Hydrodynamic Instability Experiments in High-Energy-Density Plasmas

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Applied Physics
Director, Center for Laser Experimental Astrophysics
University of Michigan
The Center for Laser Experimental Astrophysics Research studies high-energy-density phenomena that are relevant to astrophysics

• **We advance fundamental understanding of HED dynamics relevant to astrophysics**
  – Radiation hydrodynamics
  – Complex HED hydrodynamics
  – Magnetized flowing plasma

• **While advancing the required infrastructure**
  – Computer simulation
  – Target fabrication
  – X-ray diagnostics

• **The ultimate goal of these activities is to train junior scientists**

X-ray radiography of a RT experiment at the National Ignition Facility with high energy fluxes
CLEAR team is oriented toward training students

- **Post Docs:** Gray, Young
- **Recent Grad students:**
  - Rasmus (LANL), Young (UM), Wan (LANL), MacDonald (UCB/LLNL), Fein (SNL)
- **Current Grad Students:**
  - Belancourt, Elgin, Levesque, VanDervort, Angulo, Lefevre, Coffing, Melean, (Ma, Cearly, Wadas)
  - Many undergrads (10)
- **We graduate about 1 – 2 students/year**
- **We have an excellent publication record!**
  - >100 since 2009
  - ~12/year
Our graduates have proven attractive to NNSA labs

• Most of our students come through the UM Applied Physics Program
  – Outstanding applicants; highly competitive
  – Diverse program – 30% women, 30% URM
  – Imes-Moore Fellowship (1st generation citizen, 1st generation college, financial hardship)

• Since 2007 we have graduated 13 PhDs from CLEAR and its predecessors
  – 8 went into the NNSA labs (3 LLNL, 3 LANL, 2 SNL)
  – 2 went into HEDP at SLAC and General Atomics
  – 2 remain in HEDP in universities
  – 2 went into industry
CLEAR relies on experienced senior scientists with a breadth of experience

• Faculty:
  – Kuranz, Drake
• Staff:
  – Trantham, Klein, Gillespie

• Additional Faculty at UM:
  – Johnsen (ME), McBride (NERS),
  – Willingale (EECS), Thomas (NERS)
We experiment and collaborate at many HEDP facilities

<table>
<thead>
<tr>
<th>Led by CLEAR:</th>
<th>Facility</th>
<th>Collaborative participation</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Hydro</td>
<td>Omega</td>
<td>XRTS</td>
<td>Omega</td>
</tr>
<tr>
<td>Complex Hydro</td>
<td>Omega/NIF</td>
<td>LLNL Complex Hydro</td>
<td>Omega &amp; NIF</td>
</tr>
<tr>
<td>Magnetized Flows</td>
<td>Omega/JLF</td>
<td>LANL Complex Hydro</td>
<td>Omega</td>
</tr>
<tr>
<td>Astrophysical Dust</td>
<td>Jupiter</td>
<td>Complex Hydro</td>
<td>LMJ</td>
</tr>
<tr>
<td>X-ray Thomson Scatt.</td>
<td>Omega/NIF</td>
<td>Radiative shocks</td>
<td>LMJ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetized Flows</td>
<td>LULI</td>
</tr>
</tbody>
</table>
We have been fabricating targets for our experiments since 2004

Sallee Klein and students gas filling targets at LLE

Components for photoionization front gas target

Some components are fabricated at General Atomics

Omega-EP Kelvin Helmholtz target, Wan, Malamud
Where are these conditions found in nature?

