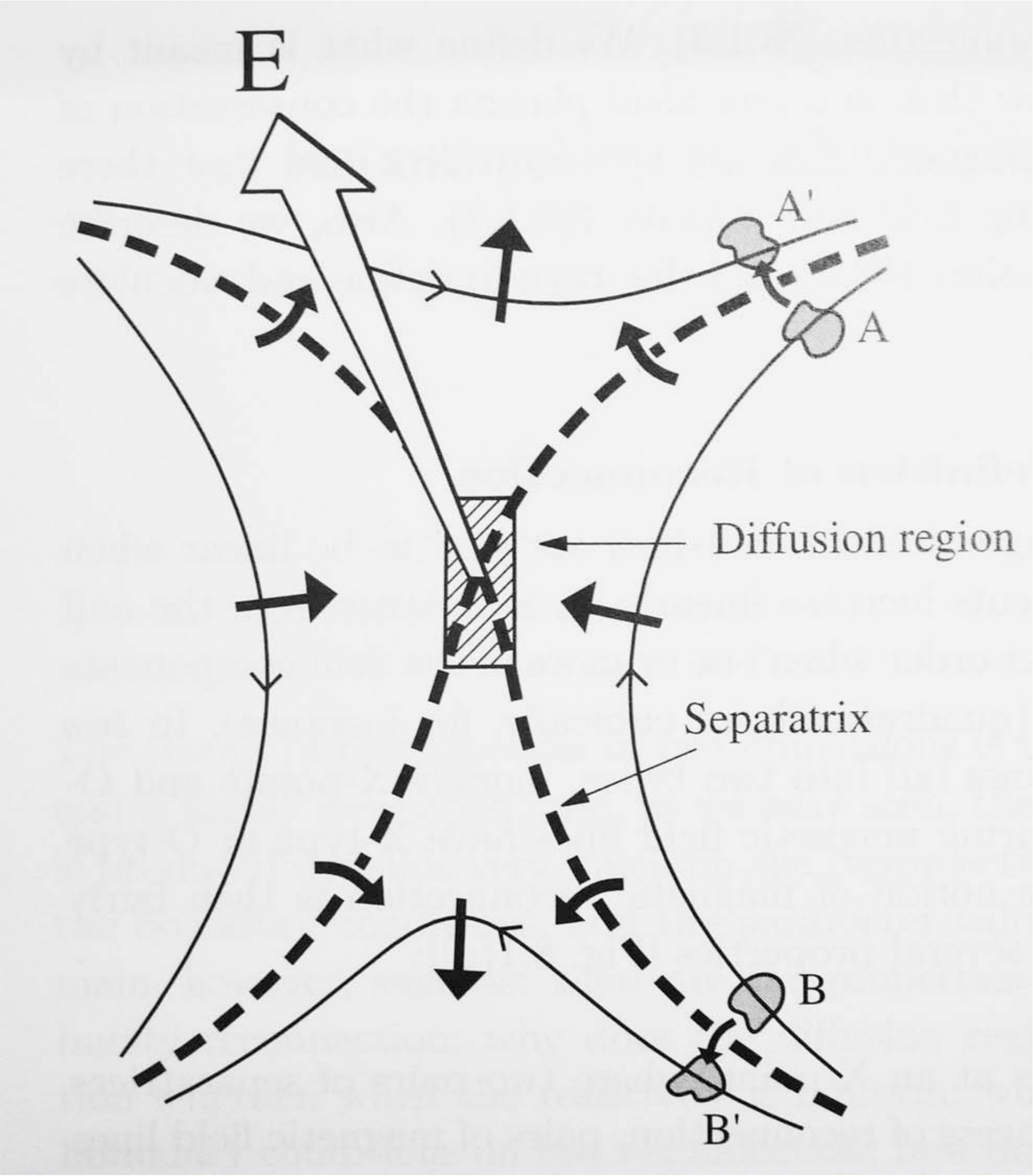
Analysis of Acceleration in Reconnection

- Recent papers (e.g. Lazarian and Opher, 2009, and Drake, et al, 2009) have proposed acceleration at reconnection events in the heliosheath, based on 2-dimensional simulations. ACR cannot be accelerated in a single event, as suggested by Lazerian and Opher.
- The electric field **E = -U x B/**c is normal to the frame of the simulation. |**U**| is about the Alfvén speed in the heliosheath, which is significantly less than the solar wind speed. Hence the electric field is significantly smaller.
- Hence, even if the scale of the reconnection event is the scale of the heliosphere, a *single reconnection event* cannot yield the 200 MeV/charge ACR.

