Exploring Astrophysical Magnetohydrodynamics Using High-power Laser Facilities

- Collimation and propagation dynamics in magnetized flows
- Radiative and reverse-radiative shock systems
- Collisionless shock interactions
- Instabilities in plasma - RT, RM, KH, MRI, MTI
- Equation of state - planetary and stellar interiors
- Relativistic electron-positron plasmas
- Nucleosynthesis - relevant Gamow energies in a ‘thermal’ plasma

Mario Manuel
Einstein Fellows Symposium
Harvard-Smithsonian Center for Astrophysics
October 28th, 2014
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*Adapted from NRC committee on HEDP (2003)
Scaled experiments provide a complimentary technique to investigate the dynamics in some astrophysical systems.

- High-power laser facilities provide a unique opportunity to generate physical conditions similar to those in various astrophysical systems.

- Laboratory results are directly scalable when similarity and geometric conditions hold between the two systems.

- Experiments also allow for detailed benchmark comparisons with numerical calculations in relevant dynamic regimes.
Magnetohydrodynamic (MHD) equations describe both laboratory and astrophysical systems

\[
\begin{align*}
\text{Continuity} & \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \\
\text{Momentum} & \quad \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} \\
\text{Energy} & \quad \frac{\partial p}{\partial t} - \gamma \frac{p \rho}{\rho} \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho = 0 \\
\text{Field Evolution} & \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})
\end{align*}
\]

Multiple dimensionless parameters determine the validity of using the MHD equations to describe system dynamics.

- The system exhibits fluid-like behavior: $l_{mfp}/L \ll 1$
- Energy flow by particle heat conduction is negligible: $Pe >> 1$
- Energy flow by radiation flux is negligible: $Pe_\gamma >> 1$
- Viscous dissipation is negligible: $Re >> 1$
- Magnetic field diffusion is negligible: $Re_m >> 1$

Astrophysical systems are large and fulfill these criteria in many cases!
Multiple dimensionless parameters determine the validity of using the MHD equations to describe system dynamics.

- The system exhibits fluid-like behavior
  \[ \frac{l_{mfp}}{L} << 1 \]

- Energy flow by particle heat conduction is negligible
  \[ Pe >> 1 \]

- Energy flow by radiation flux is negligible
  \[ Pe_\gamma >> 1 \]

- Viscous dissipation is negligible
  \[ Re >> 1 \]

- Magnetic field diffusion is negligible
  \[ Re_m >> 1 \]

Two MHD systems evolve similarly when the Euler number (Eu) and magnetization (µ) are similar.

\[
Eu \equiv \frac{v^*}{\sqrt{p^*/\rho^*}} \quad \beta \equiv \frac{1}{\mu} \equiv \frac{p^*}{(B^*)^2}
\]
Magnetized plasma jets are prominent in young stellar objects with a wide range of parameters

<table>
<thead>
<tr>
<th>Physical condition</th>
<th>Constraint</th>
<th>Stellar Jets</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity plays minor role</td>
<td>Reynolds</td>
<td>$\sim 10^3 - 10^7$</td>
<td>$\sim 10^3 - 10^5$</td>
</tr>
<tr>
<td>Magnetic diffusion plays minor role</td>
<td>Magnetic Reynolds</td>
<td>$\sim 10^{13} - 10^{17}$</td>
<td>$\sim 10^{-1} - 10^2$</td>
</tr>
<tr>
<td>Supersonic flow</td>
<td>Mach number</td>
<td>$\sim 10^1 - 10^2$</td>
<td>$\sim 10^0$</td>
</tr>
<tr>
<td>Thermal compared to magnetic pressure</td>
<td>Thermal plasma $\beta_{th}$</td>
<td>$\sim 10^{-3} - 10^1$</td>
<td>$\sim 10^0 - 10^5$</td>
</tr>
<tr>
<td>Ram compared to magnetic pressure</td>
<td>Ram plasma $\beta_{ram}$</td>
<td>$\sim 10^{-3} - 10^1$</td>
<td>$\sim 10^{-3} - 10^5$</td>
</tr>
</tbody>
</table>

Recent work by colleagues investigated astrophysical jets under similar laboratory-created environments.

