Laboratory Astrophysics: magnetically driven plasma jets on pulsed power facilities

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Fast Z-pinches

Applications:

X-ray pulses for ICF studies (~2MJ, ~0.3PW)

Dynamics of plasma driven by magnetic field
Laboratory Astrophysics applications of Z-pinches

1. Properties of matter in extreme conditions ("traditional" laboratory astrophysics):

   **X-ray driven**: opacity, photoionized plasmas, atomic physics of HED plasmas

   **Magnetically driven**: EOS via isentropic compression or flyer plates

2. Dynamical HEDP experiments (both magnetically and x-ray driven):

   - High Mach number flows (jets, shocks, turbulence etc)
   - MHD systems
   - Radiation-hydrodynamics (radiative shocks)

This talk
Outline

1. Reproducing physics of astrophysical jets in laboratory experiments

2. Plasma jets driven by toroidal magnetic field

3. Generation of episodic plasma jets

4. Future work
Scaling of laboratory jets

**Motivation:** to produce in laboratory experiments plasma jet with similar space parameters:

- **Mach number**
  \[ M \sim 10 - 50 \]

- **Density contrast:** jet / ambient
  \[ \eta \sim 1 - 10 \]

- **Cooling parameter**
  \[ \chi \equiv \frac{\tau_{\text{cool}}}{R_j / V} \sim 0.1 - 10 \]

**Magnetic fields:**
\[ \beta \sim 1 \]

\[ \lambda / R \ll 1, \quad \text{Re} >> 1, \quad \text{Re}_M >> 1, \quad \text{Pe} >> 1 \]
Hydrodynamic jets in HEDP experiments

Adiabatic jets:

\[ Z \quad \text{\cite{Sinars2004}} \quad \text{\Omega} \quad \text{\cite{Foster2005}} \]

Internal Mach number $\sim 2$  
No radiative cooling  
No magnetic field
Hydrodynamic jets in HEDP experiments

Radiatively cooled jets:

Gekko-12 laser (Shigemori et al., 2000)

Magpie Z pinch (Lebedev et al., 2002)

High Mach number (~20)

No dynamically significant magnetic field

Interaction with ambient plasma

Jets with angular momentum

(Talk by A. Ciardi)
Jet launching mechanism - “Magnetic Tower” Jets

Differential rotation in accretion disc with poloidal magnetic field

Twisting leads to generation of toroidal magnetic field

Formation of a magnetic cavity collimated by external pressure

Lynden-Bell, MNRAS 1996

Map of the toroidal magnetic field


Experiment – dynamics of magnetic bubble driven by toroidal magnetic field

s.lebedev@imperial.ac.uk  ESF workshop 2008
Magnetized outflows (Camenzind, 2007)

1. Formation of a collimated beam
2. Quasi-periodic generation of the jets
3. Trapping of the toroidal magnetic flux (high $\text{Re}_M$)
4. Efficiency of magnetic to kinetic energy conversion

Experiment: plasma outflow driven by toroidal magnetic field + ambient medium

- Poloidal Current Flow $\sim RB_{\phi}$
- Shocks, MHD Instabilities, Entrained?
- Stationary models do not explain internal structures
  ➔ Test for stability
  ➔ $t$-dep MHD
- Molecular cloud core
Schematic of the experiment

Radial array of tungsten wires (16 x 13 μm) driven by 1 MA, 250 ns current

( ~1 MG toroidal magnetic field)

Diagnostics:
- Laser probing (interferometry)
- XUV imaging
- X-ray spectroscopy
- Current, voltage → Poynting flux

Lebedev et al, MNRAS 2005
Evolution of the jet

Pressure of the toroidal magnetic field inside the cavity leads to

• axial (200 km/s) and radial (50 km/s) expansion of the “magnetic bubble”
• compression of the plasma column on axis (X-ray pulse at peak compression)
• development of MHD instabilities ($\tau \sim$ ns)

XUV emission (~30eV)
Dynamics of Magnetic Tower jets

Jet driven by the pressure of the toroidal magnetic field

Collimation of the central jet by the hoop stress

Collimation of the magnetic bubble by the ambient medium

**Instabilities do not destroy the jet but produce a clumpy outflow**

Two temporal scales for outflow variability:

