Exploring Astrophysical Phenomena in the Laboratory with Lasers

Dense hydrogen in Jupiter
Hydrodynamics of supernova remnants
Relativistic plasmas, gamma-ray bursts
MHD in the Crab nebula
Turbulent hydrodynamics in supernovae
Radiative hydrodynamic jets, HH 47

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Introduction

- Astrophysical phenomena at extreme conditions
- Why and how should we use lasers?

Connection of laboratory experiments to astrophysical phenomena

Research activities at MIT

- Magnetic reconnection
- Rayleigh-Taylor induced B fields
- High-Mach number plasma jets
- Collisionless shocks
- Proton radiography at the NIF
Astrophysical phenomena are rich in exciting physics, providing tremendous but challenging opportunities for frontier science.
Astrophysical phenomena have traditionally been studied with observations and theoretical modeling.

**Observation**
- Ground-Based Optical/Radio Image
- HST Image of a Gas and Dust Disk

**Simulation**
- Simulated disk -- black hole density structure

**Experiment**
Laboratory experiments relevant to astrophysics require plasmas at extreme conditions:

- \( n > \sim 10^{18} \text{ cm}^{-3} \)
- \( T > \sim 1 \text{ keV} \)
- \( B \text{ fields} > \sim 1 \text{ MG} \)
- \( \beta = \frac{n k T}{B^2} \sim 1 \)
- \( P > \sim 1 \text{ Mbar} \)
- Partially to fully degenerated
- Weakly to strongly coupled

**High-energy-density (HED) plasmas**

Pressure \( \geq 1 \text{ Mbar} \) or energy density \( > 10^{11} \text{ J/m}^3 \)
Generating an HED plasma with scale sizes of interest is an extremely difficult undertaking.

A HED plasma $P \geq 1 \text{ Mbar}$ (or $> 10^{11} \text{ J/m}^3$)

 Heating rate $>>$ loss rate

$\mathcal{E} > 1 \text{ kJ during}$

$\tau < 1 \mu\text{s}$

It is impossible to create such extreme conditions with conventional methods in the laboratory.
Creating extreme conditions on earth

In underground nuclear explosions:

In the laboratory:

High-energy lasers

Z, ZR magnetic-pincher facility
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High-energy lasers can create extreme conditions with high pressures, temperatures, densities, and velocities.

For $E_L = 1$ kJ, $\lambda_L = 1/3 \, \mu$m
1 ns pulse with $\phi \sim 1$ mm
$P_{\text{abl}} \approx 40[I_{15}/\lambda(\mu\text{m})]^{2/3} \sim 20$ Mbar

For $E_L = 20$ kJ, $\lambda_L = 1/3 \, \mu$m
1 ns pulse with $T_r \sim 220$ eV
$P_{\text{abl}} \approx 3 \times T_r^{3.5} \sim 45$ Mbar

Understanding planetary interiors requires understanding the properties of matter at very high pressures, temperatures, and densities.
Extreme conditions generated by ICF implosions are comparable to conditions in the solar core.

**NIF**

Solar Core:
- $T = 15$ million K
- $\rho = 160$ g/cm$^3$
- $P = 40$ GigaBar

**OMEGA**

NIF capsule:
- $T = 100$ million K
- $\rho = 2000$ g/cm$^3$
- $P = 1200$ GigaBar
Lasers are ideal for producing localized regions of high pressure to “drive” experiments in the laboratory.
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Laboratory jet dynamics can be scaled to astrophysical jet dynamics

<table>
<thead>
<tr>
<th>Dimensionless parameters</th>
<th>OMEGA experiments</th>
<th>Young Stellar Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M</strong> (Mach number)</td>
<td>5 - 20</td>
<td>20 - 40</td>
</tr>
<tr>
<td><strong>Re</strong> (Reynolds number)</td>
<td>~ $10^7$</td>
<td>~ $10^7$</td>
</tr>
<tr>
<td><strong>Pe</strong> (Péclet number)</td>
<td>~ $10^3$</td>
<td>~ $10^6$</td>
</tr>
<tr>
<td>$\eta$ ($n_{\text{jet}}/n_{\text{ambient}}$)</td>
<td>~ $10^7$</td>
<td>~ 20</td>
</tr>
<tr>
<td>$\zeta$ ($\lambda_{\text{ii}}/d_j$, collisionality)*</td>
<td>~ $10^{-5}$</td>
<td>~ $10^{-4}$</td>
</tr>
<tr>
<td>$\chi$ (Jet width/cooling length)</td>
<td>0.1 - 1</td>
<td>0.1 - 10</td>
</tr>
</tbody>
</table>
Laboratory HED dynamics can be scaled to astrophysical supernovae dynamics