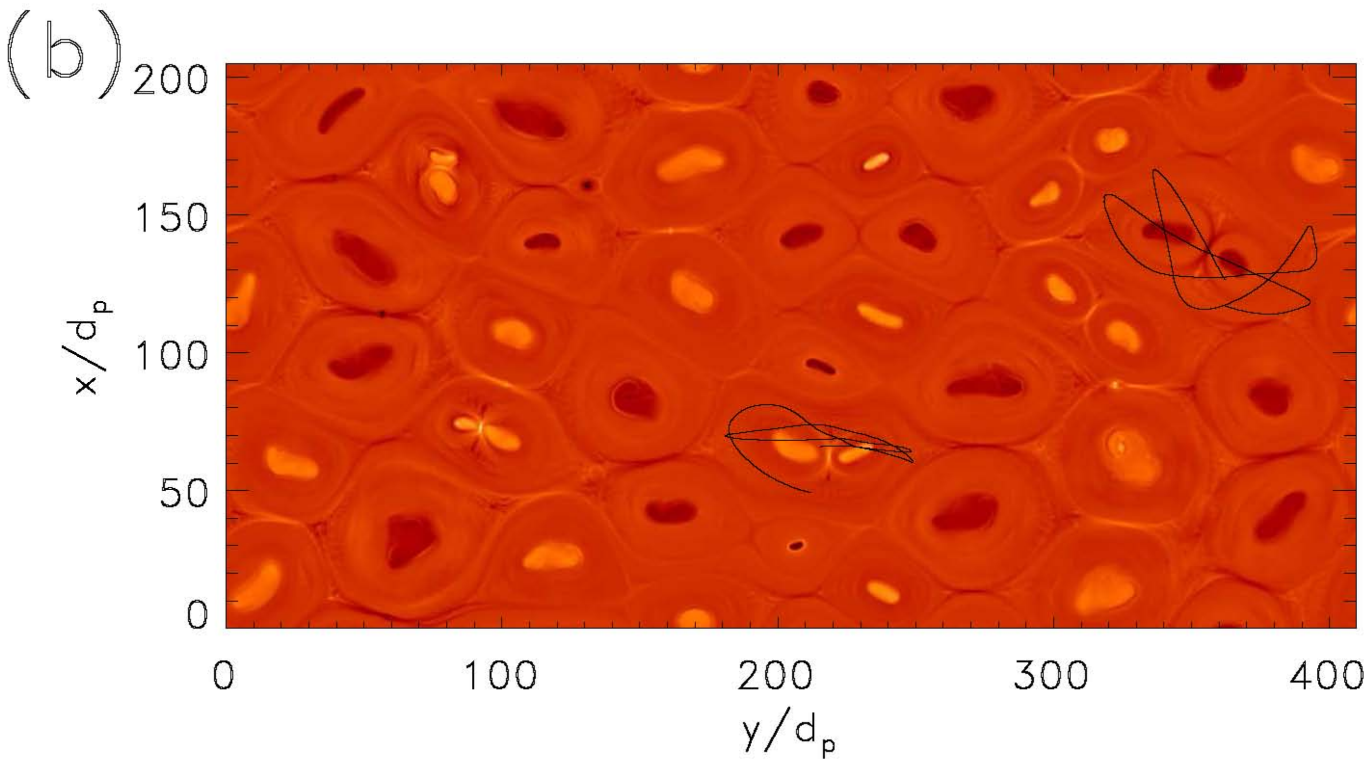
Consider the electric field.

