Cosmic Ray Acceleration: the need and ways of doing it faster

M.A. Malkov

University of California, San Diego

Ackn: R.Z. Sagdeev, P.H. Diamond
Supported by NASA and US DoE

Outline

1. Why need faster acceleration?
    - Benchmarks are challenging for acceleration mechanisms (DSA)
    - DSA sluggishness
    - Selection of astrophysical settings
2. SNR and other large scale shocks
    - NL shock modification
    - Shock Rippling
3. Proton Zevatrons in DM filaments
    - Accretion flows and CR Acceleration in Cosmic Web
    - Betatron inductive acceleration
    - Evading photo-disentegration in accelerator and exit fees

Benchmarks CR spectrum: knee, ankle, GZK

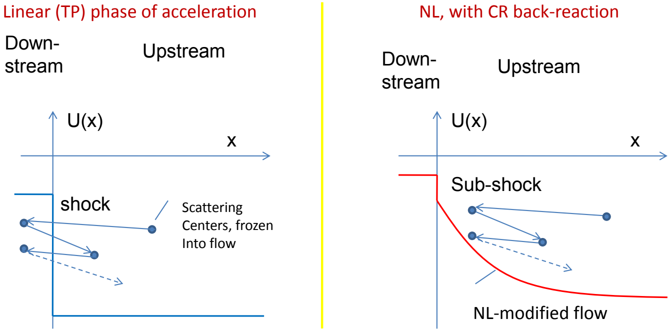
Possible interpretations of the breaks

- need single acceleration mechanism up to the knee for protons
- may argue then that the spectrum extends to the ankle because
  - heavier nuclei
  - superposition of sources, exceptional SNRs, pre-supernova dense wind (Völk & Biermann 1988)
  - change in acceleration regime (M & Diamond 2006)
- diffusive shock acceleration -DSA operating in SNRs embodies above ingredients thus appearing plausible, BUT...

Maximum energy: knee

- predictions for maximum energy/knee for DSA in SNR are model dependent
- major problem: CR scattering environment: dominant turbulence mode and saturation level
- under optimistic assummptions might reach *PeV*;
  -Bohm diffusion of CR-$\kappa_B \sim r_g c$ on resonant Alfven waves (e.g. Berezhko et al 90s);
  -spreading of short non-resonant waves to resonance at $kr_g \sim 1$ -Bell 04; Bykov et all 11,13; Diamond & M 2007; Simulations largely supportive: Zirakashvili & Ptuskin, Spitkovsky+, Caprioli...
- pessimistic estimates: DSA falls short by one-two orders of magnitude (Laggage & Cesarsky 1983, partially also Bell 2014 recapitulates concerns)
- **bottom line:** DSA needs an order of magnitude boost to reach the knee during SNR active life

DSA: operation and potential for improvement



- In both cases momentum gain is small $\Delta p/p \sim U/c$ can be deduced from adiabatic invariant

$$\oint p_{\parallel} dl = const$$

DSA: why slow?

- long waiting time upstream and downstream: number of scattering

  $$N \sim c/U \gg 1$$

  needed before momentum is increased upon shock crossing by

  $$\Delta p/p \sim U/c$$

- acceleration time grows with momentum, as both the collision time (in the linear case $\omega_c^{-1} \propto p$) and precursor crossing time $[\kappa(p_{max})/U^2 = \tau_{acc}$ in NL regime$]$ increase

DSA characteristic times cont'd

$$\tau_{acc} \simeq \frac{\kappa(p)}{U^2} \sim \lambda c/U^2 \sim \tau_{col} c^2/U^2 = \tau_{col} N^2$$

λ -particle mean free path (m.f.p.)
τ_{col} -collision time (ω_c^{-1} at least)

DSA time hierarchy

$$\tau_{acc} : \tau_{cycl} : \tau_{col} \sim \frac{c^2}{U^2} : \frac{c}{U} : 1$$

- **improvement strategy**: decouple one of these ratios (or both) from the small parameter U/c

