Bringing Cosmic Shock Waves Down to Earth:
Laboratory Studies of Laser-Driven, High-Mach-Number Collisionless Shocks

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proton radiography
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A Brief History
• We study high-energy-density (HED) magnetized plasmas in laser-driven systems

• HED plasmas can often be mapped to vastly different parameter regimes, such as space plasmas, by matching important dimensionless parameters

• Our “laboratory astrophysics” experiments include:
  • Collisionless shocks
  • Magnetic reconnection
  • Ion-scale magnetospheres
  • Biermann-battery magnetic field generation
  • Anomalous/turbulent transport in magnetized plasmas
Summary

• We have developed a platform for studying laser-driven, high-Mach-number collisionless shocks utilizing advanced diagnostics.
  • First observation of a high-Mach-number magnetized shock in the laboratory
  • First measurements of both ion and electron velocity distributions in a developing magnetized shock

• We have carried out comprehensive particle-in-cell simulations that model laser-driven shocks in experimentally-relevant conditions.
  • Observe robust signatures of kinetic-scale shock formation
• Introduction to magnetized collisionless shocks

• Particle-in-cell simulations of piston-driven shock formation

• Particle velocity distribution measurements in a shock precursor

• Observations of high-Mach-number magnetized shocks

• Conclusions
Outline

• Introduction to magnetized collisionless shocks
  
  • Particle-in-cell simulations of piston-driven shock formation
  
  • Particle velocity distribution measurements in a shock precursor
  
  • Observations of high-Mach-number magnetized shocks
  
  • Conclusions
Shocks Convert Supersonic Ram Pressure to Thermal Pressure

- Incoming supersonic flow is slowed down to subsonic speeds by increasing temperature and pressure
- Characterized by sonic Mach number $M_s = v/c_s$
- Sharp boundary between upstream and downstream regions: shock width on the order of the particle collisional mean free path
- Irreversible process (entropy increases): dissipation provided by collisions
- Energy and momentum conservation yield ratios of upstream to downstream parameters (“jump conditions”)
Collisionless Shocks are Prevalent in Many Astrophysical Systems

- Shocks observed in astrophysical systems with scale lengths orders of magnitude smaller than the collisional mean free path
- Known to be the source of very high-energy particle acceleration, including cosmic rays
- Without collisions, how do they form?

Images: NASA
Collisionless Shocks form through Collective Electromagnetic Effects

- Can be categorized as magnetized, electrostatic, or turbulent (e.g. Weibel)
- Dissipation process depends on shock criticality
  - Subcritical ($M_{ms} \lesssim 3$): anomalous resistivity
  - Supercritical: reflected ions
- Classified by magnetic geometry
  - Quasi-perpendicular: $\theta_B > 45^\circ$
  - Quasi-parallel: $\theta_B < 45^\circ$
- Shock width of order plasma kinetic scales ($d = c/w_p$)
- Characterized by magnetosonic Mach number $M_{ms} = v/v_{ms}$, $v_{ms}^2 = v_A^2 + c_s^2$

Schematic of a Supercritical Perpendicular Magnetized Collisionless Shock

[Figure 5.3: Geometry of an ideally perpendicular supercritical shock showing the field structure and sources of free energy. The shock is a compressive structure. The profile of the shock thus stands for the compressed profile of the magnetic field strength $|B|$, density $N$, temperature $T$, and pressure $NT$ of the various components of the plasma. The inflow of velocity $V_1$ and outflow of velocity $V_2$ is in $x$ direction, and the magnetic field is in $z$ direction. Charge separation over an ion gyroradius $r_{ci}$ in the shock ramp magnetic field generates a charge separation electric field $E_x$ along the shock normal which reflects the low-energy ions back upstream. These ions see the convection electric field $E_y$ of the inflow, which is along the shock front, and become accelerated. The magnetic field of the current carried by the accelerated back-streaming ions causes the magnetic foot in front of the shock ramp. The shock electrons are accelerated antiparallel to $E_x$ perpendicular to the magnetic field. The shock electrons also perform an electric field drift in $y$-direction in the crossed $E_x$ and compressed $B_z$ fields which leads to an electron current $j_y$ along the shock. These different currents are sources of free energy which drives various instabilities in different regions of the perpendicular shock.]