- fast – instability growth time (~ ns)
- slow – bubble growth time (~50 ns)

**Experiment versus 3-D MHD**
Ciardi et al, PoP 2007

<table>
<thead>
<tr>
<th>268ns</th>
<th>278ns</th>
<th>288ns</th>
<th>298ns</th>
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\[ \begin{align*}
  n_i & \sim 10^{19} \text{ cm}^{-3}, \quad T \sim 200 \text{ eV}, \\
  I & \sim 1 \text{ MA}, \quad B \sim 100 \text{ T} \\
  \text{Re} & > 10^4, \quad \lambda/R \sim 10^{-5}, \quad \text{Pe} > 10 \\
  \beta & \sim 1, \quad \text{Re}_M \sim 50
\end{align*} \]
MHD jet - summary

Opening of the “magnetic cavity”

Well collimated supersonic (200km/s, M >10) jet detached from the source

Clumps in the jet are result of MHD instabilities (assisted by radiative cooling)

$Re_M > 1 \Rightarrow B_{\text{toroidal}}$ could be trapped in the jet

What could happen next?

New material to reconnect the current through initial path (accretion)

Start of a new episode of magnetic tower jet formation (twisting of $B_p$)

*Intrinsically time-dependent scenario with repeatable eruptions*

Episodic magnetic tower jets in experiment
Episodic jets: schematic of the experiment

Radial wire array is replaced by a thin foil

1MA, 250ns current pulse
(~1 MG toroidal magnetic field)

Different radial mass distribution:
(m ~ r for foil, m=const. for wire array)
leading to a faster closure of the gap

Fast decrease of ablated material density with height

The ambient density (and material) can be controlled independently
Episodic magnetic tower jets

Time resolved XUV emission images (hv > 30eV)

Reconnection of current at the base produces several magnetically driven bubbles

2nd bubble

3rd bubble
Episodic magnetic tower jets

Time resolved XUV emission images (hν >30eV)

Reconnection of current at the base produces several magnetically driven bubbles

Subsequent magnetic bubbles move faster

![Diagram showing time-resolved XUV emission images and velocity measurements of magnetic bubbles.](image)
Episodic magnetic tower jets

Reconnection of current at the base produces several magnetically driven bubbles

Subsequent magnetic bubbles move faster

X-ray pulses correlated with formation of each bubble
Jet dynamics at late time

Formation of new magnetic cavities with collimated clumpy jets on axis, embedded in “old” outflow

Reduced radial expansion velocity, presumably due to high ambient pressure (nkT or B²/8π? Trapped magnetic flux?)
Magnetized outflows (Camenzind, 2007)

Experiment: plasma outflow driven by toroidal magnetic field + ambient medium

1. Formation of a collimated jet?
2. Quasi-periodic generation of the jets?
3. Trapping of the toroidal magnetic flux (high $\text{Re}_M$)?
4. Efficiency of magnetic to kinetic energy conversion?

Poloidal Current Flow $\sim RB_\phi$

Shocks, MHD Instabilities, Entrained?

Stationary models do not explain internal structures
- Test for stability
- t-dep MHD

Molecular cloud core
Temperature of the central jet

Spectroscopy of Al spectral lines (H-like to He-like line ratio) allow to determine jet temperature (currently time-integrated)

\[ T \sim 250 \text{ eV, } R_{\text{jet}} = 0.1 \text{cm} \Rightarrow \text{Re}_M \sim 300 \]
\[ T \sim 50 \text{ eV, } h_{\text{cavity}} = 1 \text{cm} \Rightarrow \text{Re}_M \sim 150 \]
Trapped magnetic flux

Magnetic field at the cavity wall:

Flux

\[ L_0 I_0 = L(t) I(t) \]

Inductance

\[ L(t) \approx \frac{\mu_0 h(t)}{2\pi} \ln \left( \frac{R_c}{R_j} \right) \]

B-field

\[ B(t) \approx \frac{\mu_0 I_0}{2\pi} \frac{h_0}{h(t)} \cdot \frac{\cos(\theta)}{R_c(t)} \Lambda(t) \]

e.g. \( B \sim 0.5T \) at \( R_{\text{probe}} = 1.3 \text{cm} \)

