Supernovae: Elements of Theory, Computations, Experiments

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Lecture 3

High-Energy Density
Supernova Experiments
Recap

- Thanks to Lecture 1, we now are excited about coming back to our offices to verify and validate our codes.

- Thanks to Lecture 2, we now appreciate the level of physical complexity of exploding stars that computer simulations are to capture.

- Clearly, we would be much better off if supernova conditions and physics was reproduced in controlled laboratory settings.

- Plus that offers opportunities for conducting code validation.
**HED Laboratory Astrophysics**

- **High Energy Density**: pressure > 1 Mbar (100 Mbar in IFC), energies > $10^{11}$ J/m$^3$ or > $10^{12}$ erg/cm$^3$, temperatures > $5 \times 10^6$ K or > 400 eV

Davidson et al. (2004)
# High-Energy Density Laboratory Astrophysics

<table>
<thead>
<tr>
<th>Ablation</th>
<th>Nebulae, molecular clouds</th>
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<tbody>
<tr>
<td>Equation of state</td>
<td>Planetary interiors</td>
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<tr>
<td>Jets</td>
<td>Protostars, active galaxies</td>
</tr>
<tr>
<td>Magnetic dynamo</td>
<td>Stellar physics, accretion disks</td>
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<td>Magnetic reconnection</td>
<td>Solar physics, ISM</td>
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<tr>
<td>Nuclear cross sections</td>
<td>Stellar evolution, nova/SN/xrb/GRB/etc</td>
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<td>Opacities</td>
<td>Radiatively driven winds</td>
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<td>Particle acceleration</td>
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<td>Plasma emission</td>
<td>Interstellar medium, X-ray binaries</td>
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<tr>
<td>Radiative shocks</td>
<td>SN explosions/remnants, jets, ISM</td>
</tr>
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<td>RMI/RTI interface dynamics</td>
<td>Supernovae, stellar interiors</td>
</tr>
<tr>
<td>Ultrastrong fields</td>
<td>Pulsars, magnetars, GRBs...</td>
</tr>
</tbody>
</table>

**HEDLA bi-annual conferences**

Facebook, www.hedla.org
HEDLA Founding Fathers

Dmitri Ryutov
Paul Drake
Bruce Remington
(Infamous) richness of computational models

- Triple Point
- Kelvin-Helmholtz
- Leading Shock Front
- Rayleigh-Taylor
- Reverse Shock
- Fallback + Neutrino wind
- Kelvin-Helmholtz
- Rayleigh-Taylor
- Reverse Shock
Mixing after the Shock Breakout (II)

- Time-dependent deceleration of dense layers due to unsteady supernova shock motion through the
Angular evolution of the ejecta mass distribution

SASI imprint

expansion toward poles
Post-Explosion: Shocking the Envelope
Following SN 1987A observations, $^{56}\text{Ni}$ distribution evolution is one of the primary model evaluation criteria.
Young ccSNR with radioactive decay
HEDLA Connection to Supernovae

- Initially motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

Research directions

- **SASI**: ccSN explosion
- **DivSNRT**: ccSN post-explosion RT mixing
- **RT**: the Braginskii model
**HED SNRT Experiment Scaling**

**Fundamental Hydro Properties**

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**TABLE 2**

**Derived Parameters**

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This apparent difference in Re is not a real issue for supernova experiments.
Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical... => spherical targets and diverging and/or converging flow configurations
HED/SN scaling

\[
(Eu)^2 = \frac{1 + \frac{\gamma - 1}{2} M_{pre}^2}{M_{pre}^2 - \frac{\gamma - 1}{2}}
\]

experimentally feasible region
Can We Test It?

NIF design work w/Tim Handy at FSU in progress

Ohnishi et al. (2008)

Gedanke Experiment

possible NIF design
Can We Test It?

Gedanke Experiment

imploding foil (accretion matter)

void or low-density foam

high-density (hemi)sphere (central object)

wall

Can We Test It?

- NIF concept development: Handy et al. (2012)

Ohnishi et al. (2008)
NIF SASI Study

Handy et al. (2012)
large amount of a highly stable, shocked HED plasma
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The apparent difference in Re is not a real issue for DivSNRT.
Surprises from HED RT Experiments

- Smooth spike morphology
- Spike mass extensions

Density profile analysis

Kuranz et al. (2009)
Successful Gedanke Experiments

○ Smooth spike morphology
  ○ Thermal conduction?

○ Spike mass extensions

Harden & Plewa (2009)
Gedanke Experiments

- Smooth spike morphology
  - Thermal conduction?

Success!

- Spike mass extensions
  - Not seen in the above model with thermal conduction, nor in pure hydro models

Failure!