[Balogh & Treumann 2013]
Earth’s Bow Shock is a Natural Laboratory for Studying Magnetized Collisionless Shocks

- Very successful satellite program has yielded a wealth of information on shocks
- But spacecraft studies are limited:
  - ~1D trajectories
  - Variable and uncontrolled plasma parameters
  - Focused on small-scale structure
- Telescope observations are limited to mostly large-scale structure
- Many questions remain unanswered
  - How is energy partitioned between electrons and ions across a shock?
  - How are particles injected into shock acceleration mechanism?
  - What are the characteristic scales of shock formation and reformation?
  - What is the role of turbulence and reconnection in high-Mach number shocks?
Laboratory Platforms Allow Detailed Studies of Collisionless Shocks using Laser Plasmas

- Laboratory collisionless shocks can be generated by driving a supersonic piston plasma through a magnetized ambient plasma
  - Controlled and reproducible parameters
  - Wide range of Mach numbers ($M_{ms} < 40$)
  - 2D and 3D datasets
  - Flexible magnetic geometry
  - Velocity distribution measurements, which will eventually allow direct comparisons between space and laboratory data

Model for Piston-Driven Shock Formation

- **Piston**
- **Downstream (Shocked) Ambient**
  - $B_2 > B_1$
  - $n_2 > n_1$
  - $T_2 > T_1$
- **Upstream (Unshocked) Ambient**
  - $B_1$, $n_1$, $T_1$

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[R.P. Drake PoP 2000]
### Dimensionless Parameters are Similar in Space and Laboratory Plasmas

<table>
<thead>
<tr>
<th>Plasma Parameter</th>
<th>Earth’s Bow Shock</th>
<th>Laboratory (LAPD)</th>
<th>Laboratory (HED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field $B_0$</td>
<td>$5 \times 10^{-5}$ G</td>
<td>300 G</td>
<td>$4 \times 10^4$ G</td>
</tr>
<tr>
<td>Initial Piston Expansion Speed $v_0$</td>
<td>400 km/s</td>
<td>250 km/s</td>
<td>700 km/s</td>
</tr>
<tr>
<td>Upstream Ion Density $n_0$</td>
<td>5 cm$^{-3}$</td>
<td>$5 \times 10^{12}$ cm$^{-3}$</td>
<td>$6 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Upstream Ion Inertial Length $c/\omega_{pi}$</td>
<td>100 km</td>
<td>20 cm</td>
<td>240 µm</td>
</tr>
<tr>
<td>Shocked Ion Gyroperiod $\omega_{ci}^{-1}$</td>
<td>0.5 s</td>
<td>200 ns</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>Shocked Ion Directed Gyroradius $\rho_a$</td>
<td>200 km</td>
<td>5 cm</td>
<td>1 mm</td>
</tr>
<tr>
<td>System Size $D_0$</td>
<td>100-1000 km</td>
<td>60 cm</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensionless Parameter</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfvénic Mach Number $M_A$</td>
<td>8</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Ion Collisional Length Scale $\lambda_{mfp}/D_0$</td>
<td>$10^5$</td>
<td>$10^2$</td>
<td>10</td>
</tr>
<tr>
<td>Density (B) Compression $n/n_0 (B/B_0)$</td>
<td>2-4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Shock Ramp Width $\Delta x/d_i$</td>
<td>~1</td>
<td>~1</td>
<td>~1</td>
</tr>
</tbody>
</table>

[Niemann+ GRL 2014]  [Schaeffer+ PRL 2017]
• Introduction to magnetized collisionless shocks

• Particle-in-cell simulations of piston-driven shock formation

• Particle velocity distribution measurements in a shock precursor

• Observations of high-Mach-number magnetized shocks

• Conclusions
Experimental System Simulated with Particle-in-Cell Code

**PSC**

- 2D explicit PIC with Coulomb collision operator
- Heating operator mimics laser ablation and generates supersonic piston plasma
  - Validated against experiments and rad-hydro codes
- Piston expands through uniform magnetized ambient (upstream) plasma
- Can simulate multi-species plasmas

[Germauschewski+ JCP 2016]
[Fox+ PoP 2018]
Simulations Demonstrate Piston-Driven Collisionless Shocks

- $H^+1$ ions for piston and ambient plasma
- Perpendicular magnetic geometry

Streak Plot of Magnetic Field

[Schaeffer+ PoP 2020]
Simulations Demonstrate Piston-Ambient Coupling
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I. Initial acceleration of ambient ions by piston
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I. Initial acceleration of ambient ions by piston
II. Secondary deformation of ambient ions through ambient-ambient interactions
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I. Initial acceleration of ambient ions by piston
II. Secondary deformation of ambient ions through ambient-ambient interactions
III. Onset of shock formation
Simulations Demonstrate Piston-Ambient Coupling

I. Initial acceleration of ambient ions by piston
II. Secondary deformation of ambient ions through ambient-ambient interactions
III. Onset of shock formation
IV. Begin separation of shock from piston
V. Remaining piston
Piston-Driven Magnetized Shocks Form in Three Stages