To gain energy, the particles must drift in the direction of the electric field.

Since the flow speed is V_a, which is significanlty less than the solar wind speed, the required spatial scale is larger than the scale of the heliosphere. This is not likely.



- Drake, et al suggest multiple, coalescing reconnection ‘islands’, which may not be subject to the length-scale argument.
- The time to accelerate must be considered. If particles gain of order $\Delta T = q\, r_g\, E = q\, r_g\, V_a\, B/c$ in each interaction, and each interaction takes a gyroperiod $2\pi/\omega_g$, then acceleration of oxygen to 200 MeV takes about a year, which is fine.
- So, multiple consective reconnection islands, with no time in between islands satisfies the primary constraints.


(b)
200
150
100
50
0
x/d_p
0
100
200
300
400
y/d_p

Next, consider the Parker Transport Equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j}\right] \Rightarrow \text{Diffusion}$$

$$-\mathbf{U} \cdot \nabla f \Rightarrow \text{Convection w. plasma}$$

$$-\mathbf{V_d} \cdot \nabla f \Rightarrow \text{Grad \& Curvature Drift}$$

$$+\frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ell n p}\right] \Rightarrow \text{Energy change}$$

$$+Q \Rightarrow \text{Source}$$

Where the drift velocity V_d due to the large scale curvature and gradient of the average magnetic field is:

$$\mathbf{V_d} = \frac{pcw}{3q} \nabla \times \left[\frac{\mathbf{B}}{B^2}\right]$$

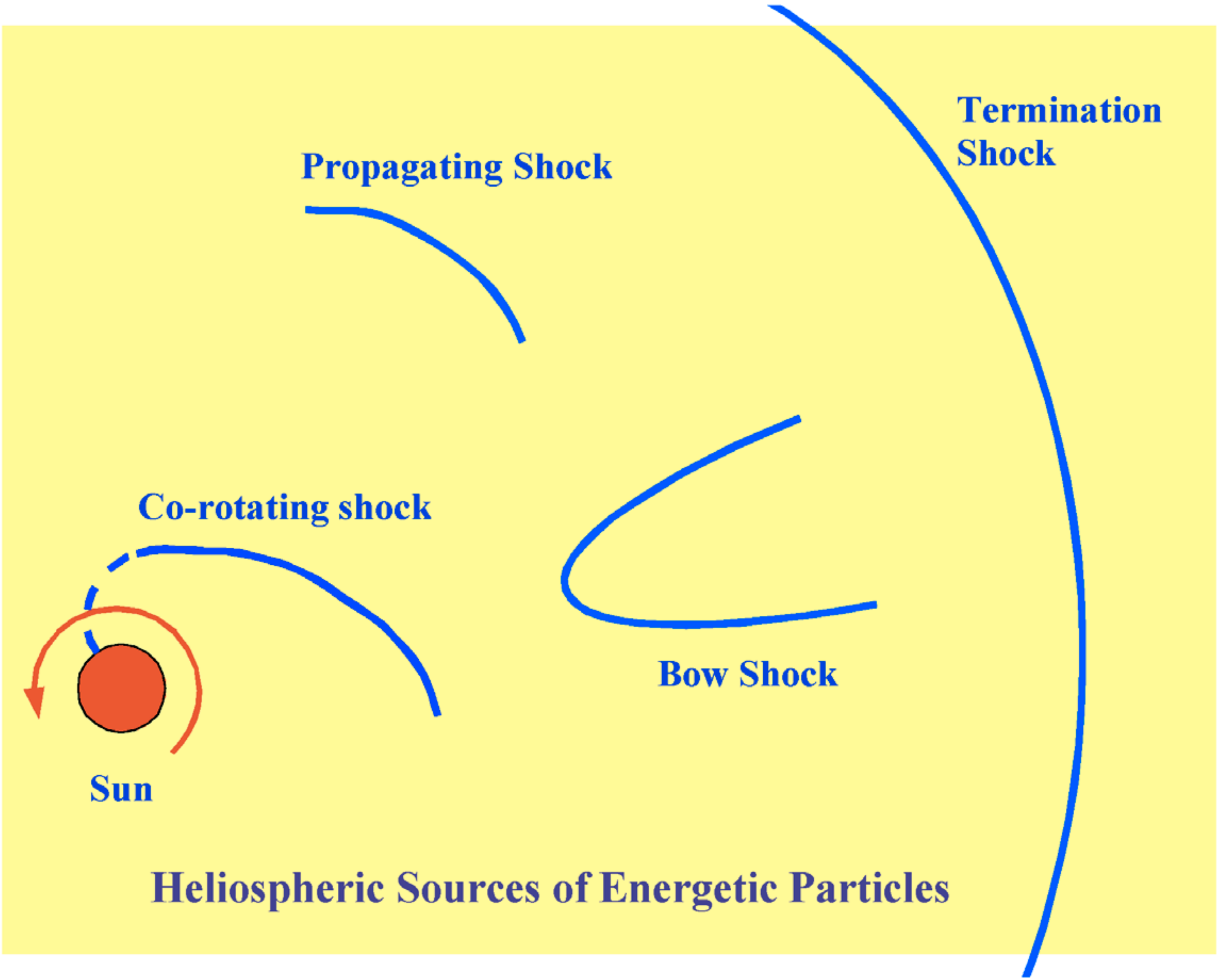
- Most models of reconnection published to date use incompressible MHD. Hence

