Laboratory Astrophysics with High Energy Density Facilities

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EXAMPLES:

Gamma-Ray Bursts --- Laser-Generated Relativistic Fireballs

Black Hole Annihilation Flares --- Laser-Generated Pair-Balanced Plasmas
KEY ELEMENTS FOR FUTURE ADVANCES

Lasers

Diagnostic Development

Numerical Simulation

Target Design & Fabrication

Theory & Scaling
Two Regimes of Laboratory Astrophysics

1. High Density/Collisional Astrophysics:
   *Physical Processes:* Rad Flow; Hydro; MHD; Atomic and Nuclear Processes; EOS; opacities
   *Astro Context:* SN; SNR; Accretion Disks; Stellar Physics; Solar flares; Jets and Bubbles; ISM and ICM; Nebulae

2. High Energy/Collisionless Astrophysics:
   *Physical Processes:* Plasma kinetics; Particle Acceleration; Pairs; Relativistic Outflows and Dissipation; Reconnection; Turbulence Cascade
   *Astro Context:* GRB; Blazars; Pulsars; PWN; Solar Flares; BH flares; Magnetars; Solar Wind and IPM; Cosmic Rays
Two Approaches to Lab Astrophysics

1. Scalable Experiments in which key Dimensionless parameters are similar for the lab and astro contexts

   Examples: Ideal hydro Instabilities and Mixing and MHD; Shock dynamics; Hydro and MHD Jets and Interactions

2. Nonscalable experiments that provide meaningful tests and calibration of numerical codes. Once tested, such codes can then be applied to astrophysics simulations with "extrapolated" or parametrized physics.

   Examples: Radiative Processes; Transport Processes; Reconnection; Turbulence Cascade; Relativistic and Pair Plasmas
Here is what such lasers do to a material

- The laser is absorbed at less than 1% of solid density

Shock waves establish the regime of an experiment

(from Drake et al)
Supernova 1987A motivates scaled hydrodynamic instability experiments

- **SN 1987A**
  - A core-collapse supernova
  - Early high-Z x-ray lines with large Doppler shifts
  - Early glow from radioactive heating
  - The issue is the post-core-collapse explosive behavior
- **In 20 years of simulations**
  - Only one (Kifonidis, 2006) makes fast enough high-Z material
  - 3D simulations coupling all the interfaces where initial conditions matter are not feasible
  - NIF experiments can do this
  - Omega experiments address a single interface

SN1987A, WFPC2, Hubble

Kifonidis, 2003
Here is a typical target for supernova hydrodynamics experiments

- Precision structure inside a shock tube

Hydrodynamics:
- $L >> \lambda_{mfp}$; $Re > 10^5$
- small heat conduction & radiation

Experiment design: Carolyn Kuranz
Obtain data from two orthogonal directions

Dec. 06 data at 21 ns

Data and analysis: Carolyn Kuranz

Mid-1990's data
We are now observing the role of complex initial conditions in spike penetration.

Interferogram of complex surface on component provided by GA (analysis: Kai Ravariere)

Preliminary data on mix layer thickness

Data and analysis: Carolyn Kuranz
HED hydrodynamics beyond simulation on NIF

- The unresolved issue in exploding stars
  - The 3D behavior of a diverging explosion
  - With multiple, structured interfaces
- This problem cannot be fully simulated with computers
  - Too big, too complex, high Reynolds number
- NIF can do a very relevant experiment
  - Also can do transition to turbulence
- Preliminary design-related simulations
  - At Michigan and LLNL
    - (Grosskopf) (Miles)
Create and study driven radiative shocks

- Laser beams launch Be piston into Xe or Ar gas at > 100 km/s
- Piston drives a planar shock
- Radiography detects dense xenon
- Gold grid provides spatial fiducial
- Parameters
  - $10^{15}$ W/cm$^2$
  - 0.35 µm light
  - 1 ns pulse
  - 600 µm tube dia.