R.P. Drake, Physics Today
Hydrodynamic fluids described by single-fluid Euler Equations

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p
\]

\[
\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho} \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho = 0
\]

  - Supernova hydrodynamics, a young SNR, ring collision, and radiative SNRs
- See also Falize et al Astrophysics and Space Science 2009 and Cross et al Nature Communications 2016
Euler Equations are invariant under transformation

If two systems are hydrodynamic and related by the transformation below then there is a direct correspondence between the two systems*

\[ r_{SN} = ar_{lab} \quad p_{SN} = cp_{lab} \]

\[ \rho_{SN} = b\rho_{lab} \quad t_{SN} = a\sqrt{b\over c}t_{lab} \]

<table>
<thead>
<tr>
<th></th>
<th>SN</th>
<th>lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>10^{11} cm</td>
<td>10^{2} \mu m</td>
</tr>
<tr>
<td>\rho</td>
<td>10^{-2} g/cc</td>
<td>1 g/cc</td>
</tr>
<tr>
<td>p</td>
<td>10 Mbar</td>
<td>1 Mbar</td>
</tr>
<tr>
<td>t</td>
<td>1000 s</td>
<td>10 ns</td>
</tr>
</tbody>
</table>

*Ryutov (1999)*
Lab experiment must be in the same regime as astrophysical object

- System must be highly collisional, $\lambda_c \ll r$
- Viscosity negligible, $Re \gg 1$
- Heat conduction negligible, $Pe \gg 1$
- Radiation flux negligible, $Pe_\gamma \gg 1$

<table>
<thead>
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<th></th>
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<th>lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r/\lambda_c$</td>
<td>$10^6$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$Re$</td>
<td>$2.6 \times 10^{10}$</td>
<td>$1.9 \times 10^6$</td>
</tr>
<tr>
<td>$Pe$</td>
<td>$1.5 \times 10^{12}$</td>
<td>$1.8 \times 10^3$</td>
</tr>
<tr>
<td>$Pe_\gamma$</td>
<td>$2.6 \times 10^5$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$\tau_{BB}/\tau_{\text{hydro}}$</td>
<td>$\ldots$</td>
<td>$580$</td>
</tr>
</tbody>
</table>
Hydrodynamics instabilities often occur in HED astrophysical systems

Ardent simulation from Tomek Plewa
Shear drives the \textbf{Kelvin Helmholtz instability}

Shear flow between two layers creates vorticity at the interface causing vortices to develop and grow

\[ \gamma_{KH} = \frac{k(\Delta u)}{2} \sqrt{1 - A^2} \]

R.P. Drake, \textit{High Energy Density Physics}
Vorticity drives the Richtmyer-Meshkov process

When a shock crosses a rippled interface, vorticity is deposited and causes the perturbation to grow.

\[ \frac{da_{RM}}{dt} = k u_{ps} A_{ps} a_{ps} \]

O. Schilling

Buoyancy drives the Rayleigh Taylor instability

A blast wave crossing an interface with a drop in density, creates an opposing pressure and density gradient, and perturbations on the interface will grow.

\[ \nabla \rho \rightarrow \nabla P \]

\[ \gamma_{RT} = \sqrt{A g k} \]
Benefits of performing hydrodynamic instability experiments using high-energy-density facilities

• We use solid materials with known perturbations and density gradients
• “Drive” conditions (laser or pulsed power) can create different acceleration histories
• We can reach high $Re = UL/ν$ and $M = U/c_s$
• We can explore radiative or magnetic effects
Observation of Single-Mode, Kelvin-Helmholtz Instability in a Supersonic Flow

W. C. Wan,1,* G. Malamud,1,2,† A. Shimony,2,3 C. A. Di Stefano,1 M. R. Trantham,1 S. R. Klein,1 D. Shvarts,1,2,3 C. C. Kuranz,1 and R. P. Drake1

1Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
2Nuclear Research Center – Negev, Beer Sheva 84190, Israel
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(Received 3 December 2014; revised manuscript received 12 June 2015; published 1 October 2015)

We report the first observation, in a supersonic flow, of the evolution of the Kelvin-Helmholtz instability from a single-mode initial condition. To obtain these data, we used a novel experimental system to produce a steady shock wave of unprecedented duration in a laser-driven experiment. The shocked, flowing material creates a shear layer between two plasmas at high energy density. We measured the resulting interface structure using radiography. Hydrodynamic simulations reproduce the large-scale structures very well and the medium-scale structures fairly well, and imply that we observed the expected reduction in growth rate for supersonic shear flow.