Ciardi et al., PRL 110 (2013); Albertazzi et al., Science 346 (2014)
Laser-irradiated cones create collimated plasma flows

\[ \theta_c \approx 80^\circ \]

\( \tau \approx 10 \text{ ns} \)

\( E \approx 200-300 \text{ J} \)

~600 \( \mu \text{m} \) spot

90-\( \mu \text{m} \)-thick plastic cone

Expanding plasma

Plasma jet collimates on-axis

~1.5 mm
Optical diagnostics and proton radiography characterized plasma flows

**Shadowography/Schlieren**

- Probe Beam
- $|B_{\text{max}}| \approx 5 \text{ T}$
- Long Pulse
  - 10 ns, ~600 µm spot
Collimated jets formed at varying drive energies

$E \approx 180 \text{ J}$

Free electron density is reduced at lower energies, but bulk jet characteristics are roughly constant:
- collimated diameter is ~500 µm
- average axial velocity is ~45 µm/ns

$E \approx 330 \text{ J}$
Complete disruption of the collimated jet was observed with an applied 5-T B-field along the jet axis.

- A tapered hollow cavity is observed in processed interferograms.
- The cavity wall is ~300 µm thick and tapers from ~3 mm to ~2 mm in diameter.
Simulations* of similar systems predict cavity formation prior to magnetized jet collimation.

\[ P_k \frac{V^2}{C_0^2} > B^2 = \frac{4}{C_2^5}, \]

where the parallel pressure \( P_k \) and perpendicular pressure \( P_\perp \) generally include both the thermal pressure, and the ram pressure due to the bulk motion of the flow. For the highly supersonic, field-aligned flows of interest here, the parallel pressure is \( \frac{P_k}{C_2^4} \), and the stability condition, assuming an isotropic thermal pressure, reduces to

\[ M_A^2 \frac{A}{C_0^2} = \frac{3}{C_1^2} > 1, \]

where \( M_A \) is the Alfvénic Mach number, and \( \frac{A}{C_1^2} \) is the ratio of thermal to magnetic pressure. Although this is only marginally met in the jet's core, the presence of a dense, strongly magnetized plasma at larger radii, may provide the apparent stabilization of the flow. Figure 3 shows a three-dimensional view of the flow at 25 ns. The axial structure consists of alternating regions where the radius of the flow, \( r_f(z) \), and curvature of the magnetic field lines change from convex to concave. In the regions where the plasma is radially bulging out, a Rayleigh-Taylor type filamentation instability can develop, with the conditions for its growth being similar to those of a theta pinch. In particular, the growth rate, \( \frac{C_0}{C_0^1} \), for the driven plasma.
Simulations* of similar systems predict cavity formation prior to magnetized jet collimation

- **Purely expanding plasma**
- **Cavity bounded by shock envelope**
- **Radial collimation (pinching)**
- **“frozen-in” magnetic field compresses at the shock**
- **Standing conical shock collimates a jet beam**

\[
F_r \approx j_\theta B_z
\]

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*Ciardi et al. PRL 110 (2013)
Cavity formation in our experiments appears similar to previous predictions.

Different plasma parameters and initial conditions yielded similar behavior.

<table>
<thead>
<tr>
<th>Cone Target</th>
<th>Flat Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [eV]</td>
<td>~1</td>
</tr>
<tr>
<td>V [µm/µs]</td>
<td>~50</td>
</tr>
<tr>
<td>Reₘ</td>
<td>~1</td>
</tr>
<tr>
<td>β</td>
<td>~1</td>
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- Purely expanding plasma
- Cavity bounded by shock envelope
- Radial collimation (pinching)
- "Frozen-in" magnetic field compresses at the shock
- Standing conical shock collimates a jet beam
Central jet disruption and shock envelope formation may be simply caused by induction

- Induced toroidal current acts to oppose the change in flux
- Direction of radial velocity sets the direction of toroidal current

\[ j_\theta(r) = -\frac{2\pi}{\eta} \int B_z v_r dr \]

\[ F_r \approx j_\theta B_z \]

The J×B force did not permit axial collimation but still formed an envelope from the radially expanding plasma.
Cavity formation is very sensitive to the plasma-$\beta$.

In the stellar analog to these systems, collimated outflows from the star may be disrupted by the background field.
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