Target: Mike Grosskopf, Donna Marion, Mark Taylor
Sample radiographic images of radiative shocks

- Average velocity 140 km/sec from $t = 0$ to 14.6 ns from laser firing
- Two Phys. Plasmas papers
- Exploration of structure will be a next theme

Data and analysis: Amy Reighard
Advanced diagnostics will measure much more

- Thomson scattering
- Collaboration with Dustin Froula and Siegfried Glenzer of LLNL

Design: Amy Reighard


Target: Trisha Donajkowski, Mike Grosskopf, Donna Marion

- Fitting to data gives
  - $110 \text{ km/s fluid velocity}$
  - $ZT_e = 12 \times 300 \text{ eV}$
  - $T_e \leq T_i \leq 500 \text{ eV}$

from Drake et al
Sample x-ray image of stellar jet deflection experiments at Omega by Hartigan, Frank and collaborators.
Schematic of the experiment

16 x 13μm W wires driven by 1MA, 250ns current pulse (~1 MG toroidal magnetic field)

MHD Jets launched by Toroidal Fields from Lebedev’s Group in UK

S.V. Lebedev et al., Rice meeting Mau 14 2007
Evolution of the jet

XUV emission

The jet demonstrates MHD instabilities typical for Laboratory plasmas (Z-pinch) but they do not destroy the jet

S.V. Lebedev et al., Rice meeting Mau 14 2007
Structure of the “magnetic tower”

Dimensionless parameters from 2-D MHD simulations

Expanding magnetic bubble
Jet pinched by the toroidal magnetic field

Experiment:
X-ray emission (~300eV)

\[ n_i \sim 10^{19} \text{ cm}^{-3}, \ T \sim 200 \text{ eV} \]
\[ I \sim 1 \text{ MA}, \ B \sim 100 \text{ T} \]
\[ \text{Re} > 10^4, \ \lambda/R \sim 10^{-5}, \ Pe > 10 \]
\[ \beta \sim 1, \ \text{Re}_M \sim 50 \]

S.V. Lebedev et al., Rice meeting Mau 14 2007
Magnetic Tower jets in laboratory experiments

Experiment versus 3-D MHD

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 lead to variability of the flow

Variability of the jet emission

Two temporal scales for outflow variability:
- fast – instability growth time
- slow – bubble growth time

S.V. Lebedev et al., Rice meeting Mau 14 2007
In High Energy Astrophysics, Five Major Questions Posed by WG:

1. What is the role of e+e- pairs in the most energetic phenomena of the universe such as gamma-ray bursts, AGN jets and pulsar wind dynamics?

2. Why are astrophysical jets spectacularly collimated over enormous distances?

3. How does tenuous plasma interact with and dissipate ultra-relativistic or electromagnetic-dominated outflows such as pulsar winds and gamma-ray bursts?

4. How do shock waves produce high energy cosmic rays?

5. How does magnetic turbulence dissipate energy in astrophysical plasmas?
Phase space of laser pair plasmas overlap some relevant high energy astrophysics regimes

- PulsarWind
- GRB
- LASER PLASMAS
- Microquasars
- Stellar Black Holes
- Blazar

$\Omega_e/\omega_{de}$

- $\log<\gamma>$
- $100$ - $1$ - $0.1$ - $0.01$
relativistic e+e- plasmas are ubiquitous in the universe

Laser-produced pair plasmas can be used to study astrophysics

Thermal MeV pairs

Nonthermal TeV pairs
Set-up of Titan Laser Experiments (Chen et al PRL 2009)
Sample Titan data

(a) EGS simulations

(b) Sample Titan data
e\(^+\) yield per emergent hot electron as function of Au thickness. Discrepancy is likely due to angular effects (from Chen et al 2009).
Assuming the conversion ratio of laser energy to hot electrons is ~ 30 %, and the hot electron temperature is ~ 5 -10 MeV, the Titan results suggest that the optimized positron yield can reach

\[ \sim 10^{12} \text{ e+ per kJ of laser energy} \]

with the Au target > 5-6 mm

The in-situ e+ density should reach \( >10^{17}/\text{cm}^3/\text{kJ of laser energy} \)

The peak e+ current should reach \( 10^{24}/\text{sec} \)

Pair content may reach 80% for thick targets
Comparison of Debye radius and electron gyroradii with fireball radius
Initial B=9.e8G and T=1MeV & 5MeV

\[ \frac{C}{\omega_{pe}} \]

Omega
NIF
Gamma-Ray Bursts: High $\Gamma$ favors an e+e- plasma outflow?

What is primary energy source? How are the e+e- accelerated? How do they radiate?

Internal shocks: Hydrodynamic

Poynting flux: Electromagnetic

Pulsae Stripe Wind Dissipation
If wrinkled current dissipates, striped field dissipates, magnetic energy coverts to flow kinetic energy, “heat” & high frequency radiation, strong waves - partition?

