Compressible Hydrodynamics on the Omega Laser: Motivated by Astrophysics

R. P. Drake, P. Keiter, K.E. Korreck, K. Dannenberg
University of Michigan

H.A. Robey, T.S. Perry, J.O. Kane, O.A. Hurricane, B.A. Remington, D.D. Ryutov, R.J. Wallace
Lawrence Livermore National Laboratory

J. Knauer, University of Rochester
R. Teyssier, CEA Saclay, France
A. Calder, B. Fryxell, R. Rosner, U. Chicago
Y. Zhang, J. Glimm, SUNY Stony Brook
J. Grove, Los Alamos National Laboratory
D. Arnett, University of Arizona
R. McCray, Univ. of Colorado
N. Turner, J. Stone, Univ. of Maryland

IWPCTM, Pasadena, CA, December 2001

Work supported by the U.S. Department of Energy under grants DE-FG03-99DP00284, DE-FG03-00SF22021 and other grants and contracts
We use the Omega laser to explore phenomena that matter for astrophysics

- Our goal is to experimentally ground the understanding of important mechanisms
  - Theory or simulation suggests explanations for astrophysical data
  - The important mechanisms have often never been observed anywhere
  - We produce and observe these mechanisms in scaled experiments
  - This tests the theory and simulations
Astrophysical systems provide strong motivations for hydrodynamic studies

2D Simulation of SN 1987A

SN 1987A provided compelling evidence that hydrodynamic instabilities are essential to supernovae
- Light curve
- Spectra

Compressible turbulent mixing is also present in other astrophysical systems
- Supernova Remnants
- Jets
- Shocks into clouds

Well-scaled experiments are feasible: D.D. Ryutov, et al.
Phys. Plasmas 8, 1804 (2001)

The velocities of the heavy element remain larger than predicted.

Muller, Fryxell, and Arnett (1991)
We often must explain to astrophysicists that we don’t understand hydrodynamics

- We understand the **EQUATIONS** of hydrodynamics
  - But NOT numerical simulations
    - They are like series solutions to differential equations without the ability to quantify errors
    - Vanishing metrics add complications
    - No stochastic backscatter in current simulations (Leith ‘90, Piomelli ‘91)
    - Also no full turbulence

**Codes disagree about structure**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>RT growth factor, $\alpha$</th>
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</thead>
<tbody>
<tr>
<td>‘91 Youngs</td>
<td>0.04-0.05</td>
</tr>
<tr>
<td>‘91 Youngs</td>
<td>0.03</td>
</tr>
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<td>‘99 S.Y. Chen</td>
<td>0.043</td>
</tr>
<tr>
<td>‘99 Dimit et al.</td>
<td>0.016</td>
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<tr>
<td>‘99 Cheng et al.</td>
<td>0.08</td>
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<tr>
<td>‘99 Glimm et al.</td>
<td>0.07</td>
</tr>
<tr>
<td>‘99 Oparin</td>
<td>0.075</td>
</tr>
</tbody>
</table>

- **This can matter for astrophysics**
- **Examples:**
  - Size of mix layers is uncertain
  - Small details affect production of “hydrodynamic bullets” or other important structures
Our hydrodynamic experiments all use similar target packages.

Photograph of target:

- Target package
- Backlighter
- Au Shield
- to gated X-ray framing camera

CAD drawing of target & beams:

- Backlighter beams generate x-ray flux for imaging
- 6 to 10 drive beams launch a strong shock into the target materials

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Our experiments have been aimed at addressing the obvious first question:

- **THE FIRST QUESTION:** Can the codes follow the evolution of such hydrodynamics deep into the nonlinear regime?
Our experiments at Omega have addressed this question while probing several mechanisms present in supernova explosions.

**Spherical divergence**

**Multi-interface coupling**

**2D vs. 3D instability**

**2D simulation of SN1987A**

Muller, Fryxell, and Arnett (1991)

**Multi-mode instability**

Drake et al., ApJ Jan. ‘02

**Finished in September**

**Ongoing experiments**

Kane et al., PRE 63, 55401 (2001)

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Coupling between spatially separated interfaces in a SN is studied with a multi-layer target

Exploded view of multi-layer target

Simulation of this experiment by the ASCI code FLASH at Chicago

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The interface coupling experiments are typical of what we have found.

THE FIRST QUESTION: Can the codes follow the evolution of such hydrodynamics deep into the nonlinear regime?

ANSWER: Yes, eventually, based on work to date.

But not in the first run in every version.
Another example: effect of spherical divergence is studied by laser illumination of a perturbed hemispherical shell

- The unperturbed hemispherical shell remains intact indicating no significant perturbation from the laser drive

- The perturbed shell ($\lambda=70\mu m$, $a_{p.V}=10\mu m$) breaks up due to R-T and R-M instability
Perturbation growth in spherical geometry is observed to be significantly smaller than in planar geometry.

Growth in spherical geometry is reduced due to:

- Wavelength increase due to divergence
- Possible effect of shock proximity

Same initial perturbation
\[ \lambda = 70\mu m, \ a_{p,v} = 10\mu m \]

Comparison of spherical vs. planar

Divergent simulation experiment

Planar simulation experiment

CALE vs. data

Spike-bubble amplitude (\(\mu m\))

Time (ns)

0 5 10 15 20

0 100 200

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CALE results show spike development

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We used FronTier to demonstrate mapping to a purely hydrodynamic code

- **FronTier**
  - Front tracking by independent updating on the two sides of the discontinuity: there is never finite differencing across the front
  - The common MUSCL (Monotonic Upstream-centered Scheme for Conservation Laws) approach is used to advance the hydro normal to the front and elsewhere
  - For this problem, outgoing boundary conditions are used within the capsule and at the outer boundaries; the remainder of the axis of symmetry is a reflecting boundary
  - Results shown on 1.5 mm x 1.5 mm scale
Our hydrodynamic experiments are ready to ask the second question

- THE SECOND QUESTION: Does this medium (plasma) exhibit a transition to turbulence like that seen in fluids?
- A: In ongoing experiments, we are working to find out.
  - If so, this will be a much bigger challenge for simulations.
  - It will probably also mean that much published astrophysical hydrodynamics is wrong.


We are excited about our progress and look forward to forthcoming experiments.

- We’ve made demanding tests of deep nonlinear hydrodynamics at high energy density.
- Next: Push high energy density systems into the “fully turbulent” regime.

At the University of Michigan in Ann Arbor.