  $\nabla \cdot \mathbf{U} = 0$. (pointed out by Drake, et al 2009)
- Parker’s equation only accelerates particles if $\nabla \cdot \mathbf{U}$ is finite and negative.
- Since Parker’s equation has been shown to be valid for nearly-isotropic particle angular distributions, acceleration in reconnection models requires *significant anisotropies*.
- This may be difficult to do, because scattering times are generally shorter than the acceleration times. We need $\tau_{scat} \approx$ the acceleration time, or one year. The mean free path is >3000 AU Note to observers: look for large anisotropies.

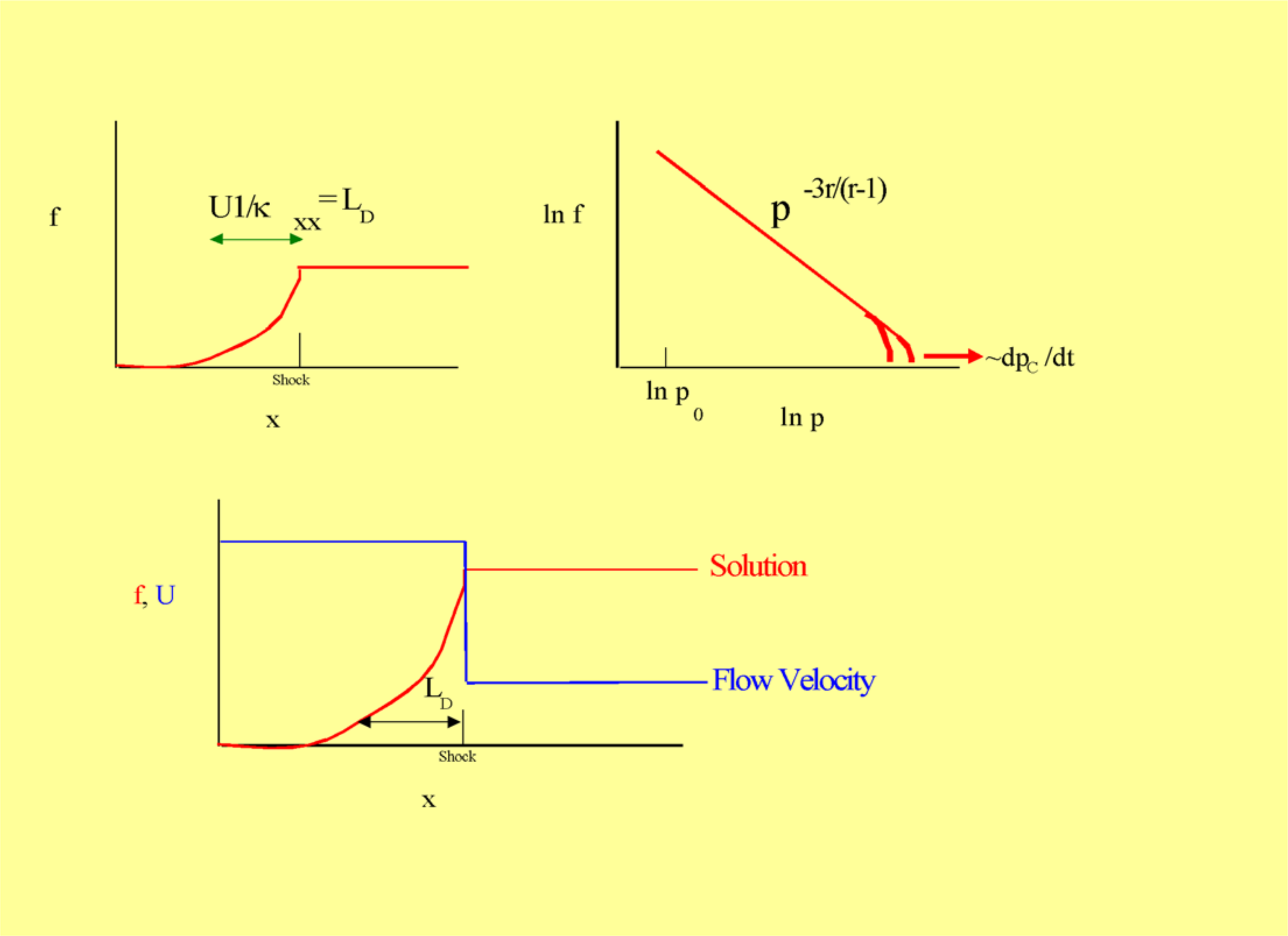
Look at Diffusive Shock Acceleration:

Apply the Parker equation to a shock.

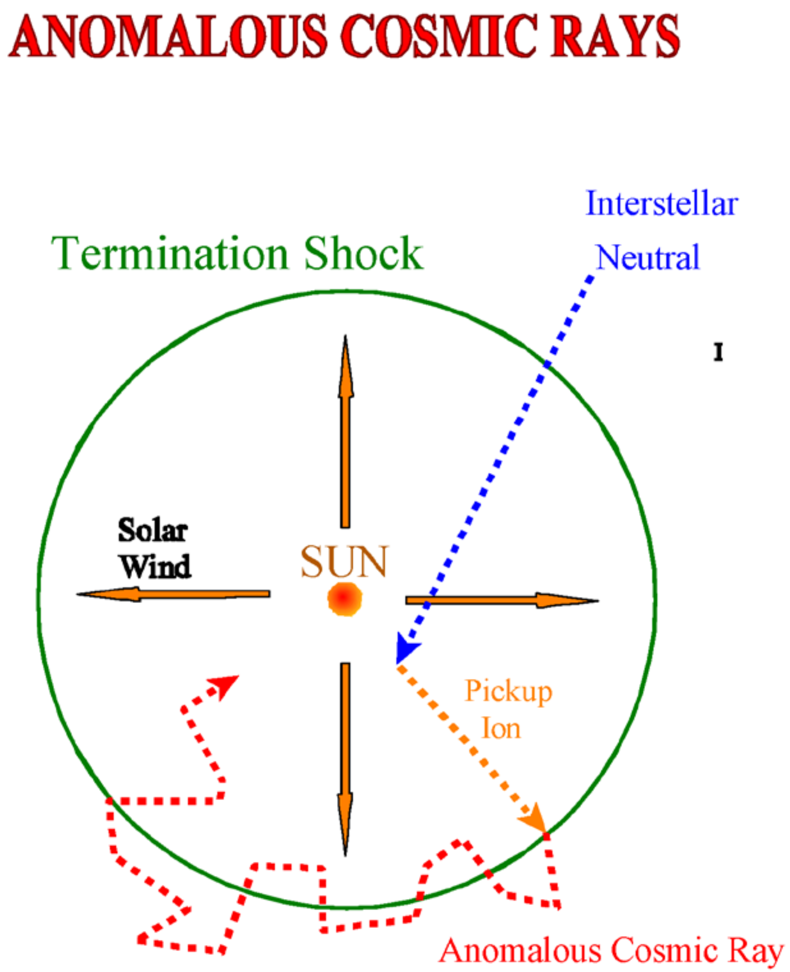
Here, $\nabla \cdot \mathbf{U}$ is large and negative at the shock and this produces the energy gain.


