Relativistic Collisionless Shocks and Particle Acceleration: an Inconvenient Truth
Anatoly Spitkovsky (KIPAC, Stanford)

Outline:

1. **Shocks in astrophysics: expectations of composition, structure and shock properties**

2. **3D shock modeling -- simulation setup**

3. **Unmagnetized shocks in pair plasma**

4. **Magnetized shocks in pair plasma**
   a) Perpendicular
   b) Oblique

5. **Acceleration properties: Where is Fermi?**

6. **Shocks in electron-ion plasma: varying mass ratio**

7. **Conclusions**

3D PIC results are generally consistent with work by Silva, Mori, Medvedev et al Nishikawa et al; Jaroshcek et al. Hededal, Frederiksen, Nordlund et al.
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Magnetization

Composition

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Relativistic collisionless shocks in astrophysics

- Pulsars + winds (plerions, J0737) $\gamma \sim 10^6$, $\sigma \sim 10^{-3}$-1, composition: pairs (+ions?)
- Extragalactic radio sources $\gamma \sim 10$, $\sigma$-?, composition -- pairs? baryons? both?
- Gamma ray bursts $\gamma > 100$, $\sigma$ -- ?, composition: ?
- Galactic superluminal sources $\gamma \sim$ few
- Sources for UHE CR?

Open issues:

- What is the structure of collisionless shock waves?
- Particle acceleration -- Fermi mechanism? Something else?
- Generation of magnetic fields (GRB shocks, primordial fields?)

By using direct ab-initio numerical simulations of collisionless shocks we can place constraints on astrophysical models of composition and structure of relativistic outflows in nature.
Particle-in-cell method:
• Collect currents at the cell edges
• Solve fields on the mesh (Maxwell’s eqs)
• Interpolate fields to particles positions
• Move particles under Lorentz force

Modified code “TRISTAN”:
• 3D cartesian electromagnetic particle-in-cell code
• Radiation BCs; moving window
• Charge-conservative current deposition (no Poisson eq)
• Filtering of current data
• Fully parallelized (128proc+) domain decomposition
• Tried upto 3 billion+ particles

Simulation setup:
Relativistic e± or e− ion wind (γ =15) with B field (σ = ωₐ² / ωₚ² = B²/(4πn₀γmc²) = 0-10)
Reflecting wall (particles and fields)
Upstream c/ωₚ =10 cells, c/ ωc >5 cells; upto 2500x320x320 grid, 250x32x32 c/ωₚₑ
Numerical simulation of collisionless shocks

**Particle-in-cell method:**
- Collect currents at the cell edges
- Solve fields on the mesh (Maxwell’s eqs)
- Interpolate fields to particles positions
- Move particles under Lorentz force

**Lessons learned:**

*Short and small simulations are dangerous*

*Reduced dimensionality is dangerous*

*Doing what you can rather than what you should is really dangerous*
Chapter I: Unmagnetized pair shocks

$\sigma m_i / m_e$ pairs

$B=0$

$B>0$

$m/m_e$

pairs

e-ions
Why does a shock exist?

Particles are slowed down either by instability (two-stream-like) or by magnetic reflection. Electrostatic reflection is important for nonrelativistic shocks and when ions are present.

Weibel instability (Weibel 1959)

Spatial growth scale $c/\omega_p$, timescale $10/\omega_p$
**Unmagnetized pair shock**

**Shock structure: Density evolution**

Shock transition is accomplished in roughly 20-50 $c/\omega_p$. **Shocks have to provide density jump!!!**

\[
\frac{N_2}{N_1} = \frac{\Gamma}{\Gamma - 1} - \frac{(2 - \Gamma)\Gamma}{2(\Gamma - 1)^3} \sigma...
\]  

**MHD jump conditions satisfied**
**Magnetic field generation**

Field cascades from $c/\omega_p$ scale to larger scale due to current filament merging.

Weibel instability generates subequipartition $B$ fields that decay. Is asymptotic value nonzero? (see Medvedev et al 04): competition between diffusion and inverse cascade.
Field cascades from $c/\omega_p$ scale to larger scale due to current filament merging. Decay of field energy $\langle B^2 \rangle \propto t^{-0.8}$. 2D simulation 240x240 $c/\omega_p$:

At late times field energy continues to decay below 0.5% equipartition, albeit slowly. It is not clear whether asymptotic value exists in simulations. Alfven critical current at peak. Transverse size of the simulation matters!!!
Streaming particles from the initial shell plow through the upstream medium, creating turbulence. This modifies shock jump conditions. These particles always outrun the shock.

**Shock structure: precursor**

Precursor physics is similar to fast ignitor! Instability growth rate depends on density ratio.

*Precursor complicates simulations, requiring larger domains or moving window*
Evolution of field energy through the 3D shock structure, including the precursor.

