Electron acceleration in collisionless shocks
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with much help from R. Xu, V. Tsiolis, D. Caprioli, J. Park, M. Riquelme
Astrophysical shocks are typically collisionless (mfp >> shock scales).  
Many astrophysical shocks are inferred to:  

1) accelerate particles to power-laws  
2) amplify magnetic fields  
3) exchange energy between electrons and ions  

How do they do this? Mechanisms, efficiencies, conditions?...
Particle acceleration:

$$u \rightarrow \frac{u}{r}$$

$$\Delta E/E \sim v_{\text{shock}}/c$$

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

- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach and recede.

- In shocks, acceleration is first order in v/c, because flows are always converging (Blandford & Ostriker 78, Bell 78, Krymsky 77)

- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?

Free energy: converging flows

We need to understand the microphysics of collisionless shocks with plasma simulations
Collisionless shocks from first principles

**Full particle in cell: TRISTAN-MP code**

- Define electromagnetic field on a grid
- Move particles via Lorentz force
- Evolve fields via Maxwell equations
- Computationally expensive!

**Hybrid approach: dHybrid code**
Fluid electrons – Kinetic protons
(Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)

- Massless electrons for more macroscopic time/length scales
Survey of Collisionless Shocks

We simulated relativistic and nonrelativistic shocks for a range of upstream B fields and flow compositions, ignoring pre-existing turbulence.

Study: physics of shock transition, presence of particle acceleration (ions and electron), and field amplification by accelerated particles as a function of flow parameters, such as field strength (magnetization), field orientation (parallel vs perpendicular shocks), and shock speed and flow composition.
How collisionless shocks work

Two main mechanisms for creating collisionless shocks:

1) For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability); Alvenic Mach # > 100

2) For large initial B field, particles are deflected by compressed pre-existing fields; Alvenic Mach # < 100
Parameter Space of shocks

\[ \sigma \equiv \frac{B^2}{4\pi (\gamma - 1) nmc^2} = \frac{1}{M_A^2} = \left( \frac{\omega_c}{\omega_p} \right)^2 \left( \frac{c}{v} \right)^2 = \left[ \frac{c/\omega_p}{R_L} \right]^2 \]

\[ M_A = \frac{v}{v_A} \quad M_s = \frac{v}{v_{th}} \quad \beta = \frac{M_A^2}{M_s^2} \quad \frac{m_i}{m_e} \]

- **Solar**
- **SNRs**
- **Cluster**
- **AGN jets**
- **PWN**
- **Filamentation (Weibel) instability**
- **Gravitational radiation**
- **Magnetic reflection**
- **Relativistic PWN**
- **GRB**

\[ \sigma = 0.1 \quad \theta = 90° \]

\[ \sigma = 0 \]

- **Counter-streaming & filamentation instability**
- **Coherent Larmor loop & particle bunching**
- **Shock**
- **Downstream**
- **Upstream**

- **B_d** (background)
- **B_d** (self-generated)
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In ISM: beta ~ 1, \(M_s = M_A\), \(c_s \sim v_A \sim 10\) km/s
SNRs: \(v = 1000-15000\) km/s, \(M_s = M_A = 100-1500\)

In clusters: beta ~ 100, \(M_s = M_A/10\)
Relics: \(v = 1000\) km/s, \(M_s = \) few, \(M_A = 10-20\)

Virial shock: \(v = 1000\) km/s, \(M_s \sim M_A \sim 100\), similar to SNR

Field orientation:
mostly transverse in relics, can be anything in viral shocks and SNRs.
Particle acceleration

Two ingredients:

Ability of the shock to reflect the particle (injection)
Ability of the particle to come back to the shock (turbulence)
Nonrelativistic shocks: shock structure

$\mu_m = 400$, $v = 18,000\text{km/s}$, $Ma = 5$, quasi-perp 75° inclination

PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers
Nonrelativistic shocks: shock structure
\[ \frac{m_i}{m_e} = 100, \ v = 18,000 \text{km/s}, \ M_a = 45 \] quasi-perp 75° inclination
Nonrelativistic shocks: quasiparallel shock

$\text{mi/me}=30$, $v=30,000\text{km/s}$, $Ma=5$ parallel $0^\circ$ inclination
Nonrelativistic shocks: heating

Heating varies between 10% of equipartition for perp shocks, to 50% in parallel

quasi-perpendicular shock  quasi-parallel shock

Not much dependence on mass ratio, speed, magnetization, etc.
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I. Quasiparallel shocks: proton and electron accelerators
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DSA slope is recovered in hybrid simulations for parallel shocks: ~1% by number, 10% by energy (see Caprioli’s talk tomorrow)
Quasiparallel shocks: ion injection

Injection of ions happens on first crossing due to specular reflection from shock potential barrier and shock-drift acceleration.

In SDA, particle can sit on the shock for several gyrations while gaining energy from motional electric field: happens for particles with right pitch angle.