Case studies for enhanced acceleration

1. DSA in large scale shocks such as SNR
    - working hypothesis of CR origin
    - DSA is robust and well established acceleration mechanism
    - plethora of new SNR observations
2. Accretion flow on DM filament – suitable site for UHECR acceleration
    - weak magnetic and photon fields in accelerator surroundings
    - synchrotron-Compton losses negligible
    - pair production losses insignificant
    - photo-pion losses are significant but beatable

Possible ways to accelerate DSA

- $p(t)$ grows linearly (slow) both in unmodified and modified shocks but for different reasons

$$\dot{p}/p \propto 1/\tau_{acc} \propto 1/p$$

- in modified shocks due to precursor inflation $L_p \propto p_{\mathrm{max}}$, as $\tau_{acc}=$ precursor crossing time
  → attempt to prevent precursor from growing

- nonlinear shock modification with fixed *precursor scale*

$$\dot{p}/p \propto U/L_p(p_{\mathrm{fixed}}) = const$$

-exponential growth of momentum

- shock corrugation resulting in partially quasi-perpendicular acceleration regime *without particle loss downstream*
  \- *reduction in acceleration time* by making τ_{cycle} short

Acceleration in CR shock precursor

acceleration rate in CR modified shocks

- $\frac{\dot{p}}{p} = \frac{1}{3}\frac{\partial U}{\partial z} \sim U/L_{NL}(p_*)$

is the same as in ordinary shocks except $L_{NL} \sim \kappa(p_*)/U$ instead of $L_p \sim \kappa(p)/U$

p_* is where CR partial pressure is at maximum

- if the spectrum is harder than p^{-2}

$$p_* \simeq p_{\max}$$

- If p_* is fixed, $p_* \ll p_{\max}$ then $p(t)$ grows exponentially rather than linearly in the range

$$p_* < p < p_{\max}$$

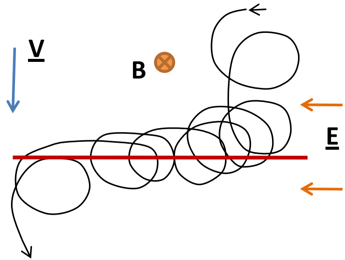
Enhanced Acceleration Scenario

1. Initial linear growth $p \propto t$ up to $p = p_*$ (M & Diamond 2006)
2. NL shock modification, Drury instability on ∇P_{CR} (Drury & Falle 1986)
3. formation of multiple shocks in precursor and CR losses for $p > p_* \to$ steeper spectrum for $p > p_*$
4. change of CR confinement regime to super-diffusive for $p > p_*$ to make a steeper spectrum
5. precursor does not grow as $\max P_{CR}(p)$ is fixed at $P_{CR}(p_*)$
6. particle momentum grows exponentially for $p \gtrsim p_*$

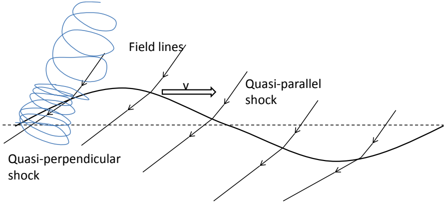
Limitation: $r_g(p) \ll \kappa(p_*)/U \sim r_g(p_*)c/U$

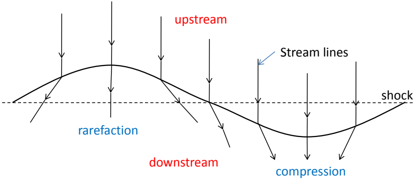
Switch to quasi-perpendicular geometry

-No idling but short acceleration, Jokipii 1987+



-rippled shock surface may result in protracted particle interaction with shock

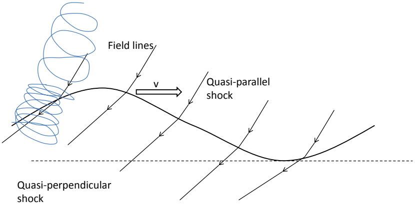




- but ordinary shocks are stable with respect to corrugations (LL, Mond and Drury'98 +CRs)