DOI: 10.1103/PhysRevLett.115.145001 PACS numbers: 52.35.Tc, 47.20.Ft, 47.40.Ki, 52.38.-r
Omega EP has 4 individual lasers

- 4 beams, 1 ps to 10 ns
- Can be sequentially fired
We “stack” 3 beams in time to create a steady shock

We stitch together 3, 10 ns beams for a ~27 ns pulse

Spherical Crystal Imager

We aim to study the effects of compressibility on KH growth

Grad student: Willow Wan
Design: Guy Malamud
We modeled the experiment in CRASH, a radiation hydrodynamic code

- 1D, 2D or 3D
- Dynamic adaptive AMR
- Level set interfaces
- Self-consistent EOS and opacities
- Multigroup-diffusion radiation transport
- Electron physics and flux-limited electron heat conduction
- Laser package
  - 3D ray tracing for 2D or 3D runs

3D Nozzle to Ellipse @ 13 ns

Material & AMR

Log Density

Log Electron Temperature

Log Ion Temperature

CRASH has aided in the design and analysis of this experiments

\[\text{log rho}\]

\[\begin{array}{cccc}
500 & 1000 & 1500 & 2000 \\
400 & 200 & 0 & -200 \\
\end{array}\]

\[\begin{array}{cccc}
0.0 & 0.5 & 1.0 & -0.5 \\
-1.0 & -0.5 & 0.0 & 0.5 \\
\end{array}\]

\(nx=*****\),  \(1, \text{it}=0, \text{time}=0.0000\)
We use the Spherical Crystal Imaging diagnostic for high SNR radiographs

Wan, PoP, 2016
Post processing the images allows us to see small structures.

The data support an inhibited KH growth rate

\[
\gamma = \gamma_{inc} \frac{\sqrt{-1 - M_c^2} + \sqrt{1 + 4M_c^2}}{M_c}
\]

- \(\gamma\) = growth rate coefficient
- \(\gamma_{inc}\) = incompressible growth rate coefficient
- \(c\) = speed of sound
- \(M_c\) = convective Mach number (supersonic at >0.5)

\[
M_c = \frac{\Delta u}{c_1 + c_2}
\]

Normalized data vs. shear flow simulations

Wan, PRL 2015
Richtmyer-Meshkov evolution under steady shock conditions in the high-energy-density regime

C. A. Di Stefano,1,a) G. Malamud,1,2,a) C. C. Kuranz,1 S. R. Klein,1 C. Stoeckl,3 and R. P. Drake1

1University of Michigan, Ann Arbor, Michigan 48109, USA
2Nuclear Research Center - Negev, Beer-Sheva 84190, Israel
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(Received 9 August 2014; accepted 8 March 2015; published online 17 March 2015)

This work presents direct experimental evidence of long-predicted nonlinear aspects of the Richtmyer-Meshkov process, in which new modes first arise from the coupling of initially-present modes, and in which shorter-wavelength modes are eventually overtaken by longer-wavelength modes. This is accomplished using a technique we developed employing a long driving laser pulse to create a strong (Mach \(\sim\) 8) shock across a well-characterized material interface seeded by a two-mode sinusoidal perturbation. This technique further permits the shock to be sustained, without decay of the high-energy-density flow conditions, long enough for the system to evolve into the nonlinear phase. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4915303]
We have performed the first HED “light-to-heavy” Richtmyer-Meshkov experiment

Design enables 20 ns constant shock on OMEGA EP

Grad student: Carlos Di Stefano
Design: Guy Malamud
Hyades aided in the RM experimental design

Data confirm the 1D hydro

- PAI
- Initial structured interface
- CRF
- TI
- Ablator
- Forward shock
- Reshock

Graph showing the progression of different layers over time and density.
We observed the RM unstable interface using spherical crystal imager (SCI)
We observed RM mode coupling

Seeded modes

Harmonic mode

A planar blast is created in the experiment using a 1 ns laser pulse
Key components of target

150 μm plastic (1.41 g/cc)
- Tracer strip material: $C_{500}H_{457}Br_{43}$ (1.42 g/cc)
- Entire surface machined with seed perturbation