(for \( V_Z = 170 \text{km/s}, V_R = 50 \text{km/s}, I_0 = 1 \text{MA} \))

Probe voltage

\[ V(t) = -\frac{d(BS)}{dt} \]

Magnetic probe

Cavity wall

Probe signal starts after arrival of the cavity wall
Trapped magnetic flux

Magnetic field at the cavity wall:

Flux

\[ L_0 I_0 = L(t) I(t) \]

Inductance

\[ L(t) \approx \frac{\mu_0}{2\pi} h(t) \ln \left( \frac{R_c}{R_j} \right) \]

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(for \( V_Z = 170\) km/s, \( V_R = 50\) km/s, \( I_0 = 1\) MA)

Probe voltage

\[ V(t) = -\frac{d(BS)}{dt} \]

\( V_R \sim 30 - 60\) km/s \( \Rightarrow B \sim 0.35 - 0.15\) T

Magnetic field

Probe signal

s.lebedev@imperial.ac.uk  ESF workshop 2008
Magnetized outflows (Camenzind, 2007)

Experiment: plasma outflow driven by toroidal magnetic field + ambient medium

1. Formation of a collimated jet?
2. Quasi-periodic generation of the jets?
3. Trapping of the toroidal magnetic flux (high Re_M )?
4. Efficiency of magnetic to kinetic energy conversion?

Poloidal Current Flow \( \sim R B_\phi \)

Shocks, MHD Instabilities, Trapped model? Stationary models do not explain internal structures

Test for stability t-dep MHD

10,000 – 100,000 AU

Molecular cloud core
Kinetic energy of the outflow can be estimated assuming that:

- velocity linearly decreases with height \( V_{\text{max}} = 130 \text{km/s} \)
- \( Z_{\text{eff}} \sim 5 \)

\[
\frac{mV^2}{2} \approx 100 J
\]
Energetics of the magnetic tower

Poynting flux \((E_r B_\varphi)\) at the base of the bubble

\[
\frac{dW_P}{dt} = \frac{1}{\mu_0} E_r B_\varphi 2\pi R \delta R = U \cdot I
\]

Voltage at the base of the bubble

\[
U = \frac{d}{dt} (LI) \Rightarrow L(t), \ W_M = \frac{LI^2}{2}
\]

1st episode \quad 2nd episode

\(R_c\) \quad \(R_j\)

\(h\)

\(U(t) & I(t)\) can be measured

Voltage, \(dI/dt\) (a.u.)

Energy (J)

Inductance

Poynting energy

Magnetic energy

\(V_{pr}\) \quad \(\text{didtmittl}\)

Voltage

\(\Delta L\) (nH)

\(200\ 220\ 240\ 260\ 280\ 300\ 320\)

\(0\ 2\ 4\)

\(0\ 1\ 2\)

\(0\ 1000\ 2000\ 3000\ 4000\)

\(0\ 500\ 1000\ 1500\)

\(200\ 220\ 240\ 260\ 280\ 300\ 320\)

\(0\ 2\)

\(0\ 0.5\ 1\ 1.5\)

s.lebedev@imperial.ac.uk  ESF workshop 2008
Episodic jets: addition of ambient gas

Radial wire array is replaced by a thin foil

1MA, 250ns current pulse
(~1 MG toroidal magnetic field)

Different radial mass distribution:
(m ~ r for foil, m=const. for wire array)
leading to a faster closure of the gap

Fast decrease of ablated material density with height

The ambient density (and material) can be controlled independently
Jet – ambient interaction

Foil setup allows independent control of the ambient density

Bow shock ahead of jet (~110km/s)
Shock from the foil (~60km/s)

laser shadowgraph, 233ns
Argon, n ~10^{17} cm^{-3}

3mm
Effect of ambient gas on the jet dynamics

Gas cloud (Ar) above the foil
Jet is overtaking previously launched “slow” shock
Bow shock ahead of the jet (V= 110km/s)
Contact point of two colliding shocks (V~40km/s)
Effect of ambient gas on the jet dynamics (late time)