Harden & Plewa (2009)
Discovery Science, At Last?

- In-situ generation of magnetic fields via the Biermann battery mechanism (Kuranz et al. 2010)
  - cross of electron density and temperature gradients

\[
\frac{\partial B}{\partial t} = \frac{c k_B}{e} \left[ \nabla T_e \times \nabla \ln n_e \right]
\]

- usually neglected term in the induction equation
- induced magnetic field => extra pressure

Fryxell et al. (2010)
Biermann battery only
Discovery Science, At Last?

- In-situ generation of magnetic fields via the **Biermann battery** mechanism (Kuranz et al. 2010)
  - cross of electron density and temperature gradients
  \[
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  \]
  - usually neglected term in the induction equation
  - induced magnetic field => extra pressure

- **Consequences for supernovae**
  - Magnetic pressure contribution to the thermal pressure at the deflagration front (impact unknown)
  - Rayleigh-Taylor spikes in core-collapse (estimated negligible)

Fryxell et al. (2010)
Non-ideal MHD equations

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

\[ \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left( \rho \mathbf{u} \mathbf{u} - \frac{\mathbf{B} \cdot \mathbf{B}}{4\pi} \right) + \nabla P = \rho \mathbf{g} \]

\[ \frac{\partial \rho \mathbf{E}}{\partial t} + \nabla \left[ (\rho \mathbf{E} + P) \mathbf{u} - \frac{\mathbf{B} \cdot \mathbf{B}}{4\pi} \cdot \mathbf{u} \right] = \rho \mathbf{u} \cdot \mathbf{g} + \nabla \cdot (\mathbf{q}_e + \mathbf{q}_i) + Q \]

\[ \frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{B} - \mathbf{B} \mathbf{u}) = \frac{c}{e} \left[ \nabla \times \frac{\nabla P_e}{n_e} - \nabla \times \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi n_e} - \nabla \times \frac{\mathbf{R}_T + \mathbf{R}_U}{n_e} \right] \]
Verification tests

A number of test simulations were done to verify that our magnetic field generation and anisotropic heat conduction modules were working properly. The first test is for the Biermann battery term with the following initial conditions (Toth et al., 2010):

\[ \mathbf{B} = 0, \mathbf{u} = 0, n_e = n_0 + n_1 \cos(k_x x), p_e = p_0 + p_1 \cos(k_y y), \]

\[ k_x = k_y = \frac{\pi}{10}, n_0 = p_0 = 1, n_1 = p_1 = 0.1 \]

The exact solution for the rate of magnetic field generation is:

\[ \frac{\partial B_z}{\partial t} = -\frac{k_x k_y n_1 p_1 \sin(k_x x) \sin(k_y y)}{[n_o + n_1 \cos(k_x x)]^2} \]
Biermann battery term verification

(left panel) Numerical solution of the generated magnetic field source term, \( \frac{\partial B_z}{\partial t} \), on a 160 x 160 grid.
(right panel) Error relative to the analytical solution. Time \( t = 0.05 \) s.
More comprehensive BB test

Magnetic field generation source term, $\dot{B}_z$ as a function of electron number density and temperature gradient orientation.
Thermal transport is anisotropic

\[
T(r, \theta) = \begin{cases} 
12 \text{ if } (0.5 \leq r \leq 0.7) \text{ and } \left( \frac{11}{12} \leq \theta \leq \frac{13}{12}, \right), \\
10 \text{ otherwise}
\end{cases}
\]

Results of the Parrish & Stone anisotropic thermal conduction verification test on a 400 x 400 grid. The temperature distribution is shown at times t = 0, 10, 50, and 200. Heat flows along magnetic field lines, as expected.
Convergence of the L1 error norm of temperature as a function of the mesh resolution for the Parrish & Stone test problem. Our results are shown in red, and those of Parrish & Stone are shown in blue.
Extended Physics RT Model

- Single mode RT
- Generalized Ohm’s law with the Braginskii coefficients
Braginskii’s RT Model (early time)
Braginskii’s RT Model (late time)
Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical… => spherical targets and diverging flow configurations, or DivSNRT
Purpose

- This experiment attempts to observe extensive Rayleigh-Taylor driven mixing in the exploding massive stars.
- Data will give physics insights of inter-shell penetration outwards to surface via turbulent mixing, shell breakouts, growth of secondary instabilities, vorticity-enhanced mixing.

Comments

- NIF is the unique facility enabling studies with spherical targets (diverging flow geometry)
- Natural continuation of the previous work on Omega
- New diagnostics (IXTS, Dante, proton radiography…) in addition to standard diagnostics (x-ray radiography)
- 15 shots starting in FY 2013 ($70k per target cost)
Purpose

- DivSNRT experiment is designed to study and reproduce by means of a well-scaled experimental design the extensive mixing observed in the exploding massive stars.