(a) Initial acceleration of ambient ions by piston
(b) Onset of shock formation (shock precursor)
(c) Formation of shock on ion scales and separation of shock from piston
(d) Development of well-defined downstream region and emergence of shock structure on MHD scales
Piston-Driven Shock Formation is a Complex Process

Signatures of shock formation include

- Onset of shock formation ($\sim 1/\omega_{ci}^{-1}$)
  - Deformation of piston and upstream flows
  - Strong density and magnetic compressions
  - Upstream ion reflection from compressed magnetic fields
- Piston-shock separation ($\sim 1 - 2.5/\omega_{ci}^{-1}$)
  - Double-bump structure in density profiles
- Development of a downstream region ($\sim 2.5 - 5/\omega_{ci}^{-1}$)
  - Consistent with RH jump conditions
- Important to distinguish piston-dominated and shock-driven processes
  - Magnetic and density compressions necessary but not sufficient conditions

Key experimentally-relevant observables can be extracted from simulations
A brief interlude to discuss diagnostics
Proton Radiography Measures Path-Integrated Magnetic Field

- Protons generated by intense laser interaction with Cu foil (TNSA) or implosion of DHe3 capsule
- Magnetic fields in plasma deflect protons (electric fields negligible)
- Deflected protons collected at detector (image plate or CR-39)
- Signal can be inverted to estimate path-integrated magnetic field

\[ \alpha = \frac{e}{m_p v_p} \int B \times d\ell \]

\[ x_i = x_0 \left(1 + \frac{L_2}{L_1}\right) + L_2 \alpha \]
Optical Thomson Scattering Measures Plasma Parameters

- Collective TS measures scattered light from electron plasma waves (EPW) and ion acoustic waves (IAW)

\[
S(k, \omega) = \frac{2\pi}{k} \left| 1 - \frac{X_e}{\epsilon} \right|^2 f_{e,0}(\omega/k) + \frac{2\pi Z}{k} \left| \frac{X_e}{\epsilon} \right|^2 f_{i,0}(\omega/k)
\]

- From EPW features, one can extract electron density and temperature
- From IAW features, one can extract flow speed, electron temperature, and ion temperature
- Parameters obtained by iteratively fitting an analytic scattered spectrum to the data
Angular Filter Refractometry Measures Path-integrated Density Gradient Contours

- Light from probe laser is collected after passed through angular filter placed in Fourier plane
- The result is a discrete set of bands corresponding to specific plasma refraction angles
- The angles are proportional to the path-integrated plasma density gradient

\[ \theta_\alpha = \frac{1}{2n_{cr}} \int_{-\infty}^{\infty} \frac{\partial n_e}{\partial \alpha} \, dz \]

- Narrow bands = large change in density gradient
- Broad bands = small change in density gradient

[Haberberger+ PoP 2014]
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Experimental Setup for Collisionless Shocks on OMEGA 60

- Interaction probed with **Thomson scattering** (TS) and **proton radiography** (PR) diagnostics
- TS probed along expansion direction ($x$) at TCC
- PR probed the $x$-$y$ plane by sending protons along $z$
Proton Radiography Indicates Strong Magnetic Field Compression

14.7 MeV Proton Radiography Image

- Piston plasma sweeps out background field $B_y$, forming magnetic cavity
- Transition from low fluence (black) to high fluence (white) regions indicate large proton deflections and magnetic compressions
- $B_y$ can be re-constructed by comparing data and synthetic fluence profiles

Measured proton fluence
Synthetic proton fluence
Path-integrated $B_y$ $B_y(x,y=3)$
Spectra Reflect 1D Ion Velocity Distributions

Null shot: piston plasma only

Fast moving piston ions (500-1000 km/s)

Only one pair of peaks: scattered signal primarily from C ions

Spectra show passing of simple ablation flow (increasing density, decreasing speed and temperature)
Weak Interaction Observed between Piston and Ambient Ions in Unmagnetized System

Null shot: piston plasma only

- Fast moving piston ions (500-1000 km/s)
- Ambient ions partially accelerated by piston

Null shot: unmagnetized
Strong Flow Deformations Observed with Magnetic Field

Null shot: piston plasma only
- $x=3\text{ mm}$

Null shot: unmagnetized
- $x=4\text{ mm}$

Magnetized
- $x=3\text{ mm}$

- Free streaming piston ions
- Decelerating piston and accelerating ambient ions
- “Merging” plasmas
- Stationary ambient ions
Electron Density, Temperature, and Ion Flow Speed Extracted from Spectra

Null shot: unmagnetized

Magnetized

EPW Lineouts w/ Best Fits

$\Delta \lambda$ [nm]

$\Delta \lambda$ [nm]

$\Delta \lambda$ [nm]

$\Delta \lambda$ [nm]

time [ns]

time [ns]

wavelength shift [nm]
Strong Correspondence between Observations and Simulations

Null shot: unmagnetized

Magnetized

PIC Simulation

Ambient ions have not connected, so shock has not fully formed.
Strong Correspondence between Observations and Simulations

Null shot: unmagnetized

Magnetized

PIC Simulation

Ambient ions have not connected, so shock has not fully formed.