New magnetic tower jet grows inside the cavity formed by the previous episodes

Velocity of the outer shock
~100km/s

Velocity of the inner magnetic tower
~170km/s
Conclusions

Scaled laboratory experiments can be used as a tool complementary to numerical simulations:

- Benchmark 3-D codes under scalable conditions (Re, Re_M in experiment are comparable to numerical)
- May prompt the emergence of new concepts

Variability of astrophysical jets:
perturbations on steady outflows or quasi-periodic eruptions?
Future work

Jet experiments on high current (~10 MA) and/or long pulse facilities:

(Z at SNL, USA – 26MA, 100ns; Sphinx at CEG, France – 8MA, 1µs)

→ better dimensionless scaling parameters, magnetized jets

\[
\text{Re} \equiv \frac{V \cdot L}{\nu} \propto \frac{V \cdot L \cdot Z^4 \sqrt{A \cdot n_i}}{T^{5/2}} \gg 1
\]

\[
P\text{e} \equiv \frac{V \cdot L}{\chi} \propto \frac{V \cdot L \cdot Z \cdot (Z + 1) \cdot n_i}{T^{5/2}} \gg 1
\]

\[
\text{Re}_M \equiv \frac{V \cdot L}{D_M} \propto \frac{V \cdot L \cdot T^{3/2}}{Z} \gg 1
\]

Future work

Magnetically driven plasma jets on long pulse z-pinch facilities

**Jets from Al radial wire arrays on Oedipe facility (1μs, ~500kA)**

[H. Calamy et al, Gramat, France]

![Images of plasma jets at different times](image)

Well collimated “large” scale jet

**Velocity ~100km/s**
Future work

**Improvement of diagnostic capabilities:**

Need to know spatial and temporal distributions of density, temperature, magnetic fields etc.

→ **Quantitative comparison with models**

**Example:**

Multi-beam laser diagnostic capability for study of magnetically driven jets on MAGPIE pulsed power facility (3 x 20J, ~1ns and ~1ps beams)

For X-ray radiography ($\rho(r)$), laser scattering ($T(r)$) and proton probing ($B(r)$)
Future work

**Most important:**

Close interaction with the astrophysics community is needed
Models of episodic jets were discussed (e.g.)

Romanova et al., Ad. in Space Res., 2006

Episodic accretion on the star and episodic jets in simulations of accretion disk around rotating magnetized stars

Character of periodicity depends on the disk transport coefficients ($\alpha$)

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**Fig. 10.** Matter fluxes to the star and to the jet when $\alpha_{\text{vis}} = 0.3$ and $\alpha_{\text{diff}} = 0.2$. Time is measured in periods of Keplerian rotation at $r = 1$.

**Fig. 11.** Matter fluxes at $\alpha_{\text{vis}} = 0.6$ and $\alpha_{\text{diff}} = 0.2$. Time is measured in periods of Keplerian rotation at $r = 1$.

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Several other papers (e.g. Goodson et al., ApJ 97, 99(I,II))
Evolution of the jet

Formation of the magnetic tower starts after complete evaporation of wires at the central electrode.

Expansion of the cavity is faster in the axial direction (200km/s vs 50 km/s) due to stronger $B_{tor}$ at small radius.

X-ray pulse at maximum compression.

Development of MHD instabilities ($\tau \sim$ ns)

$\Delta t=10\text{ns}$
Opening of the “magnetic cavity”

“Opening” of the magnetic cavity leads to formation of a well collimated but clumpy jet, detached from the source
Magnetized outflows (Camenzind, 2007)

- Poloidal Current Flow $\sim RB_\phi$
- Cooled Bow Shock
- Shocks, MHD Instabilities, Entrained?
- Stationary models do not explain internal structures
  - Test for stability
  - t-dep MHD

- Swept-up material (molecular outflow)
- Terminal shock
- Hot bubble of old jet material
- Magnetic confinement
- Magneto-centrifugal launching ($<AU$ scale)

- Cooled down Magnetized?
- Hydrodynamic confinement?
- 10,000 - 100,000 AU

Molecular cloud core

Camenzind 2007

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Jets in the Universe (The Movies)

