The Role of Nonlinearities in Collisionless Shocks

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Outline:

Overview of shock acceleration: PIC results
Mutual interaction of self-generated turbulence with particle acceleration
Two examples of nonlinear structures:
  Weibel filaments in unmagnetized shocks
  Nonlinear stage of Bell instability in magnetized shocks: “SLAMS”
Long term feedbacks from nonlinearities
\[ \sigma \equiv \frac{B^2 / 4\pi}{(\gamma - 1)nmc^2} = \frac{1}{M^2_A} = \left( \frac{\omega_c}{\omega_p} \right)^2 \left( \frac{c}{\nu} \right)^2 = \left[ \frac{c/\omega_p}{R_L} \right]^2 \]
Relativistic shock acceleration

Conditions for acceleration in relativistic shocks:
low magnetization of the flow
or quasi-parallel B field ($\theta<34^\circ/\Gamma$);
electrons & ions behave similarly

$N(E) \sim E^{-2.4}$;
1\% by number, ~10\% by energy.
Superluminal vs subluminal shocks

\( \sigma \) is large \( \rightarrow \) particles slide along field lines

\( \theta \) is large \( \rightarrow \) particles cannot outrun the shock

unless \( v > c \) (“superluminal” shock)

\( \Rightarrow \) no returning particles in superluminal shocks

\( \sigma = 0.1 \), \( \gamma_0 = 15 \), e-\( p^+ \) shock

Subluminal / superluminal boundary at \( \theta \sim 34^\circ \)

\( \rightarrow \) Fermi acceleration should be suppressed in superluminal shocks!

If \( \sigma > 10^{-3} \), particle acceleration only for:

\( \theta < \theta_{\text{crit}} \approx 34^\circ \) (downstream frame)

\( \theta' < 34^\circ / \gamma_0 << 1 \) (upstream frame)

Easy to kill!
Astrophysical implications

- Pulsar Wind Nebulae
  - Toroidal magnetic geometry will accelerate particles if field is weak at the shock
  - Implies efficient magnetic dissipation in the wind
  - Low equatorial magnetization -- consistent with PWN morphology
Astrophysical implications

- **AGN Jets**
  
  High magnetization toroidal field configuration is disfavored
  
  Either magnetic field is dissipated in the process of acceleration,
  
  or field is reoriented to lie along the flow (sheath vs spine flows?)

- **GRB jets**
  
  Low magnetization external shocks can work; Field survival?
  
  Efficient electron heating explains high energy fraction in electrons
Particle acceleration:

\[ \frac{\Delta E}{E} \sim \frac{v_{\text{shock}}}{c} \]

\[ N(E) \sim N_0 E^{-K(r)} \]

Free energy: converging flows

- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Does this realistically happen?
Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback: self-sustaining and replicating nonlinear structure

Long evolution is often required
Two Examples of Nonlinear Structures:

\[ \frac{\delta B}{B_0} \gg 1 \]

Unmagnetized shocks — \( B_0 = 0 \): nonlinearity regulates injection

High Mach number shocks — \( B_0 \) is weak, but finite: nonlinearity changes spectra
Reflection physics in relativistic unmagnetized pair shocks

\( \Gamma = 5 \)

About 1% particles in the tail. How did they get into the tail?

We track a shell of particles through the shock, marking those that eventually reach high energy:

- If $\gamma_f > 20$, particle is considered to be ‘high-energy’ (ends simulation with high energy)
- If $\gamma_f < 20$, particle is considered to be ‘thermal’ (does not end simulation with high energy)
Behavior of high-energy electron subshell vs thermal electron subshell

- High-energy electrons are not evenly distributed amongst thermal electrons
Behavior of high-energy positron subshell vs thermal positron subshell

- Same thing: high-energy positrons are not evenly distributed amongst thermal positrons
Behavior of high-energy positron subshell vs high-energy electron subshell

- But location of the high-energy electrons and positrons also aren’t correlated when hitting the shock
Behavior of high-energy subshells vs thermal subshells

- When comparing high-energy vs thermal **across species**: high-energy particles of one species hit the shock at the same place as the thermal particles of the opposite species.
Particle reflection and transmission

Orbits of electron and positron from same filament hitting shock at same place, same time

- **Electron is reflected**, positron is transmitted
Nonlinear structures reflect (and transmit)!