2-3 mm Carbonized Resorcinol Formaldehyde (CRF) foam (50 - 400 mg/cc)
HED RT experiments have been performed on many laser facilities over the past 2 decades.
Comparing data to the 2D and 3D buoyancy-drag model

An incompressible model for Rayleigh-Taylor mixing

\[
(\rho_1 + C_a \rho_2) \frac{du}{dt} = (\rho_2 - \rho_1) g - \frac{C_d}{L} \rho_2 u^2
\]

2D: \( C_a = 2; \quad C_d = 6\pi \)

3D: \( C_a = 1; \quad C_d = 2\pi \)

G. Dimonte, Phys. Plasmas 7 (6), 2255-2269 (2000)
D. Oron, Phys. Plasmas 8 (6), 2883-2890 (2001)
Once corrected for decompression data agree with buoyancy-drag model
How high energy fluxes may affect Rayleigh–Taylor instability growth in young supernova remnants

C.C. Kuranz¹, H.-S. Park², C.M. Huntington², A.R. Miles², B.A. Remington², T. Plewa³, M.R. Trantham¹, H.F. Robey², D. Shvarts⁴, A. Shimony⁴, K. Raman², S. MacLaren², W.C. Wan⁵, F.W. Doss⁶, J. Kline⁶, K.A. Flippo⁶, G. Malamud¹, T.A. Handy¹, S. Prisbrey², C.M. Krauland⁷, S.R. Klein¹, E.C. Harding⁸, R. Wallace², M.J. Grosskopf⁹, D.C. Marion¹, D. Kalantar², E. Giraldez⁷ & R.P. Drake¹

Energy-transport effects can alter the structure that develops as a supernova evolves into a supernova remnant. The Rayleigh–Taylor instability is thought to produce structure at the interface between the stellar ejecta and the circumstellar matter, based on simple models and hydrodynamic simulations. Here we report experimental results from the National Ignition Facility to explore how large energy fluxes, which are present in supernovae, affect this structure. We observed a reduction in Rayleigh–Taylor growth. In analyzing the comparison with supernova SN1993J, a Type II supernova, we found that the energy fluxes produced by heat conduction appear to be larger than the radiative energy fluxes, and large enough to have dramatic consequences. No reported astrophysical simulations have included radiation and heat conduction self-consistently in modeling supernova remnants and these dynamics should be noted in the understanding of young supernova remnants.
We performed these experiments at the National Ignition Facility.
We use to NIF drive a create a high- and low-energy flux in an RT unstable system.
Typical data show qualitative and quantitative differences between cases.
We must compare the RT growth of each case

\[ \tau = \int \gamma_{RT} dt \]

\[ \gamma_{RT} = \sqrt{A(t)g(t)k} \]

A(t) is the Atwood number, g(t) is the acceleration and k is the wave number of the initial perturbation.
Experimental data and CRASH simulations are in good agreement.
Experimental data and CRASH simulations are in good agreement
CRASH simulations also show a reduction in RT growth

\[ \tau = \int \gamma_{RT} dt \]

\[ \gamma_{RT} = \sqrt{A(t)g(t)k} \]
CRASH simulations also show a reduction in RT growth

Comparison of simulated nominal and reduced opacities
## Astrophysical and experimental parameters