Termination
Shock
Propagating Shock
Co-rotating shock
Bow Shock
Sun
Heliospheric Sources of Energetic Particles

The general result from applying the Parker equation to a shock (diffusive shock acceleration).



Acceleration about a year for ACR at the termination shock



The solar-wind termination shock is essentially a perpendicular shock.   Hence the energy gain comes from drift in the **-U x B/**c electric field.

The change in electric potential between the pole and the equator is ≈ 300 Z MeV

Hence this this can readily provide the 200 MeV kinetic energy.

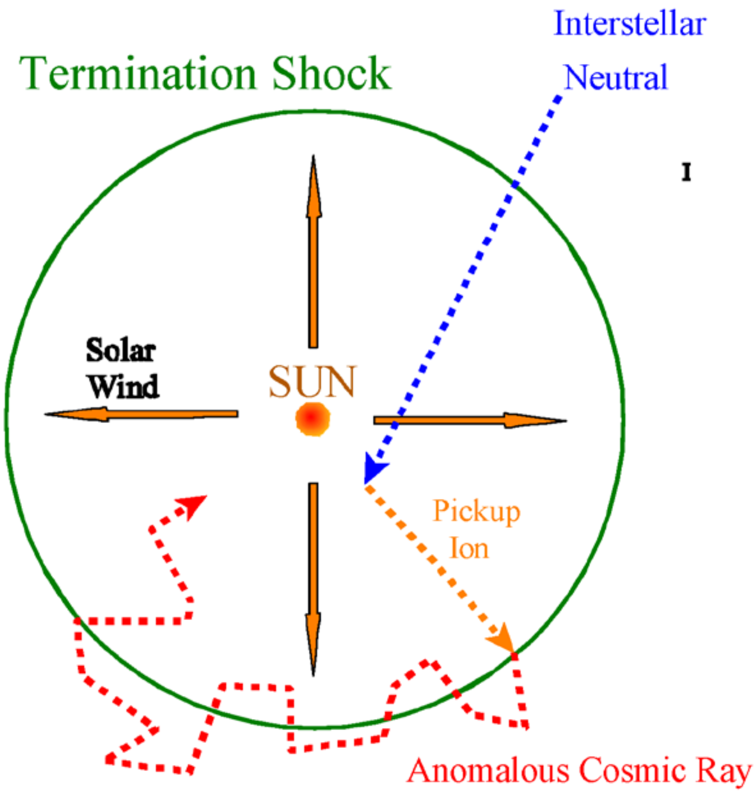
But the Voyager observations at the termination shock did not see what was expected!

The acceleration of the high-energy ACR must be occurring elsewhere, perhaps elswhere on the termination shock (McComas, Schwadron, Kóta).

Or perhaps multiple, coalescing reconnection islands.

Or perhaps some complicated combination of deterministic and stochastic acceleration which has not yet been worked out.