Sheet Dissipation: Tearing of one locally ~ plane sheet?
(Coroniti; too slow? - Kirk & co.)
Cause: Current starvation? (everybody)
sheet → strong waves? - Melatos-vacuum)
Sheets Interact - Two Stream (Weibel-like) instability

\[ x_0 = R_L << r \]

Thin Sheet \((kr_L << 1)\) dynamics as if each sheet is unmagnetized although intersheet medium MHD \((B^2 \gg 4\pi\rho_0c^2)\)

\[
\langle f(x_n) \rangle = \frac{1}{2} [f(x_n^{(+)}) + f(x_n^{(-)})]
\]

\[
mc\Sigma_b \frac{D(\gamma_b\beta_b)}{Dt} = q\Sigma_b (\langle E \rangle + \beta_b \times \langle B \rangle) = q\Sigma_b (\langle \delta E \rangle + \beta_b \times \langle \delta B \rangle), \quad \langle B_0 \rangle = 0
\]
Possible Experiments

Computational: 3D PIC, must be MHD between sheets (frozen-in pairs) resolve current layer: Larmor and $c/\omega_p$ scales of beam particles could use rectangular geometry

Lab Experiment?
Use laser on dense slab to launch relativistic electron-positron plasma onto field lines of reversed B (RFP?)
Launch beams into field reversal region?

\[ R_m = R_L \left( \frac{q \Phi}{2m_b c^2 B_b \gamma_b} \right)^2 \]

Charged particle beam currents

Laser generated MHD electron-positron plasma

Perp E to give cross field plasma flow?

Expt improves on simulation?
Short pulse laser plasma interactions (solid targets) can generate ultra-strong fields > $10^9$ gauss

from Krushelnick et al
Mechanisms of magnetic field generation in intense laser plasma interactions

1. Non parallel temperature and density gradients.

\[
\frac{dB}{dt} = -\nabla \times E
\]

\[
\frac{dB}{dt} = -\nabla \times \left( \frac{\nabla p_e}{n_e e} \right) = \frac{k_e \nabla T_e \times \nabla n_e}{n_e e}
\]

2. Current due to fast electrons generated during the interaction (Weibel instability)

3. DC currents generated by the spatial and temporal variation of the ponderomotive force of the incident laser pulse \( B_{dc} \sim B_{laser} \)

Experimental schematic

- Laser p-polarised
- Ablated plasma
- \( \mathbf{B} \) (s-polarised O-wave)
- \( \mathbf{B} \) (p-polarised X-wave)
- \( \mathbf{E}_{n\omega} \perp \mathbf{B} \) (p-polarised X-wave)
- \( \mathbf{E}_{n\omega} \parallel \mathbf{B} \) (s-polarised O-wave)
EM wave propagation in magnetized plasma

- Ordinary Wave (O)
  \[ \mu_O^2 = 1 - \frac{\omega_{pe}^2}{\omega_0^2} \]

- Extraordinary Wave (X)
  \[ \mu_X^2 = 1 - \frac{\frac{\omega_{pe}^2}{\omega_0^2} \left( 1 - \frac{\omega_{pe}^2}{\omega_0^2} \right)}{1 - \frac{\omega_{pe}^2}{\omega_0^2} - \frac{\omega_{ce}^2}{\omega_0^2}} \]

- Ellipticity
  \[ \frac{b}{a} = 2.49 \times 10^{-21} \lambda_{\mu m}^3 \int nB_{MG}^2 \, dl \]
X-Wave cutoffs

Region of harmonic generation

Electron density (cm$^{-3}$) vs. Magnetic field (MG)

- $\gamma n_c$
- $n_c$
- $\omega_o = 1\mu$m

Harmonic frequencies:
- $2\omega_o$
- $3\omega_o$
- $4\omega_o$
- $5\omega_o$
- $6\omega_o$
- $7\omega_o$
- $8\omega_o$
- $9\omega_o$
Observation of cutoffs

Indicates fields up to ~ 400 MG
Pair annihilation-like features had been reported for several black hole candidates, but only CygX-1 has been confirmed.
2D model of an e+e- pair-cloud surrounded by a thin accretion disk to explain the MeV-bump

\( n_+ \sim 10^{17} \text{/cc} \)
The Black Hole gamma-ray-bump can be interpreted as emissions from a pair-dominated MeV plasma with \( n_+ \sim 10^{17} \text{cm}^{-3} \).

Can laser-produced pair plasmas probe the pair-dominated temperature limit?
Summary

1. Most successful experiments so far are in ideal hydro MHD regimes. Some radiative experiments have successfully compared with codes. Jets and their interactions are exciting new frontiers.

2. In the high energy/collisionless regime, creation of copious pairs and ultra-strong fields with PW class lasers have been demonstrated. Meaningful astrophysics experiments remain to be conceived and designed.

3. Diagnostics is the biggest challenge. Much more thought, manpower and resource need to be devoted to diagnostic development.