Hartigan (2002)
“Magnetic Tower” jet inside collapsing stars

Differential rotation in accretion disc with poloidal magnetic field

Twisting leads to generation of toroidal magnetic field

Formation of a magnetic cavity collimated by external pressure

Experiment – dynamics of magnetic bubble driven by toroidal magnetic field

Uzdensky et al., PoP 2007

SN & GRB
Interferometry and XUV image

Interferometry allows measurements of mass distribution
Approach very well known in Aerodynamics!
Summary

The experiment shows formation of episodic collimated outflows

Variability of astrophysical jets: perturbations on steady outflows or quasi-periodic eruptions?
Outline

Introduction

Formation of “magnetic tower jets” in laboratory

Experiments with episodic “magnetic tower jets”

Conclusions

XZ Tauri

Cygnus X-1

SW7 2BW
Hydrodynamic scaling

1. Both systems are described by the same set of equations

Validity of fluid description: Negligible dissipation:

\[ \delta \equiv \frac{\lambda_{m.f.p.}}{L} \ll 1 \]

Viscosity (Reynolds Number)
\[ \text{Re} \equiv \frac{V \cdot L}{\nu} \gg 1 \]

Heat Conduction (Peclet Number)
\[ \text{Pe} \equiv \frac{V \cdot L}{\chi} \gg 1 \]

2. Initial conditions (dimensionless) are the same

There are additional constraints for MHD systems:

\[ \beta \propto \frac{P^*}{(B^*)^2} = \text{inv} \]

and Magnetic Reynolds Number
\[ \text{Re}_M \equiv \frac{V \cdot L}{D_M} \gg 1 \]

Facilities for Inertial Confinement Fusion

High power lasers (NIF at Livermore)  Fast Z-pinches (Z at Sandia Labs)

Characteristic parameters:
energy ~2MJ, time-scale ~5ns, volume <1cm³, pressure ~1Mbar

Diagnostics:
high resolution (time, space) imaging, radiography, spectroscopy etc.

Plus several smaller scale laser and z-pinch facilities, including at Universities (capable of delivering >1kJ into object <1mm)
MAGPIE Z-pinch facility

1TW, 1.5MA, 250ns

1. Marx Generator (x4)
2. Pulse Forming Line (5 Ohm)
3. Trigatron Switch (x4)
4. Transfer Line (1.25 Ohm)
5. Diode Stack, MITL and Z-Pinch load
6. X-ray shielding
7. Data acquisition screened room
3-D MHD simulations of the experiment (A. Ciardi)

16 tungsten wires, $\Phi = 13 \, \mu m$, isodensity, log -3.3 -2.3 -1.3 -0.3 kg/m$^3$
Effect of ambient gas on the jet dynamics

Fast shock overtakes a slower moving flow, producing inversed bow shock

Gas cloud (Xe) above the foil
Jet is overtaking previously launched “slow” shock
Bow shock ahead of the jet (V= 110km/s)
Contact point of two colliding shocks (V~40km/s)
Evolution of the jet

Pressure of the toroidal magnetic field inside the cavity leads to

- axial (200 km/s) and radial (50 km/s) expansion of the “magnetic bubble”
- compression of the plasma column on axis (X-ray pulse at peak compression)
- development of MHD instabilities ($\tau \sim$ ns)
Extreme Laboratory Astrophysics: why now?

New experimental facilities allowing to achieve extreme states of matter (high pressure, high density / temperature etc…)

Scaling considerations (need to have sufficiently high temperature in sufficiently large samples to study a relevant regime)

New diagnostics allowing to study the processes with sufficient accuracy

Advances in computing
Extreme Laboratory Astrophysics: facilities

Jupiter, Trident, Z-Beamlet, Vulcan, LULI, Gekko lasers

Z, ZR magnetic-pincher facility

National Ignition Facility (NIF) laser

Magpie magnetic-pincher facility

Omega, EP lasers
Astrophysics Dynamics in Laboratory

- Study subset of a problem, described by the same set of equations (e.g., MHD), which can be correctly scaled.
- Control and vary initial conditions, follow the evolution.
- Especially promising for studies of 3-D problems.
- Scaling: difference in 15-20 orders of magnitude?