Directly observe the interaction between piston and ambient ions in a collisionless shock precursor
Simulations show formed H shock. However, H IAW would be heavily Landau damped.
Plasma Parameters Exhibit Strong Dependence on Initial Conditions

- Ion Flow Speed
- Electron Density
- Electron Temperature

- Magnetized
- Unmagnetized
TS and P-RAD Data Show Piston-Ambient Coupling Process

- Magnetic field compressed by ambient plasma
- Piston plasma piles up behind magnetic field
- Electron temperature adiabatically heated by density compression
- Ambient ions accelerated by electron pressure and magnetic field gradients
- Piston flow also modified by these electric fields

Velocity distribution measurements critical to understanding magnetized collisionless shock formation

[Schaeffer+ PRL 2019]
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Experimental Setup for High-\(M_A\) Shocks on OMEGA EP

- Interaction probed with **angular filter refractometry (AFR)**, **shadowgraphy**, and **proton radiography (PR)** diagnostics
- AFR probed along \(z\)
- Shadowgraphy coincident with AFR
- PR probed the \(x-z\) plane by sending protons along \(y\)
Experimental Setup for High-$M_A$ Shocks on OMEGA EP

MIFEDS coils provide background magnetic field up to 8 T

Precursor beam ablates ambient plasma 12 ns before drive beams

Drive beams create supersonic piston plumes that expand into ambient plasma
Ambient Plasma Characterized with Thomson Scattering

$$k_s \equiv k - k_L$$

Electron density $n_{e0} = 2 \times 10^{18} \text{ cm}^{-3}$

Electron temperature $T_{e0} = 30 \text{ eV}$
Without background magnetic field or ambient plasma, only piston plumes observed.
Shock-Like Gradients Observed with $B_0 > 0$ and $n_0 > 0$

$T_0 + 2.35$ ns

Piston Plume

Shock-like gradient

$T_0 + 2.85$ ns

$T_0 + 3.85$ ns

$v_0 \approx 700$ km/s ($M_A \approx 15$)
Shock-Like Gradients Observed with $B_0 > 0$ and $n_0 > 0$

Piston Plume

Shock-like gradient

Compression width $\Delta x \sim 0.6 \, c/\omega_{pi}$
Shock-Like Gradients Observed with $B_0 > 0$ and $n_0 > 0$

Piston Plume

Shock-like gradient

$T_0 + 2.35 \text{ ns}$

$T_0 + 2.85 \text{ ns}$

$T_0 + 3.85 \text{ ns}$

Density compression $n/n_0 > 4$
Magnetic Compressions Observed with Proton Radiography

13 MeV Proton Radiograph

Magnetic Compression

Piston Target

Ambient Target

Magnetic Cavity

B₀

B₀

T₀ + 3.80 ns

x=0

v₀

1 mm
Magnetic Compressions Observed with Proton Radiography

13 MeV Proton Radiograph

\[ B \frac{L_y}{L_x} \approx 70 \left( \frac{OD_{bg}}{OD_r} - 1 \right) \text{ [T]} \]

Background field \( B_0 \approx 4 \text{ T} \)
Magnetic compression \( B/B_0 \approx 3 \)
Density Profiles Show Separation of Shock from Piston

Early time density compression mostly associated with pile-up of piston ions

At late time clear double bump feature associated with shock and trapped piston ions

$M_A \sim 15$ magnetized collisionless shock observed

[Schaeffer+ PRL 2017, PoP 2017]
Summary

• We have developed a platform for studying laser-driven, high-Mach-number collisionless shocks utilizing advanced diagnostics.
  • First observation of a high-Mach-number magnetized shock in the laboratory
  • First measurements of both ion and electron velocity distributions in a developing magnetized shock

• We have carried out comprehensive particle-in-cell simulations that model laser-driven shocks in experimentally-relevant conditions.
  • Observe robust signatures of kinetic-scale shock formation
Future Work

• The development of this platform allows key questions of magnetized shocks to be addressed:
  • Shock heating and energy partitioning
  • Particle injection and acceleration
  • Spatial and temporal scales of shock formation and reformation
  • Interplay between shocks, reconnection, and turbulence
• PIC simulations show that laboratory shocks can lead to non-thermal electron populations
• Experiments underway to explore quasi-parallel collisionless shocks
Thank You!