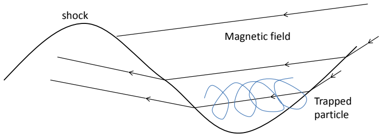
Combined ⊥ / || acceleration scenario

- CRs destabilize shock surface since CR mirror force depends on shock normal angle



- set ripples in motion horizontally
- acceleration cycle comprises two phases: perpendicular and parallel
- particle return to shock through quasi-parallel parts of its surface
- perpendicular (fast) phase has no idling time
- parallel (slow) phase has p-independent duration
- $\tau_{acc} \lesssim \kappa/U^2$ with fast acceleration spikes in ⊥-regime
- bottom line: a factor of a few gain in acc'n rate

Stronger acceleration speed-up by particle trapping



- CR trapped between rapidly converging mirrors
- trapping suggests

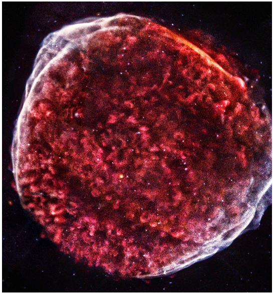
$$\oint p_{\|} dl = const$$

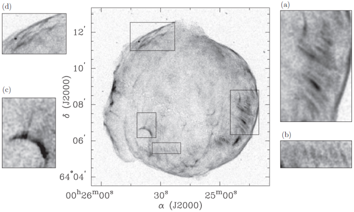
- promotes corrugations

- energy gain up to factor c/U in one trapping event ($l_{min} \sim r_g$, $l_{max} \sim r_g c/U$)
- l_{max} may be longer if ripple dynamics results in their coalescence, akin 1D shock dynamics (bad for the previous $\perp / \|$ scenario)
- loss cone particles downstream have chances to reappear upstream on $\|$ shock region

Evidence of shock rippling?

Chandra SNR 1006
-may be interpreted as shock corrugation or projected radial shocks





- Tycho (Eriksen et al 2011)
- straiates appear to be more consistent with surface phenomenon

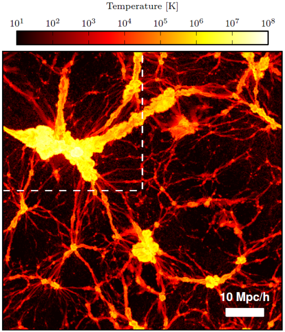
Why new UHECR acceleration mechanism?

Proton Zevatrons in DM filaments

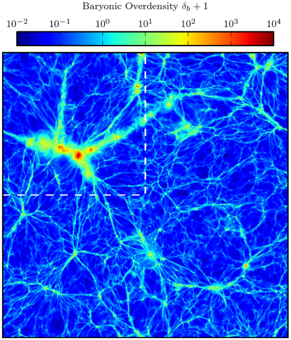
- GRB origin of UHECR is likely ruled out: neutrino upper limit factor ~3.7 below predictions (Abbasi et al, IceCube, 2012)
- AGN scenario encounters problems with IC/synchrotron losses, photo-pion losses; powerful accelerators generate strong photon- and magnetic fields (Norman et al 95)
- large-scale structure shocks accelerate particles too slow to overcome losses (Norman et al 95, Jones 04) → BUT: seed population $10^{19.5}$eV for the mechanism suggested here:
- operates inside accretion flow onto a filament between two nodes (M, Sagdeev & Diamond 2011)

Large-scale structure simulation

- DM web: filaments and nodes Schaal & Springel 2014



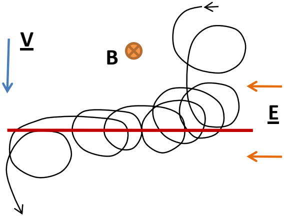
- accretion flow onto filaments from voids