<table>
<thead>
<tr>
<th>Scale Parameter</th>
<th>SN1993J</th>
<th>NIF experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intershock distance $L$ (cm)</td>
<td>$2.8 \times 10^{14} t_{yr}^{0.95}$</td>
<td>0.02</td>
</tr>
<tr>
<td>Shock separation speed $U$ (cm/s)</td>
<td>$3.0 \times 10^{8} t_{yr}^{-0.046}$</td>
<td>$6.8 \times 10^6$</td>
</tr>
<tr>
<td>Ejecta density at RS (g cm$^{-3}$)</td>
<td>$3.4 \times 10^{-19} t_{yr}^{-1.6}$</td>
<td>0.026</td>
</tr>
<tr>
<td>SEL Density (g cm$^{-3}$)</td>
<td>$1.4 \times 10^{-16} t_{yr}^{-1.6}$</td>
<td>0.5</td>
</tr>
<tr>
<td>SCSM Density (g cm$^{-3}$)</td>
<td>$9 \times 10^{-19} t_{yr}^{-1.6}$</td>
<td>0.18</td>
</tr>
<tr>
<td>SEL Temperature (eV)</td>
<td>$3800 t_{yr}^{-0.092}$</td>
<td>20</td>
</tr>
<tr>
<td>SCSM Temperature (eV)</td>
<td>$7.8 \times 10^{5} t_{yr}^{-0.092}$</td>
<td>80</td>
</tr>
<tr>
<td>RS Velocity (km s$^{-1}$)</td>
<td>$1.7 \times 10^{4} t_{tyr}^{-0.046}$</td>
<td>35</td>
</tr>
<tr>
<td>FS Velocity (km s$^{-1}$)</td>
<td>$2 \times 10^{4} t_{tyr}^{-0.046}$</td>
<td>170</td>
</tr>
<tr>
<td>$Z$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$A$</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>
Key dimensionless parameters

<table>
<thead>
<tr>
<th>Dimensionless number</th>
<th>SN1993J</th>
<th>NIF experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_c/L$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-8}$</td>
</tr>
<tr>
<td>$Re$</td>
<td>$\sim 10^6$</td>
<td>$\sim 10^7$</td>
</tr>
<tr>
<td>Energy flux ratio $R$</td>
<td>$\sim 10^3$</td>
<td>$\sim 2$</td>
</tr>
</tbody>
</table>

Both systems are highly collisional with negligible viscosity and energy fluxes due to radiation and heat conduction are higher or comparable to the mechanical energy flux.
Heating is possible by radiation and electron heat conduction

\[ F_{\text{rad}} = n_e n_i \Lambda D \]  
Energy flux due to cooling by radiative losses from the shocked layer

\[ Q_e = 0.1 n_e m_e v_{e,cs}^3 \]  
Electron heat flux, 10% the free-streaming heat flux

\[ F_{\text{mech}} = \rho_{ej} v_{rs}^3 \]  
Mechanical energy flux driving the shock-heating of the shocked matter

- \( n_e \) electron density
- \( n_i \) ion density
- \( \Lambda \) cooling function
- \( D \) shocked layer thickness
- \( m_e \) electron mass
- \( v_{e,cs} \) electron thermal velocity
- \( \rho_{ej} \) ejecta density
- \( v_{rs} \) reverse shock velocity
Radiative and heat conduction fluxes are large in SN1993J

<table>
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<th>Scale Parameter</th>
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<th>NIF experiment</th>
</tr>
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<tbody>
<tr>
<td>$F_{mech}$ (ergs/cm$^2$/s)</td>
<td>$1.8 \times 10^5 t_{tyr}^{-1.76}$</td>
<td>$2.8 \times 10^{19}$</td>
</tr>
<tr>
<td>$F_{rad}$ (ergs/cm$^2$/s)</td>
<td>$3.6 \times 10^7 t_{tyr}^{-2.26}$</td>
<td>$4.2 \times 10^{19}$</td>
</tr>
<tr>
<td>$Q_e$ (ergs/cm$^2$/s)</td>
<td>$2.0 \times 10^8 t_{tyr}^{-1.76}$</td>
<td>$1.7 \times 10^{19}$</td>
</tr>
</tbody>
</table>

$$R = \frac{Q_{ecs} + F_{rad}}{F_{mech}}$$

<table>
<thead>
<tr>
<th>Energy flux ratio $R$</th>
<th>$10^3$</th>
<th>2</th>
</tr>
</thead>
</table>
Conclusions

• We create and observe the evolution of hydrodynamic instabilities in the HEDP regime
• We have observed the reduction in KH growth due to compressibility effects (Wan, PRL 2015)
• We have observed mode coupling in RM (Di Stefano, APL 2015)
• We have observed ablative stabilization of the RT instability (Kuranz, Nature Communications 2018)
  — Future work through NIF DS to measure temperature