Upstream turbulence created by the precursor may be important for particle acceleration. Electrostatics is important for segregating downstream from upstream (Miloslavlevic, Nakar, AS 05)
How does it work? Electrostatic diode (Milosavljevic, Nakar, A.S. 06) due to charge separation in the filaments.
In relatively short 3D simulations no obvious nonthermal tail appears in the downstream; particles are efficiently thermalized by interacting with the Weibel magnetic field. Thermalization leads to particle with energies up to 7kT.

More on this in a few slides.
Chapter II: Magnetized pair shocks

\[ \sigma \frac{m}{m_e} \]

\( B > 0 \)

\( B = 0 \)
Shock structure for $\sigma=0.1$

Shock is clearly magnetized -- anisotropy with respect to $B$. Shock thickness -- several Larmor radii.

3D density
Shock structure $\sigma = 0.1$ -- particle phase space

Shock structure dominated by magnetic reflections as in 1D (Hoshino & Arons, 92). No nonthermal acceleration even in 3D.
Shock structure $\sigma=0.1$ -- electromagnetic precursor

Shock compression is $\sim3$. Plasma is quasi-2D with $\Gamma=3/2$

Efficient thermalization, no Fermi. Injection doesn’t help.
Chapter III: Pair shocks at intermediate magnetization

\[ \sigma \]

Pairs

\( \frac{m}{m_e} \)

\( B=0 \)

\( B>0 \)
Magnetized perpendicular pair shock

**Shock structure** $\sigma=1$

**Plane of** $v_x-B_y$

**Plane of** $v_x-E_z$

Cover VIS5d!!!
Magnetized perpendicular pair shock

Shock structure $\sigma=0.01$

Plane of $v_x-B_y$

Plane of $v_x-E_z$

COVER VIS5d!!!
Magnetized perpendicular pair shock

Shock structure $\sigma = 0.003$

Plane of $v_x - B_y$

Plane of $v_x - E_z$

Spectrum

Quantity/upsream
Shock structure is controlled by magnetization parameter \( \sigma = \omega_c^2 / \omega_p^2 = B^2 / (4\pi n \gamma m c^2) \)

\( \sigma < 0.001 \) pair shocks are effectively unmagnetized. Such shocks don’t have coherent magnetic overshoots characteristic of higher magnetization shocks (cf also Hededal & Nishikawa 05)

Roughly, if the Larmor radius is comparable to the Weibel shock lengthscale (>20c/\( \omega_p \)) Weibel instability dominates. Self-generated Weibel field exceeds background field.

Interestingly, even though in 1D coherent low magnetization shocks are possible, in 3D they cannot exist -- Weibel instability dominates and significantly perturbs the field.

1D studies of shock-drifting acceleration in low-sigma shocks are suspect because of this (e.g. Hoshino et al 03). 1D maser-modulated shocks (Lyubarsky 06) can be overwhelmed by Weibel in multi-D.
Oblique pair shocks

45 degrees -- like magnetized shocks
15 degrees -- like unmagnetized

Shock structure is determined by the effective transverse $\sigma$. Oblique simulations so far too short to talk about Fermi acceleration in oblique shocks.
Both test-particle and analytic analysis of Fermi I assumes efficient diffusion and scattering.

In magnetized pair shocks level of downstream small-scale turbulence is insufficient to efficiently scatter. Monte-Carlo simulations use $\Delta B/B >> 1$. Hard to see how realistic shock structure produces this level of turbulence. Maybe oblique?

Unmagnetized shocks show more promise, if $B$ field survives far enough downstream, and upstream turbulence exists, or is self-generated.

Can Fermi I accel. be seen in PIC simulations?
Test-particle orbits suggest turbulence in unmagnetized shocks.

To see if this turbulence can be tapped we need

a) To reach a steady-state shock;
b) Give it enough time;

Full 3D is prohibitive even for pair plasma. At $3000 \times 320 \times 320 \times 12$ particle/cell -- 150Gb of memory. ($300 \times 32 \times 32 \ c/\omega_p$). And this should be increased by a factor of 10 at least to see steady state. Not impossible, but prohibitive.

To explore the parameter space we go back to 2D.

We checked that early evolution is very similar between 2D and 3D.

2D allows both Weibel (transverse) and longitudinal / magnetic modes.

Evolution of magnetic field is suspect in 2D. Downstream may behave differently in 3D.
Tentative detection of self-consistent Fermi acceleration

2.5D simulation on large domain (1000x80 c/ωₚ).
Tentative detection of self-consistent Fermi acceleration

Use 2.5D simulation on large domain (3000x80 c/\omega_p). Verified that initial evolution is very similar to 3D. Run long enough to establish steady state. Nonthermal tail develops, \( N(E) \sim E^{-2.4} \). Nonthermal contribution is 5% by number, 20% by energy.

Early signature of this process is seen in the 3D data as well.
Tentative detection of self-consistent Fermi acceleration

Use 2.5D simulation on large domain (3000x80 c/ω_p). Verified that initial evolution is very similar to 3D. Run long enough to establish steady state. Nonthermal tail develops, N(E)~E^{-2.4}. Nonthermal contribution is 1% by number, 6% by energy.