Opposite currents pushed together at the shock. Particles of “wrong sign” reflect. “Right sign” transmit.
Behavior of high-energy subshells post-reflection
Behavior of high-energy subshells post-reflection

- High-energy electrons and high-energy positrons in incoming filaments of same sign of current that they’re carrying (hence anti-correlated)
Behavior of high-energy particles post-reflection: filament swimming
Model for shock injection

- Two step process:
- Incoming density filaments are non-neutral, about 35% of particles are in the “wrong” filaments, and are reflected.
- To join DSA, particles need to stay ahead of the shock and accelerate so they can cross filaments.
- To stay in the upstream, they have to find filaments of the right sign of current, “swim in them”, and switch them when filaments stop. 4-5 switches, each lossy with ∼50% probability, 0.1 factor.
- Result: ∼35% * 0.1 ∼ few %
Implications

- Time dependent feedbacks in the shock.
- Larger charge separation in filaments — less injection!
- Larger structures in the upstream — easier to survive in the upstream — more injection?
- If filaments are asymmetric — one sign of charge could be injected preferentially. Shock charging?
- Long term evolution of shock structure and acceleration efficiency is likely.

Keshet et al 09,
Gro selj et al in prep
Quasi-par electron-ion shocks

Depending on Mach number (magnetization), returning ions can trigger resonant, Bell (non-resonant), or Weibel instabilities in the upstream.

Bell instability can grow to large dB/B0

What does dB/B0 >> 1 do to particle injection and acceleration?

Can imagine injection being suppressed because shock becomes quasi-perpendicular!

Is large turbulence bad or good?
Long-term evolution of dominant instability

$\sigma=0.1 \ \theta=15^\circ \ \gamma_0=15 \ \text{e}^-\text{p}^+ \text{ shock}$

- Dominant mode changes from electron filamentation to Bell's nonresonant instability: transverse box is now too small!
- Shock reformation (and SLAMS) seen in the density profile at late times
Mach=80 non-relativistic shock

Ion phase space

Electron phase space

Density

Ion, e- spectra

SLAMS form: short large-amplitude magnetic structure. Wavelength — Bell, modulated at 5-10xBell
Mach=80 non-relativistic shock: 2D

SLAMS form: short large-amplitude magnetic structure. Wavelength — Bell, modulated at 5-10xBell

(Zekovic, AS, Hemler in prep. 2023)
Wave packets are good for injection

Even though maximum amplitude in a strong wave makes the local field direction very oblique, and thus unlikely to easily inject particles, amplitude modulation in a wave packet creates regions of smaller obliquity that are favorable for injection. Thus, the filling fraction of favorable obliqueness (both spatial and temporal) determines and regulates injection fraction.

Test particle simulation in prescribed circularly polarized wave packet (Zekovic, Hemler, AS, in prep)
Electron Acceleration at High Mach Number Shocks

QUASI-PERIODIC SHOCK ACCELERATION (QSA): trapping between SLAMS and shock

\[ t = 648000.0 \frac{1}{\omega_{pe}} \]

\[ p/\mu, B \parallel B_0 \]

\[ x - x_{sh} [c/\omega_{pe}] \]
We observe steepening of electron spectrum to $p^{-5.6}$.

Combination of SDA and DSA — come with different time dependence and lead to steeper spectra in nonrel shocks.

Expect steepening till energy resonant with the wavelength of SLAMS. Beyond that — join DSA spectrum.
SLAMS and Electron Acceleration

Large amplitude (>10) SLAMs are possible in high Mach # shocks.

To get a steep e- spectrum:

High Mach # shock with SLAMS

Quasiperiodic Shock Acceleration (QSA) — electrons trap between shock and first SLAM. Probability of escape is different than in DSA, so steep spectrum.

Superluminality (expected in shocks of young SNRs). Electrons are stuck for longer near the shock, so transition to DSA is delayed to higher energy.
Conclusions:

Nonlinear structures naturally develop in upstream of all kinds of collisionless shocks.

Unmagnetized shocks — they regulate injection fraction.

Magnetized high Mach shocks — SLAMS formation and superluminal wave packets affect injection at the shock.

High Mach number shocks with SLAMS can lead to trapping near shock and steep electron spectra at low energies.

Long term evolution will lead to global feedbacks! Stay tuned.