ANOMALOUS COSMIC RAYS



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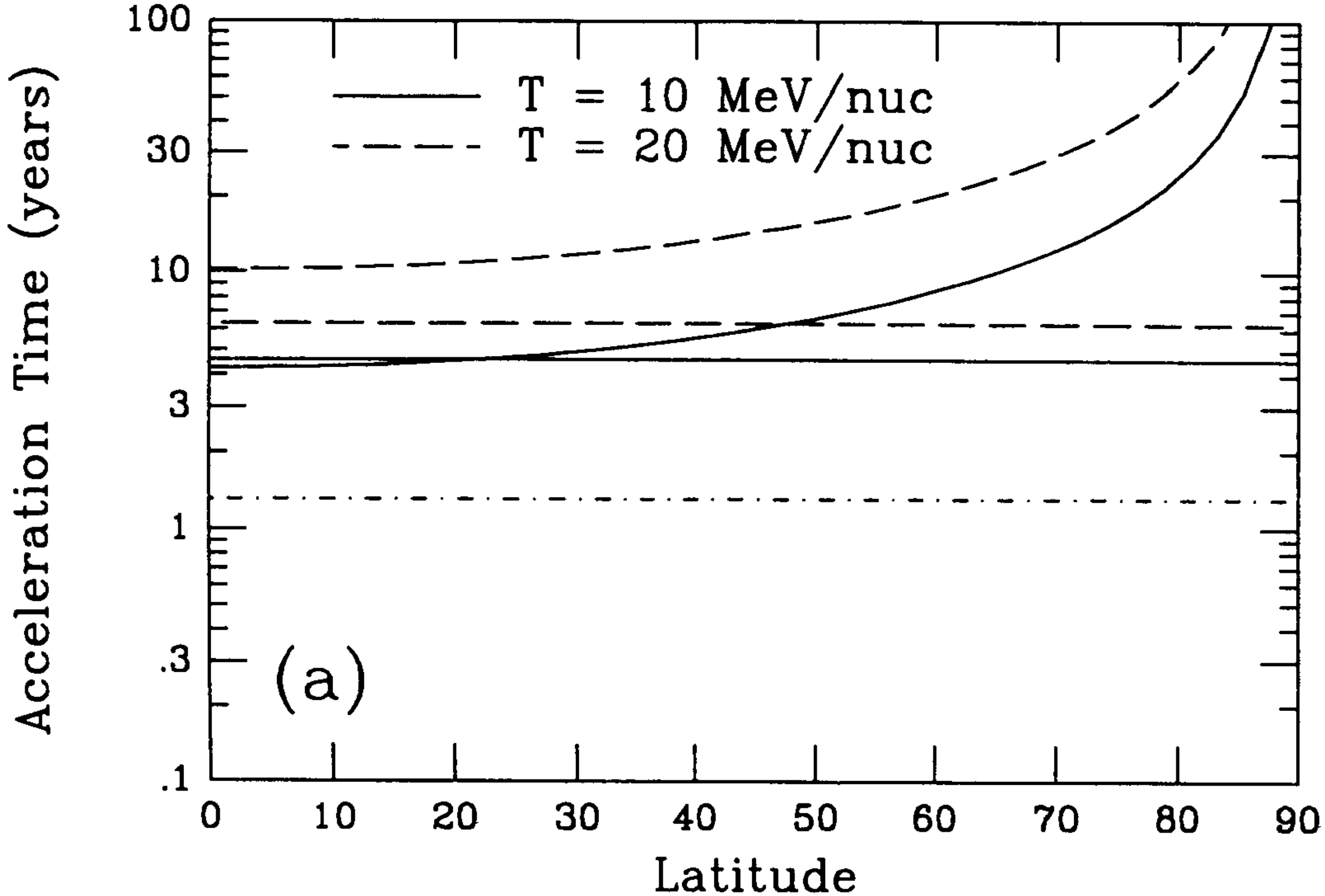

Acceleration Time (years)
100
30
10
3
1
.3
.1
T = 10 MeV/nuc
T = 20 MeV/nuc
(a)
0
10
20
30
40
50
60
70
80
90
Latitude

Conclusions

- Charged-particle acceleration in the heliosphere, especially of the ACR remains controversial.
- Statistical acceleration is far too slow.
- Reconnection has been proposed, but issues of the large anisotropies and mean free paths must be resolved.
- The ACR can be accelerated at the termination shock, if the acceleration has hot spots which the Voyagers missed.