(see Caprioli’s talk tomorrow)
Quasiparallel shocks: electron acceleration

Recent evidence of electron acceleration in quasi parallel shocks. PIC simulation of quasiparallel shock. Very long simulation in 1D. Alfven Mach = Sonic Mach = 20; mi/me=100-400; Ion-driven Bell waves drive electron acceleration: correct polarization
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Ion-driven Bell waves drive electron acceleration: correct polarization

DSA spectrum recovered in _both_ electrons and ions. Electron-proton ratio obtained: $K_{ep}=10^{-3} - 10^{-2}$

Park, Caprioli, AS (2015)
Electron acceleration at parallel shocks

Multi-cycle shock-drift acceleration, with electrons returning back due to upstream ion-generated waves.
Electron acceleration mechanism: shock drift cycles + diffusion in upstream

Electron track from PIC simulation.
Electron-proton ratio $K_{ep}$:

$K_{ep} = \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\text{inj}} \quad K_{ep} \approx 3.8 \times 10^{-3} \quad \text{for } m_p/m_e = 100$

Measured on Earth at $E \sim 10\text{GeV}$

Tycho’s SNR (Mrolino & Caprioli 2012)
II. Quasiperpendicular shocks: electron acceleration

Low sonic Mach # = 2; 63 degrees shock inclination, \( \frac{m_i}{m_e} = 100 \), \( M_A = 12 \). Reflected electrons and electron-driven waves upstream. Growth of nonthermal tail in electrons. First obtained by Guo, Sironi, Narayan (2014)
II. Quasiperpendicular shocks: electron acceleration

Low sonic Mach # = 2; 63 degrees shock inclination, mi/me=100, MA=12. Reflected electrons and electron-driven waves upstream. Growth of nonthermal tail. First obtained by Guo, Sironi, Narayan (2014):

Hot electrons can mirror from the shock and enter shock drift cycle. As they leave towards the upstream they drive waves (electron firehose(?) or non-resonant streaming waves). These waves eventually bring the particles back. NB: no nonthermal ions!
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II. Quasiperpendicular shocks: electron acceleration

We tried it at higher Mach numbers: Sonic Mach # = Alfvenic = 50; 63 degrees shock inclination, mi/me=100. (Xu, Caprioli, AS in prep). Acceleration proceeds even with cold upstream. Electrons are pre-heated before the shock by ion ring instabilities.
Downstream spectra for range of $M_A$ and $M_s$

- For $M_A = 8$, $M_s = 2$
  - Time: $2.7 \times 10^4 \omega_0^{-1}$
  - Temp: $0.308 m_e c^2$
  - Weaker reflection

- For $M_A = 40$, $M_s = 8$
  - Time: $4.8 \times 10^4 \omega_0^{-1}$
  - Temp: $0.065 m_e c^2$
  - Weaker reflection

- For $M_A = 70$, $M_s = 40$
  - Time: $6.2 \times 10^4 \omega_0^{-1}$
  - Temp: $0.127 m_e c^2$
  - Weaker reflection

- For $M_A = 80$, $M_s = 80$
  - Time: $6.7 \times 10^4 \omega_0^{-1}$
  - Temp: $0.150 m_e c^2$
  - Weaker reflection

- For $M_A = 80$, $M_s = 2$
  - Time: $2.1 \times 10^4 \omega_0^{-1}$
  - Temp: $0.090 m_e c^2$
  - Weaker reflection
Upstream spectra for range of $M_A$ and $M_S$

- $M_A = 8$
  - $M_S = 2$
  - Time: $2.7e+04\omega_p^2$
  - Temp: $0.308m_c^2$

- $M_A = 40$
  - $M_S = 8$
  - Time: $4.8e+04\omega_p^2$
  - Temp: $0.065m_c^2$

- $M_A = 70$
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  - $M_S = 80$
  - Time: $2.1e+04\omega_p^2$
  - Temp: $0.090m_c^2$

Weaker reflection
Electron acceleration in quasi-perp shocks

Electrons seem to be injected at low and high Ma. In general low Ma is not conducive to electron reflection unless Ms is small (electrons are hot).

For low Ma and high Ms, the shock becomes filmentary and does not reflect well (quasi-parallel regions).

At high Ma and high Ms, ion loop is more unstable and causes pre-heating of electrons, making it conducive to injection.

To be understood: evolution of the turbulence (fraction returning to the shock in DSA is still small). Downstream spectra are still steep ($E^{-3-5}$).

Also, the role of 3D, and in-plane vs out-of-plane B field not clear.
Shock acceleration: the big picture

Acceleration in laminar field:

quasi-parallel -- accelerate both ions and electrons
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)

quasi-perpendicular -- accelerate mostly electrons
(Guo, Sironi & Narayan 2014; Xu, Caprioli, AS in prep)

NB: downstream e- spectra not fully evolved yet;
upstream waves need more resolution

This helps to understand morphology and CR
content of relics and supernova remnants
Injection of e- without CRs at quasi-perp shock can help to explain the lack of gamma-ray signal in clusters.

SNR morphology in external field explained by quasirallel and quasiperp regions.

Magnetosphere preferentially reflects electrons in a range of oblique angles.
Conclusions

Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction.

Magnetization (Mach #) of the shock and B inclination control the shock structure.

Nonrelativistic shocks accelerate ions and electrons in quasi-par if B fields are amplified by CRs. Energy efficiency of ions 10-20%, number ~few percent; $K_{ep} \sim 1e^{-3}$

Electrons are accelerated in quasi-perp shocks, likely weaker (energy < several percent, number <~1%).

Long-term evolution & 3D effects need to be explored more, new “hybrid” ideas to come.