Early signature of this process is seen in the 3D data as well.
High energy particles are accelerated while moving along the shock front, and sampling upstream and downstream. At early times (3D sim) they haven’t spread downstream yet, so they didn’t appear in the 3D downstream spectra.

There is a cap on gamma factor, presumably when the shock becomes transparent even at high obliqueness angle. Electrostatics is not ruled out yet.

Tentative detection of self-consistent Fermi acceleration

Location of nonthermal electrons inside the shock @ different times
Tentative detection of self-consistent Fermi acceleration

Trace particles that end up in the tail.
Can fit two maxwellians, one with $T = \gamma_{up}/2$, another with $T_1 = 3 \gamma_{up}$. Hot distribution is $\sim 1\%$ by number, $\sim 6\%$ by energy, max $\gamma$ is 40 times upstream.
Nonthermal or just hot?

Power-law with index 2.4 can be fit with a strong exponential cutoff, sometimes leaving small dynamic range for the powerlaw.
Chapter IV: Unmagnetized electron-ion shocks

\[ \sigma \]

\[ \frac{B}{m} \]

\[ \frac{m}{m_e} \]

pairs  \rightarrow  e-ions
Electron-ion shocks

Unmagnetized ion-electron shock: $\sigma=0$, $m/m_e=16$

Electron density

After 300 $c/\omega_{pe}$ ions are still not thermalized. Weibel instability works very fast in electrons but slow in ions (see also simulations of Nordlund et al).
Electron-ion shocks: shielding

Unmagnetized ion-electron shock: $\sigma=0$, $m/m_e=16$

Electrons shield ion current filaments, slowing down the recombination of filaments.
2.5-dimensional simulations are better suited for long term, large size evolution of electron-ion plasma. We find steady state shocks mediated through ion Weibel instability.

Try different mass ratios:

\[ m/m_e = 10 \]
2.5-dimensional simulations are better suited for long term, large size evolution of electron-ion plasma. We find steady state shocks mediated through ion Weibel instability.

Try different mass ratios:

$m/m_e=30$

Width of the shock (in units of $c/\omega_{p\text{ ion}}$), peak Lorentz factor of electrons and magnetic energy density all scale with the mass ratio. Electrons and ions reach equipartition in energy, so that $\gamma_e \approx \gamma_{\text{shock}} \frac{m_i}{m_e}$. Ion shocks are possible through Weibel (cf Lyubarsky & Eichler 06). Simulations of Nordlund et al are too short.
Chapter V: Magnetized electron-ion shocks
Electron-ion shocks

Magnetization is mainly determined by ion energy density $\sigma = B^2/(4\pi n_\gamma (m_i + m_e)c^2)$

Electrons are magnetized much stronger than ions. $\sigma = 0.1$
Electron-ion shocks

Magnetization is mainly determined by ion energy density \( \sigma = B^2/(4\pi n\gamma(m_i+m_e)c^2) \)

Electrons are magnetized much stronger than ions. \( \sigma = 0.1 \)

Even with ions acceleration is non-Fermi: thermalization and electrostatics at the head of the shock.

More work remains to understand all effects.
Conclusions

- Collisionless shocks exist in 3D, 2D, and sometimes in 1D.
- Shocks are mediated by Weibel instability or magnetic reflection.
- Shock structure is controlled mainly by magnetization parameter, $\sigma \sim 0.001$ is the transition region for pairs. Composition also important.
- Very low-sigma shocks do not exist as magnetic shocks in more than 1D, shocks with ions can also be mediated by Weibel.
- Magnetized pair shocks do not efficiently produce nonthermal particles, unmagnetized shocks and oblique shocks show more promise.
- First evidence of self-consistent Fermi-type process operating near the unmagnetized shock. For pairs it cuts off very early -- no extended powerlaws. Need to understand magnetic turbulence decay.
- Electron-ion temperature equilibration for any B. Can we see thermal component in the observations?
- Short and small simulations can be very misleading.
- What about nonthermal generation for electron-ion or ion-pair case?
- Do pure pair plasmas really exist in astrophysics? (very feeble accelerators!!)
Conclusions

• Hunting for Fermi (nonthermal) acceleration. What are the options?
  • Main difficulty for both magnetized and unmagnetized shocks is the absence of sufficient turbulence/magnetic field downstream. Can self-consistent shock structure with high-energy component amplify turbulence?
  • Possibility of Bell’s instability: high energy particles (effectively unmagnetized) don’t respond in the same way as a magnetized upstream plasma to fluctuations. Current can be unbalanced, leading to instability. Need parallel electric field, and bulk of the high-energy particles to be of one sign of charge, e.g. protons (won’t work for pairs)
  • Resonant and nonresonant amplification of Alfven waves.
  • Composition -- e.g., only electron-ion shocks can do this.
  • Perhaps only shocks with certain magnetic geometry in the upstream accelerate. What is it?