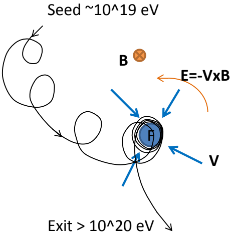
Acceleration mechanism

Compare and Contrast with SDA

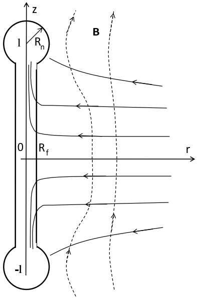
- starts similarly to shock-drift acceleration (SDA)
- in SDA part of the orbit is decelerating



- change of orbit topology from drift to circumscribing the filament -betatron regime
- pure energy gain, no deceleration phase



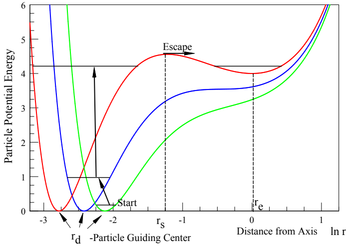
Accelerator setup



- two nodes connected by a filament provide magnetic trap as the field increases toward nodes

- flow pattern (solid lines) magnetic field (dashed lines)
- magnetic field increases towards filament $B_z \propto r^{-3/2}$
- initial drift acceleration regime: $p_\perp^2/B_z = const$ -slow phase
- change to betatron regime: *explosive acceleration*

Particle Dynamics

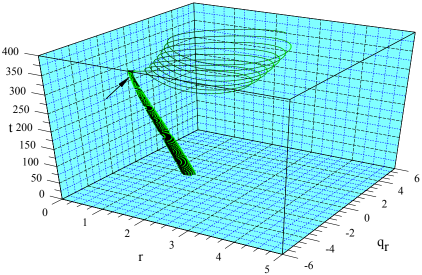


- drift motion toward filament, slow energy gain $p_\perp^2/B_z = const$
- acceleration control parameter

$$v = -\frac{r u_r B}{R_\mathrm{B} c B_\infty}$$

R_B- Bondi radius

- betatron regime $\nearrow$



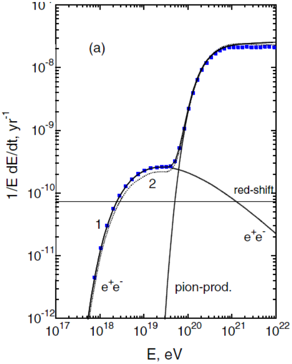
- explosive acceleration

$$p(t) = (\mathscr{P}_0 - vt)^{-1}$$

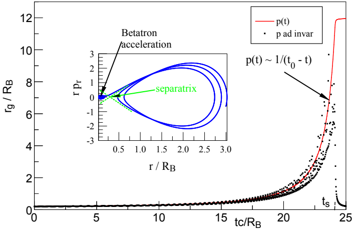
$\mathscr{P}_0$ -canonical momentum

Why short explosive acceleration is critical?

Overjumping the photopion "wall"



- $\gamma\pi$ "wall" at $E \simeq 10^{19.5}$eV (Berezinsky et al 2006)
- BUT! betatron energy growth is explosive!



- the photo-pion wall can be overjumped
- likely need tunneling with m.f.p $l_\pi \sim 10$Mpc
- upon crossing separatrix particles escape immediately, thus evading high magnetic and photon fields

Summary

- Galactic CR, SNR, DSA
  - NL shock modification speeds up acceleration in the smooth part of the upstream flow
  - sizable fraction of $U_{shock}/c \gg 1$ factor can be used to increase acceleration rate
  - shock surface is shown to be corrugationally unstable due to CR shock reflection
  - acceleration at CR-corrugated shocks is significantly enhanced
- UHECR
  - betatron acceleration in DM filaments suggested
  - acceleration end-thrust overcomes losses, fatal for other mechanisms (e.g., DSA)
  - mechanism is capable of proton reacceleration to the maximum energy $\gtrsim 10^{20}$eV
  - seed particles with energies $\sim 10^{19}$ eV are required