- DivSNRT experiment will probe fundamental physics of
  - inter-shell penetration outwards to surface via turbulent mixing;
  - shell breakouts;
  - growth of secondary instabilities;
  - vorticity-enhanced mixing.
DivSNRT Team

- Paul Drake (experimenter, UM)
- Mike Grosskopf (designer, UM)
- Tim Handy (designer, SN hydro exp, FSU grad)
- Konstantinos Kifonidis (designer, SN hydro mixing)
- Carolyn Kuranz (experimenter, UM)
- Aaron Miles (designer, LLNL)
- Frank Modica (designer, multiphysics RT, FSU grad)
- Hye-Sook Park (experimenter, liaison scientist, LLNL)
- Tomasz Plewa (PI, FSU)
- Kumar Raman (designer, LLNL)
- Bruce Remington (experimenter, LLNL)
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- Much more mass involved than in the planar case, thus requiring much more energy to drive
- Early attempts on Omega (Drake et al.) unsuccessful (shell breakup) => NIF!
DivSNRT 3 Layer Target

0.1g/cc CRF foam

1 g/cc CH

Ag plate pressure retainer

CHI tracer, 200 μm wide small section in the middle

Cu

0.0

0.728

0.928

1.928

20 μm thick CH ablator inside

6.528 mm radius
DivSNRT Diagnostics
DivSNRT Theory for Target Design

- **A. Miles (2009)** analysis of the blast wave instability problem provides analytic framework for target design
- The model combines drag-buoyancy, bubble merger, and assumes (quasi) self-similarity to account for the flow divergence and compressibility effects
- Demonstrates that the memory of the explosion is generally preserved by the system unless modes are very high (higher than considered typical in ccSN)
- **High-amplitude perturbations favor RM over RT**, at least at early times, resulting in the shock proximity to growing spikes (if $ka_0 > 1/3$ for adiabatic index $5/3$; if $ka_0 > 0.2$ for index $4/3$).
Relevant Computer Model

- Radiation hydrodynamics with the laser energy deposition.

\[
\partial_t U + \nabla F(U) = S(U)
\]

- A coupled set of parabolic and hyperbolic PDEs
- Radiation transport in multigroup flux limited diffusion
- Linearized Newton-Krylov solver
- Ray tracing for the laser energy depositions
- Level sets for tracing material interfaces
- Adaptive in space and time (AMR)
DivSNRT Target Evolution

\((k, k_{a_0})\): inner(4,2), outer(10,2)
DivSNRT Target Evolution

(k, ka₀): inner(10, 1), outer(2, 2)
SN Model vs Sample Designs

inn: $k=4, k_a=2$
out: $k=10, k_a=2$

inn: $k=10, k_a=1$
out: $k=2, k_a=2$
CALE Designs vs SN Model
## Proposed Schedule of Shots

### FY13

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Target Type</th>
<th>Perturbation between interfaces</th>
<th>Drive</th>
<th>Diagnostic Technique</th>
<th>Note</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>hemispherical 2 layers</td>
<td>none</td>
<td>80-300kJ 3ns</td>
<td>radiography</td>
<td>drive test, RT/RM at a nominally smooth interface</td>
</tr>
<tr>
<td>2</td>
<td>as above</td>
<td>((kA)_1)</td>
<td>as above</td>
<td>as above</td>
<td>RT/RM at high-Z/med-Z interfaces</td>
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<tr>
<td>3</td>
<td>as above</td>
<td>((kA)_2)</td>
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<td>4</td>
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<td>reproducibility test</td>
</tr>
<tr>
<td>5</td>
<td>hemispherical 3 layers</td>
<td>none</td>
<td>as above</td>
<td>as above</td>
<td>drive test, RT/RM at a nominally smooth interface</td>
</tr>
</tbody>
</table>

### FY14

3 layer target studies, demonstrate Imaging X-ray Thomson Scattering technique

### FY15

3 layer target studies with aspherical shocks with radiography and IXTS
Summary

- Mixing of elements in core-collapse SNe
  - Exploring possible SASI experimental designs
  - SASI asymmetries may suffice to explain SN 1987A and alikes
  - Crab-like spongy morphologies at late times (months) due to radioactive decay

- In-situ generated magnetic fields
  - Constructed required computational machinery
  - Identified as a possible new physics in HED RTI experiments
Can We Test It?

NIF design work w/Tim Handy at FSU in progress

Ohnishi et al. (2008)

Questions and Discussion