[Kifonidis et al., AA. 453, 661 (2006)]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SN1987A</th>
<th>Lab experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(cm)</td>
<td>9x10^{10}</td>
<td>5.3x10^{-3}</td>
</tr>
<tr>
<td>v(cm/s)</td>
<td>2x10^{7}</td>
<td>1.3x10^{5}</td>
</tr>
<tr>
<td>ρ(g/cm³)</td>
<td>7.5x10^{-3}</td>
<td>4.2</td>
</tr>
<tr>
<td>P(erg/cm³)</td>
<td>3.5x10^{13}</td>
<td>6x10^{11}</td>
</tr>
<tr>
<td>Eu</td>
<td>0.29</td>
<td>0.34</td>
</tr>
<tr>
<td>Re</td>
<td>2.6x10^{10}</td>
<td>1.9 x10^{6}</td>
</tr>
<tr>
<td>Pe</td>
<td>2.6x10^{5}</td>
<td>1.8x10^{3}</td>
</tr>
<tr>
<td>Pe_{Rad}</td>
<td>2 x 10^{15}</td>
<td>5 x 10^{9}</td>
</tr>
</tbody>
</table>
Although they have very different spatial, temporal, and density scales, laboratory experiments and astrophysical phenomena share a large variety of hydrodynamic similarities.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \text{Mass continuity equation}
\]

\[
\rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla p + \frac{(\nabla \times \vec{B}) \times \vec{B}}{4\pi} + \text{viscous term} \\
\sim \frac{1}{\text{Re}} \quad \text{J x B force term}
\]

\[
\frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p - \gamma p \nabla \cdot \vec{v} = \text{thermal conduction term} \\
\sim \frac{1}{\text{Pe}}
\]

\[
\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B}) = \text{magnetic diffusion term} \\
\sim \frac{1}{\text{Re}_M}
\]

where:

\[
\text{Re} = \frac{t_{\text{viscous dissipation}}}{t_{\text{hydro}}}, \quad \text{Pe} = \frac{t_{\text{heat conduction}}}{t_{\text{hydro}}}, \quad \text{Re}_M = \frac{t_{\text{resistive heating}}}{t_{\text{hydro}}}
\]

The ideal MHD equations apply to a broad class of astrophysical phenomena where dissipative processes are negligible. Hydro is ok as long as Re, Pe, & Pe_{Rad} are large.
Experiments with strong shock-induced, turbulent plasma flows are used for understanding core-collapse supernovas.

Kelvin-Helmholtz makes mushrooms on Rayleigh-Taylor spike.

\[ R \approx 3 \times 10^{12} \text{ cm} \]

[Kifonidis et al., AA. 408, 621 (2003)]
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Magnetic reconnection occurs in many important astrophysical phenomena.


Magnetic reconnection has been observed and quantified in two laser-produced, colliding plasma bubbles.

Li et al. PRL, 99 055001 (2007)

>95% field strength was reduced in the region where bubbles overlap.
Thomson-scattering measurements indicate little enhancement of electron and ion temperatures due to magnetic reconnection.

Rosenberg et al. PRE, 86, 056407 (2012)
What we have found in these experiments

- Fluid dynamics dominate the reconnection for $\beta \gg 1$ plasmas.

- Reconnection rates are much faster than predicted.

- Work in progress will study reconnection in $\beta \sim 1$ regime
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Ablatively driven Rayleigh-Taylor instabilities occur in a large variety of astrophysical phenomena.

Rayleigh-Taylor may be responsible for the dramatic structures seen in the Eagle Nebula and other star-forming regions. Hester et al. Astro. J. 111 2349 (1996)

Core collapse Supernovae

Crab Nebula Supernova Remnant

[Forumidis et al., AA. 408, 621 (2003)]

SN1987A Nov 2003 Possible Rayleigh-Taylor on ring
Does Rayleigh-Taylor instability generate B fields?

Faraday’s law
\[
\frac{\partial B}{\partial t} = -\nabla \times E
\]

Ideal Ohm’s law
\[
E = -v \times B - \frac{\nabla p_e}{en_e}
\]

In an ideal plasma (\(\eta=0\)), the B-field like the vorticity accumulates inside the bubble.

\[
E_y \approx \frac{\nabla p_e}{en_e}
\]

\[
\frac{\partial B_z}{\partial t} \approx \frac{\nabla T_e \times \nabla n_e}{en_e}
\]
Proton and x-ray radiography experiments were performed to provide complementary information on plasma evolution.

**Proton Radiography**

D³He-filled Backlighter

15 MeV protons

Drive Beams

CH foil

CR-39

**X-ray Radiography**

Uranium Backlighter

X rays

Drive Beams

Framing Camera

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Data show clearly that B fields are generated by Rayleigh-Taylor instabilities. 

Unablated \( \rho_L \) [mg/cm\(^2\)]

Lineout Position [\( \mu m \)]

Normalized Proton Fluence

Lineout Position [\( \mu m \)]

\( <BL>_{rms} \) [T-\( \mu m \)]

Time [ns]

Sim

Data (B only)
For the first time, experiments demonstrate spontaneous B fields induced by Rayleigh-Taylor instabilities.

We are studying how these fields affect plasma dynamics.
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High-Mach-number plasma jets, fundamental astrophysical phenomena in the universe, are commonly defined as well-collimated outflows from a compact object.

A jet of charged particles shoots out of the galaxy.


Sources: young stars (YSO), active galactic nuclei (AGN), $\mu$–quasars, gamma-ray bursts, planetary nebulae, pulsars.
Previous work used x-ray and other optical diagnostics, which are sensitive to plasma density and temperature but not sensitive to electromagnetic fields and MHD instabilities.

**X-ray backlighting**

![Image of x-ray backlighting](image)

Courtesy of J. Knauer

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**X-ray self-emission**

![Image of x-ray self-emission](image)


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**X-ray laser interferometry**

![Image of x-ray laser interferometry](image)

B. Blue et al PRL 94, 095005 (2005)

M. Puris et al PRE 81, 036408 (2010)
Proton probing provides powerful diagnostics for plasma density and electromagnetic fields.
Spontaneous B fields are generated during collisions of two plasma jets, and are transported rapidly to nondissipative regions.
What we have found in these experiments

- The known, tightly-collimated propagation of astrophysical jets may be explained by effects of self-generated B fields.

- Jet structures are modulated due to fields and associated MHD instabilities.

- Spontaneous B fields are generated during collisions of two jets, and these fields are rapidly transported by plasma flow to nondissipative regions in the direction of $\frac{1}{2}$ collision angle between the two colliding jets.
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Collisionless shocks are widely recognized as responsible for the properties of many important astrophysical events*

Because of the low density of astrophysical plasmas, the mean free path due to Coulomb collisions is typically very large

* Such as supernova remnants, gamma-ray bursts and jets from Active Galactic Nuclei.


Subsequent to collision of two jets with each other, low-Mach-number plasma shocks (a nonlinear consequence of plasma instabilities and fields) are observed.

Blue arrows point the fronts of outgoing shocks, which are moving from the midplane to both sides.

Diffusion time: \( \tau_D \sim \frac{1}{2} \delta_{\text{shock}}^2 D_m^{-1} \sim 15 \text{ ns} \quad \Rightarrow \tau_D \gg 2 \text{ ns} \)
What we have found in these experiments

- Collisionless shocks can be generated in head-on astrophysical jet collisions.
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NIF provides a unique opportunity for exploring astrophysical phenomena in the laboratory.

NIF: 192 beams, 1.8 MJ and 500 TW, enhanced pulse shaping capabilities and pulse durations, and greatly improved symmetry, large-scale plasmas, etc.
First two shots will be devoted to the optimization of the proton source.

Dhe3 exploding pusher target
1.5 mm diameter

Only 16 beams are used versus 192 on the standard exploding pusher

Laser:
- 1-ns pulse
- 2.5 kJ/beam

Simulation results:
- $Y_p$: $3.4 \times 10^{11}$
- $Y_n$: $3.92 \times 10^{11}$
- Bangtime: 1.69 ns
- Hot spot: 82 um
- Ti: 9.93 keV
- Fuel $rR$: 5.5 mg/cm$^2$

Laser energy or pulse shape might be modified if proton yield comes low on the first shot
With the advent of high-energy lasers, exploring fascinating astrophysical phenomena in laboratory with lasers becomes feasible.

Laboratory-scaled experiments provide important insight into frontier astrophysics phenomena.

The MIT HEDP/ICF Division is actively conducting state-of-the-art experiments to address various astrophysics issues.